Timing Laboratory Updates at the US Naval Research Lab

Civil GPS Service Interface Committee

Timing Sub-Committee Meeting

Convened with ION GNSS+

Denver, Colorado

Monday 11 September 2023

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Advanced Space PNT Branch

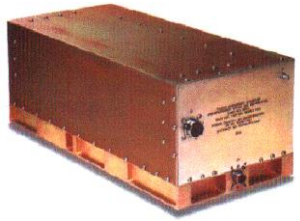
U.S. Naval Research Laboratory

Washington, DC

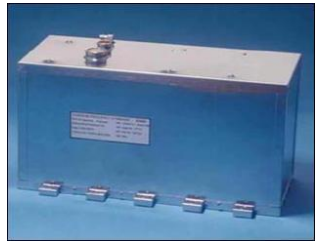
GPS Extended Clock Life Testing

Life testing serves as a baseline for GPS on-orbit clock performance.

- Provides long term (multi-year) testing that cannot be performed in the manufacturer's environment.
- Installation duplicates satellite mount.
- Environmental controls mimic temperature and pressure experienced on orbit.
- Evaluation of performance parameters.
  - Clock phase output and telemetry monitors.
  - Local environmental measurements.
- Identify and report on premature failure modes.
- Validate performance ahead of actual flights.



Cs AFS



Rb AFS

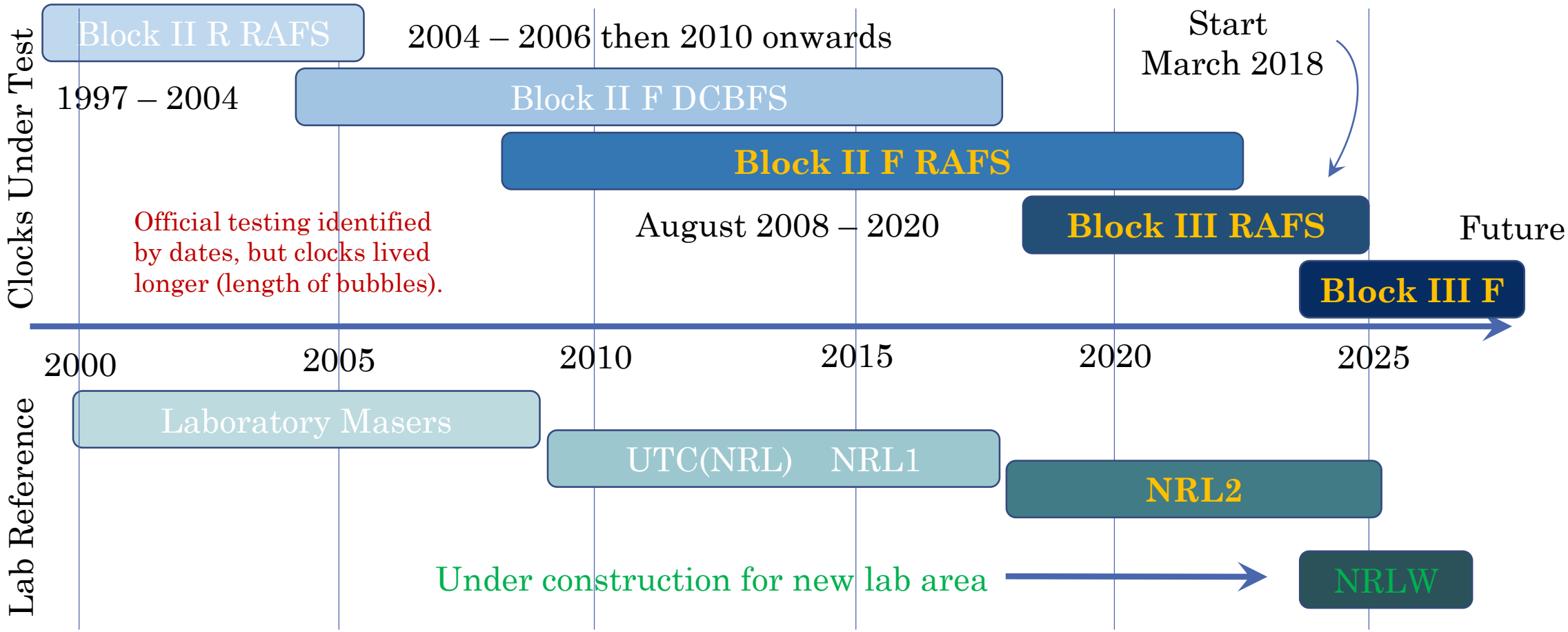
Precise Clock Eval Facility

Joint collaborative effort involving:

NRL USSF Clock & Satellite manufacturers

GPS Extended Clock Life Testing

Series of GPS satellite clocks have been tested over the past few decades.



UTC(NRL) Reference

Key benefits of clock ensemble reference:

- Improved stability against high performing GPS clocks.
- Continuity in event of a maser requiring service.

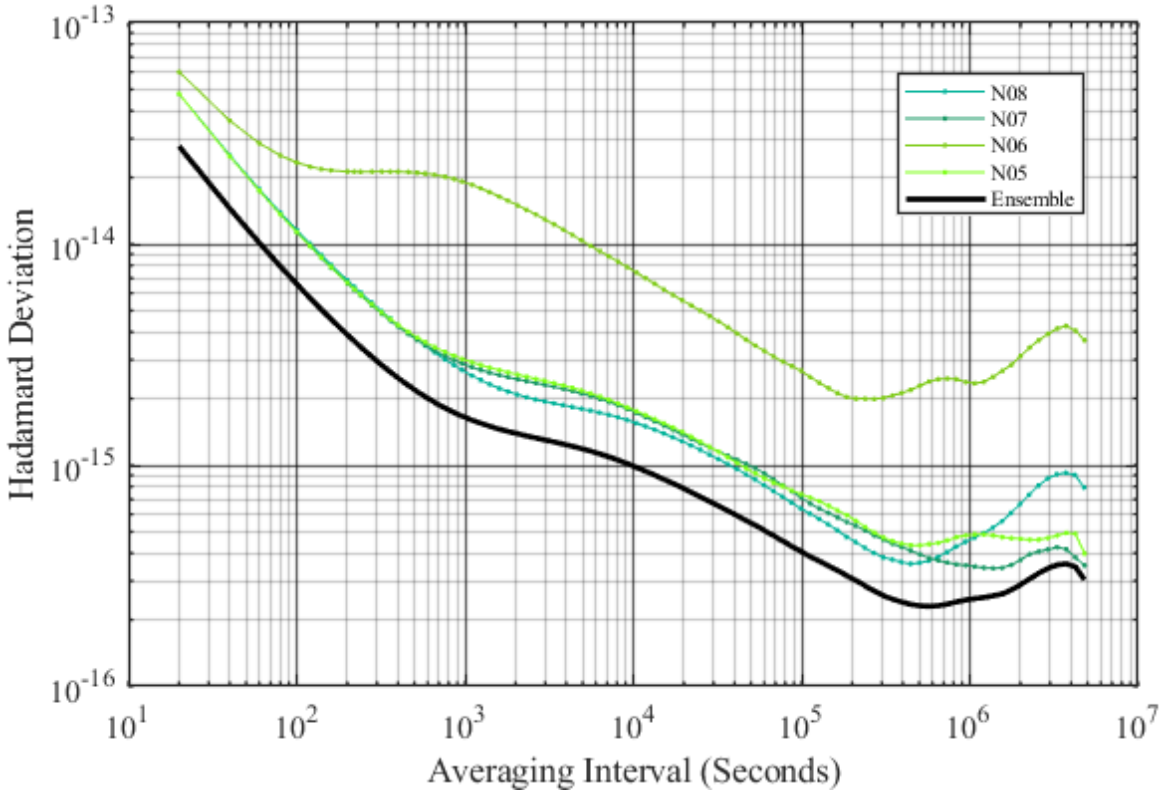
Members of the NRL clock ensemble:

- 6 Hydrogen Masers
- 3 Cesium (5071A)
- Link to UTC(USNO)

Microsemi HMH2020

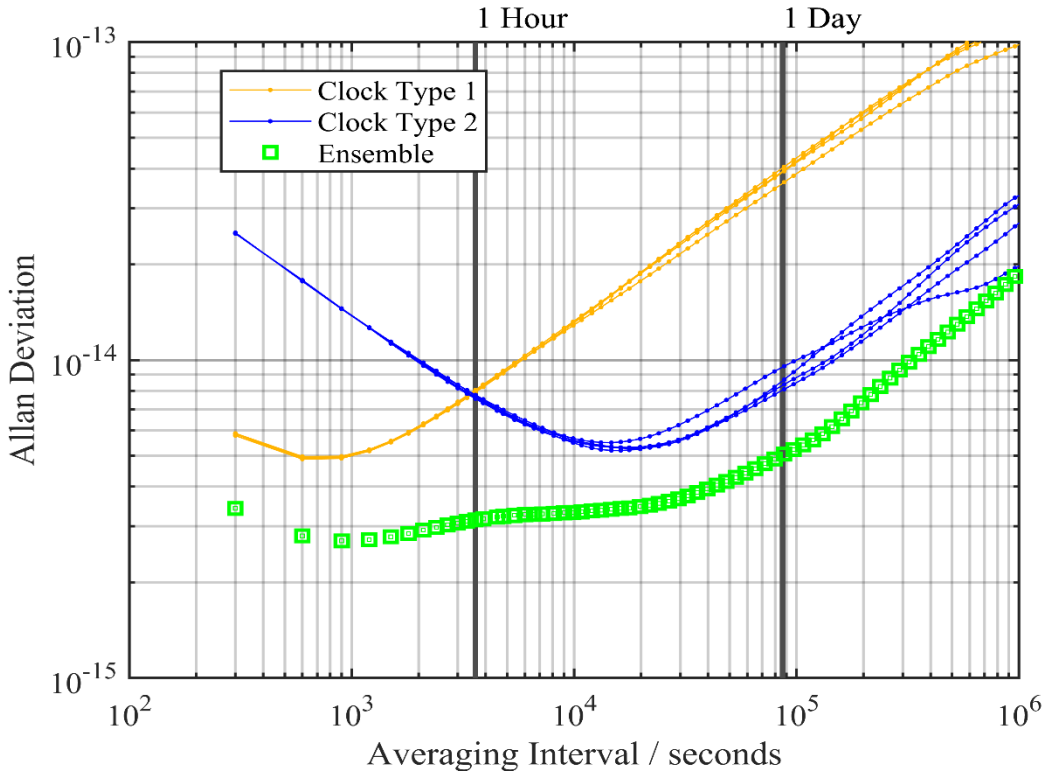
Cesium 5071 A

Stability of Selected Hyrodgen Masers versus Ensemble



Clock Multi-weighting

The ensemble algorithm has a dynamic clock weighting routine that updates the weights from one epoch to the next depending on: clock noise spectral densities, clock state error covariance, and recent clock anomalies.



- Utilize multi–weighting to gain the most stable components of the various clocks.
- Allows the ensemble to achieve better stability for a wider range of averaging intervals.
- One set of weights exists for each noise process. For example, the constrain on the phase state random walk is:

$$\sum_{i=1}^{N} w_{pi}\left[\hat{x}_p(t_k) - \hat{x}_p(t_k^-)\right] = 0$$

Automatic Responses

If a break in the clock measurement has been identified, the break handling algorithm attempts to adjust the clock state and covariance to match.

Phase Break

Following a break in phase, an impulse can be added immediately:

$$\mathbf{x}(t_k) = \Phi\,\mathbf{x}(t_{k-1}) + \delta\mathbf{x}$$

- Typically the filter estimates converge to the new phase value quickly (within one epoch).
- Clock can participate as ensemble member immediately after the impulse.

Frequency Break

After a frequency break, one can add to the process noise parameter to inflate the covariance:

$$\mathbf{Q} = \int_{t_j}^{t_k} \Phi\,(\,\mathbf{S} + \delta\mathbf{S}\,)\,\Phi^T\,dt$$

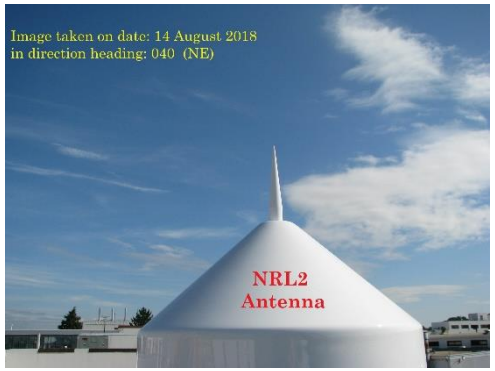
- Gives flexibility for the filter to converge on a new frequency value.
- Clock must lose ensemble membership until state error covariance reduces.

For a laboratory timescale, frequency breaks are better corrected after the fact with a timescale reprocessing for the day containing the break event. These are rare during normal operation.

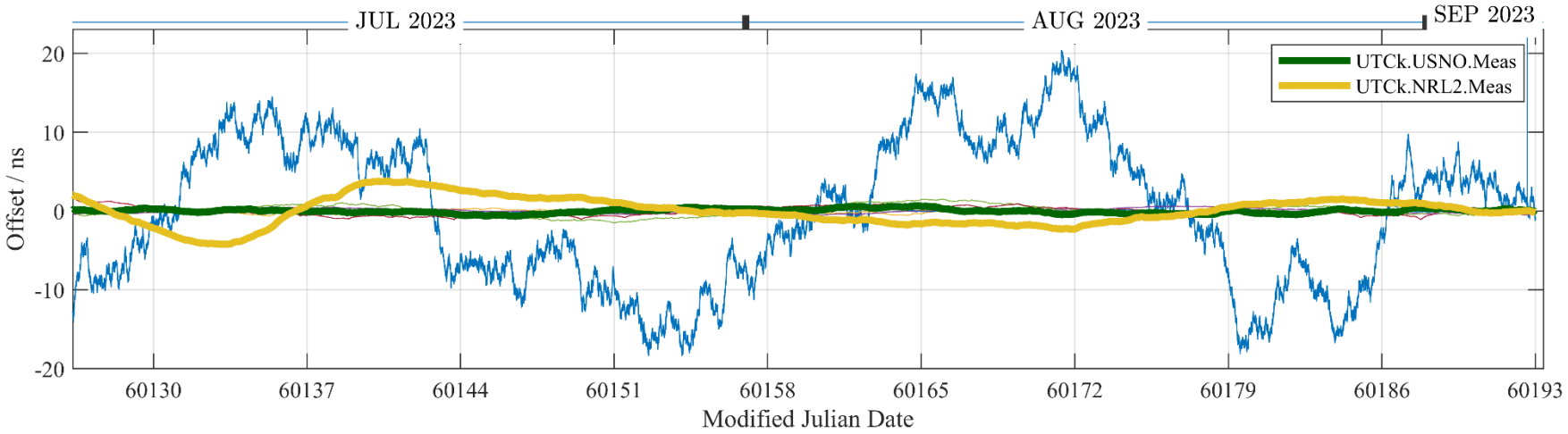
UTC(NRL) Reference

Contributions to UTC and IGS Network facilitated by:

- Septentrio PolaNT antenna
- Septentrio PolaRx5TR receiver
- Microsemi Auxiliary Output Generator



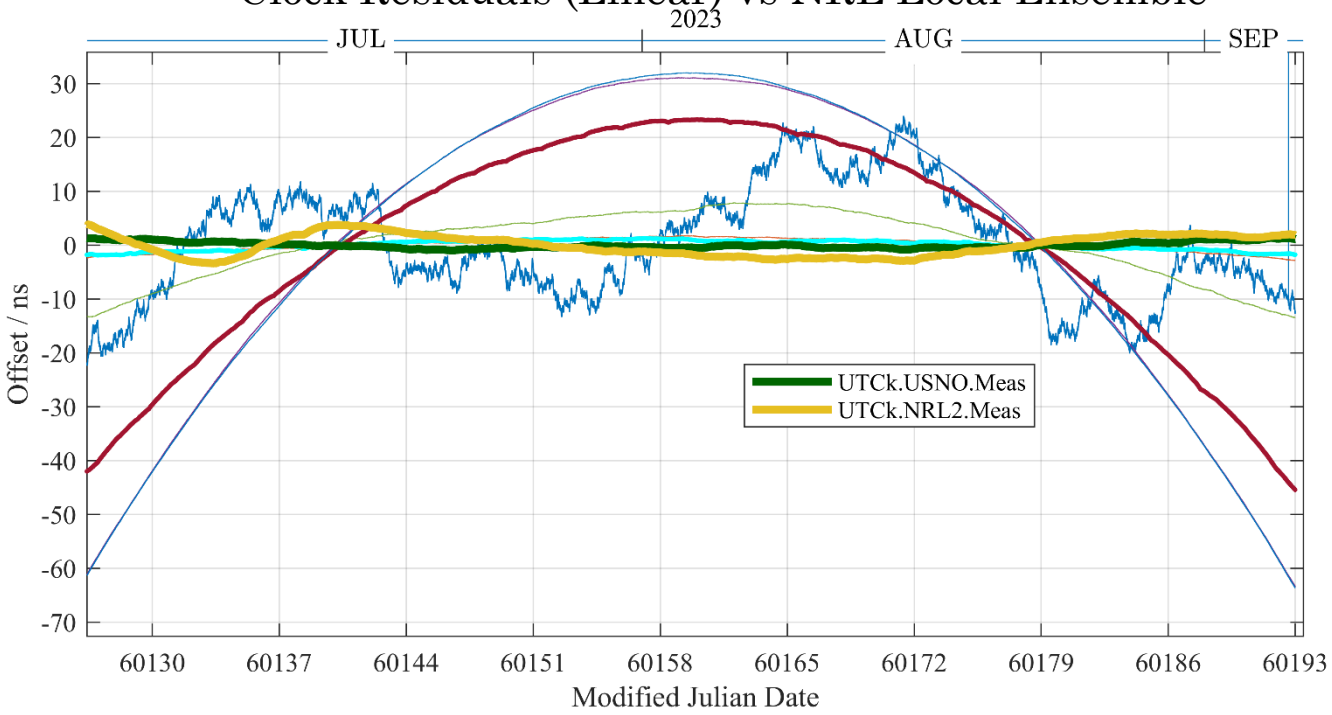
Clock Residuals (Quadratic) vs NRL Local Ensemble

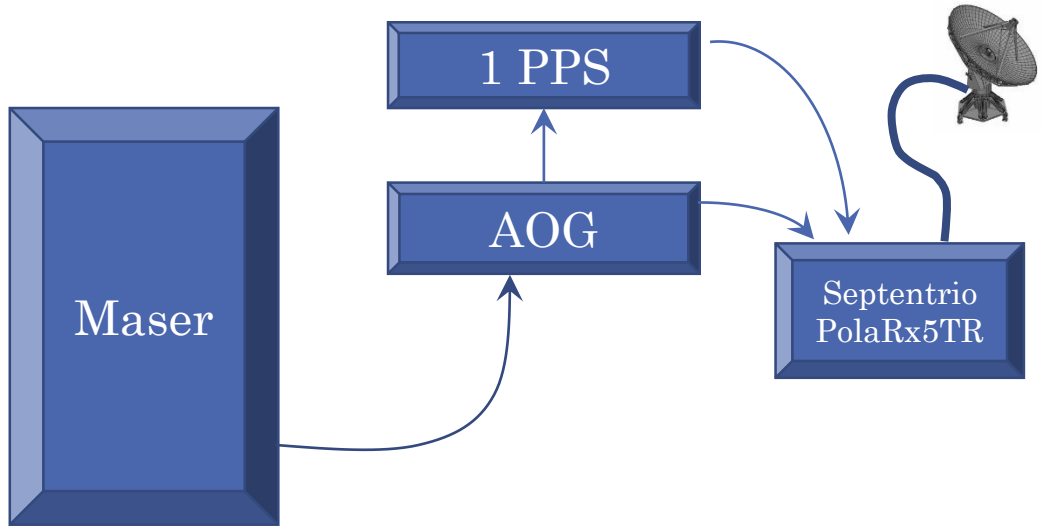


UTC(NRL) Signal Generation

UTC(NRL) signal generated by any chosen Hydrogen maser, but each has its own drift.

Auxiliary Output Generator (AOG) synthesizes an output signal based on input maser and commands from steering control.





Maser Stability:
(Hadamard Dev)

~ 7 E–16 / day

Deterministic drift:
(observed up to)

~1 E–15 / day.

AOG

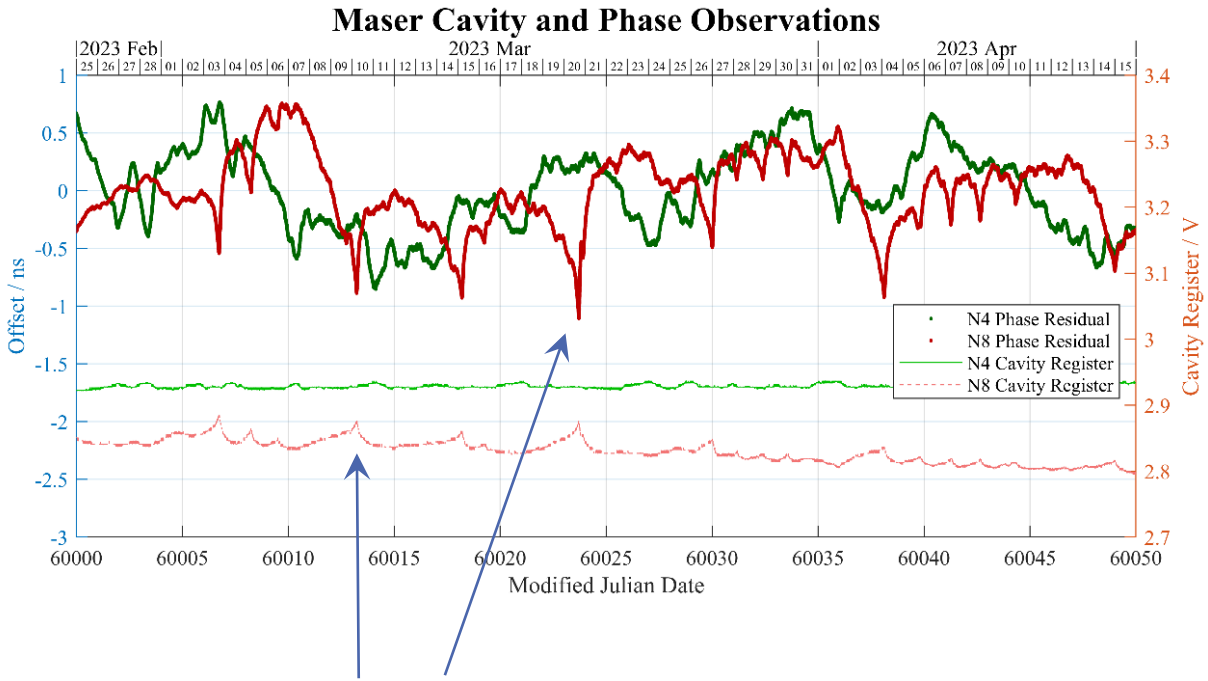
Compensates for drift and clock process noise.

Newer masers tend to have higher drift than older ones.

Timing Receiver

Accepts external clock so observation files can be used to compare UTC signal at this station with others.

UTC(NRL) Maser Swap

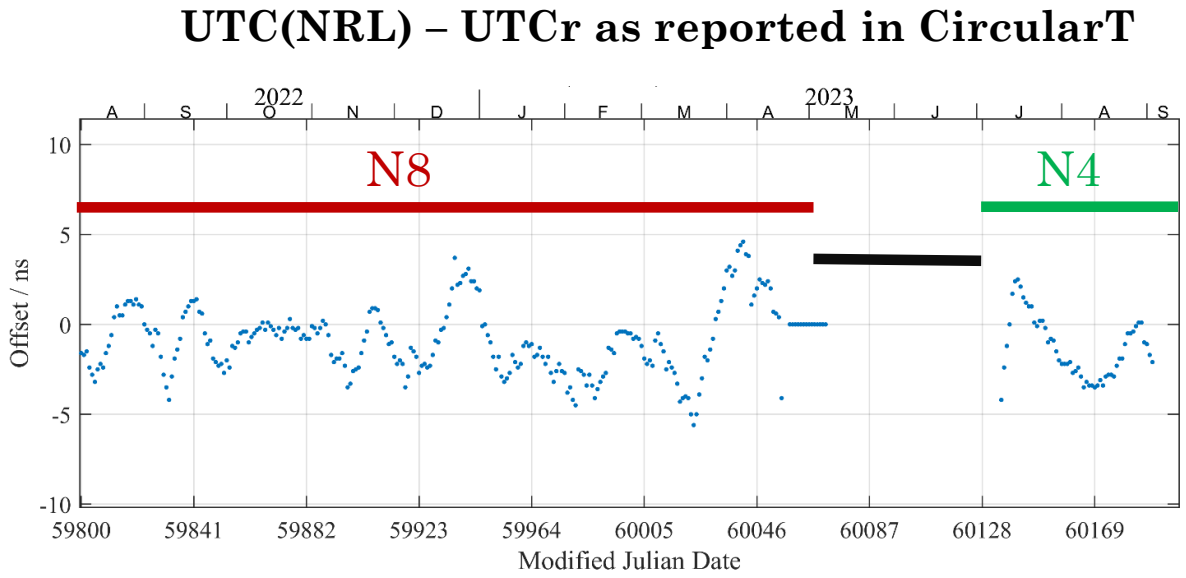


Cavity register problems causing (N8) causing localized frequency shifts.

Switch to N4 following outage, which is not plagued with this problem.

Two month outage in UTC(NRL) signal during early summer 2023 when maser signal was replaced and receivers re-calibrated.

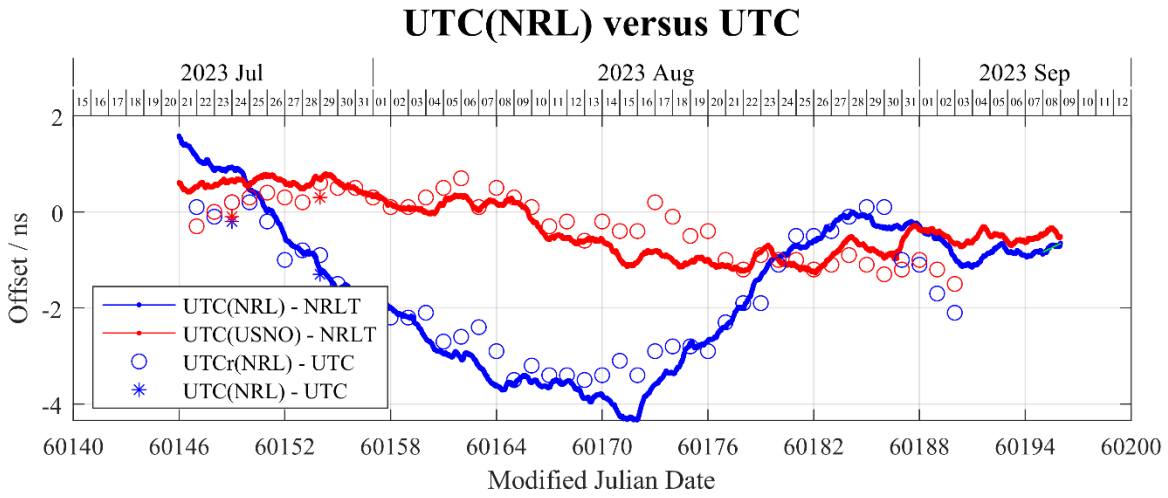
Outage period identified by black line below.

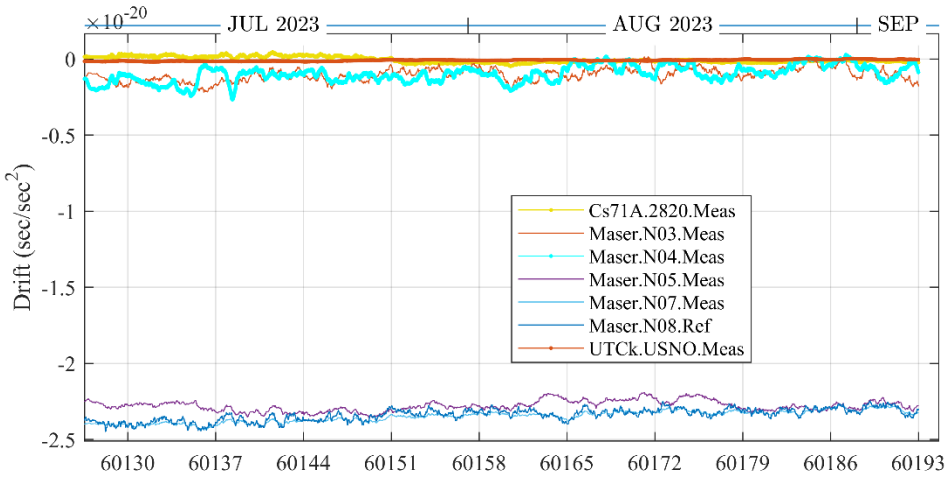


UTC(NRL) Control Loop

Controls to maintain the UTC output signals based on observations from either the local timescale or the BIPM.

- Drift adjustments — 4 times per day. — Constant adjustment of 1.44 pp17.
- Steer to NRLTSC — 1 time per day. — Linear Quadratic Gaussian response to offset.
- Adjust to UTCr — 1 time per week. — Linear fit of timescale data to UTCr points.





Timing System Development and Testing

Updated or new capabilities on the horizon with several sponsored developments.

TFC

Time and Frequency Component

- Designed by Brandywine Communications.
- NRL supported with some firmware development.
- Extended operations testing on-going at NRL.

Autonomous capabilities being tested in this design.

Testing presently under way at NRL.

NGAC

Next Generation Atomic Clock

- Cesium Model 5071A remains a reliable clock for critical operations.
- Program seeks to expand the suite of clocks that can match this capability with:
  - Lower SWaP
  - Better performance
  - Cost effective

Future testing possible depending on candidate clocks.

GNSS Receivers

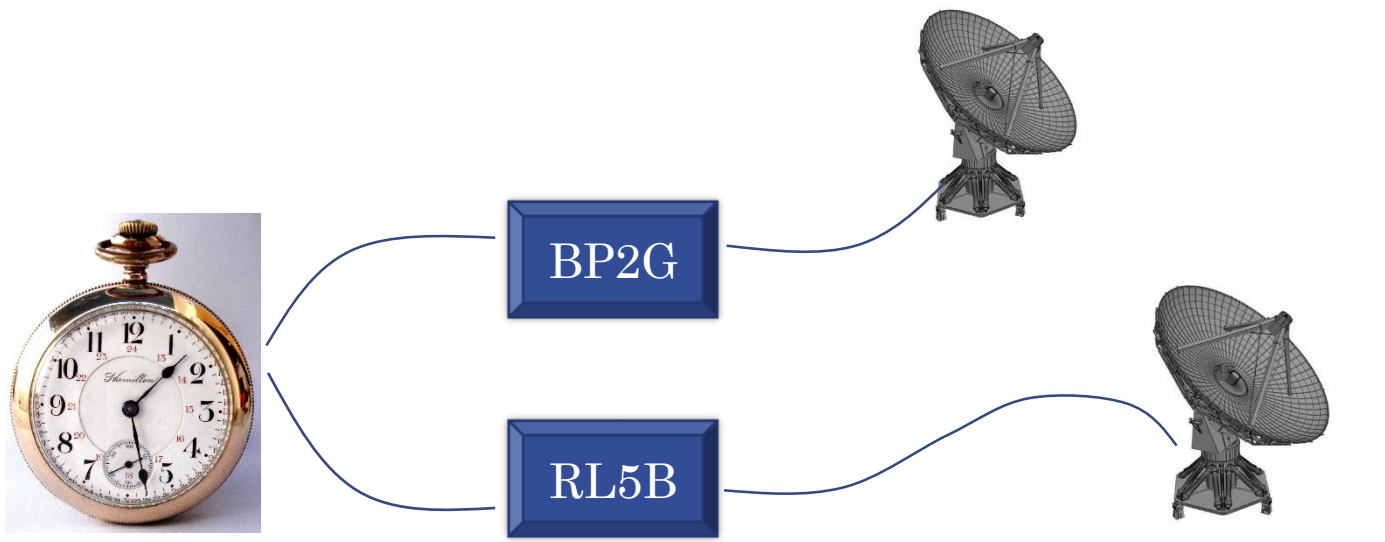
(Not necessarily ONR sponsored)

- Analyze output of receivers that claim sufficient timing output.
- Comparison can be made to UTC at either NRL or USNO.
- Simulators on site allow us to specify scenarios and test receiver performance under various conditions.

UTC Site Calibration Status

Take advantage of BIPM's traveling receiver to perform standard relative calibration of UTC(NRL) GNSS equipment:

- Supply common external clock to both receiving chains.
- Cable delays are all measured so that the only unknown delays are those through the antenna and receiver.



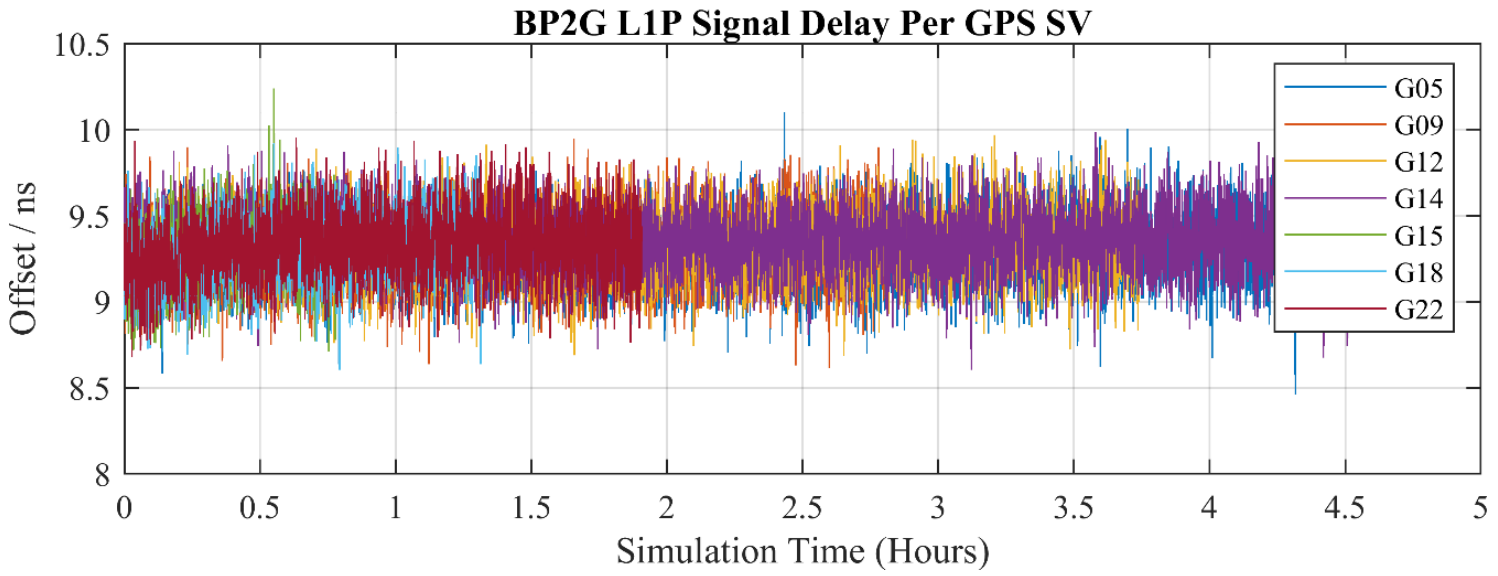
Antenna installation

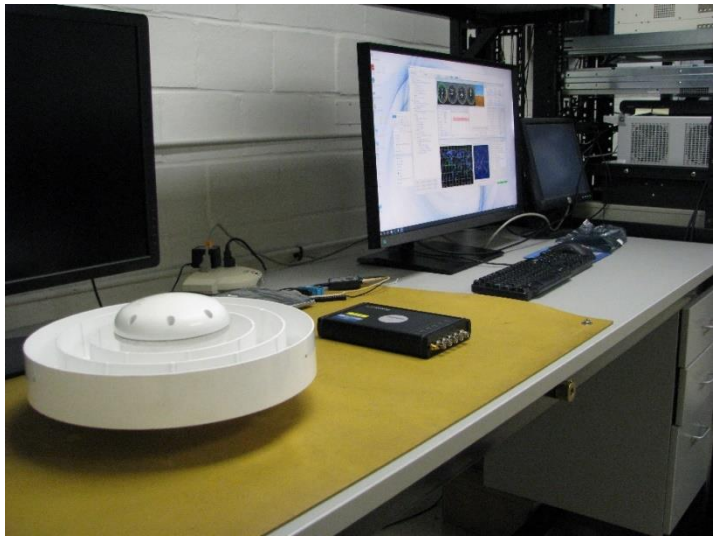
Subject receivers

BIPM Traveling Receiver Calibration

Measured several components of BIPM's traveling calibration kit:

- Receiver BP2G measured with Spirent GPS 9000 Simulator
- Antenna measured in anechoic chamber with Fieldfox Network Analyzer

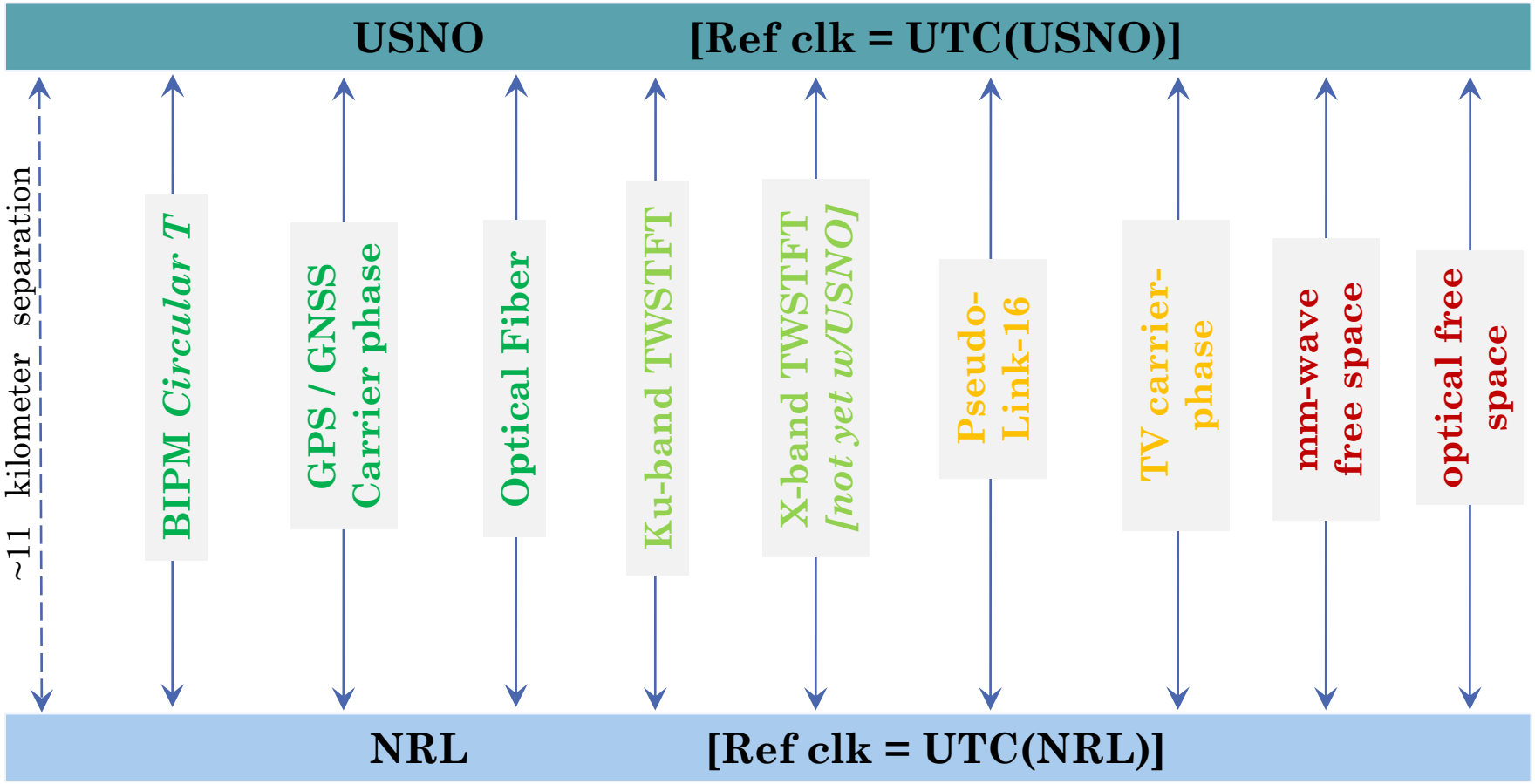




GPS Simulator Station

Results largely consistent with a relative calibration made earlier at the BIPM.

NRL – USNO Time Transfer Test Bed



Operational

Recently Started

Needs Repair

In Development

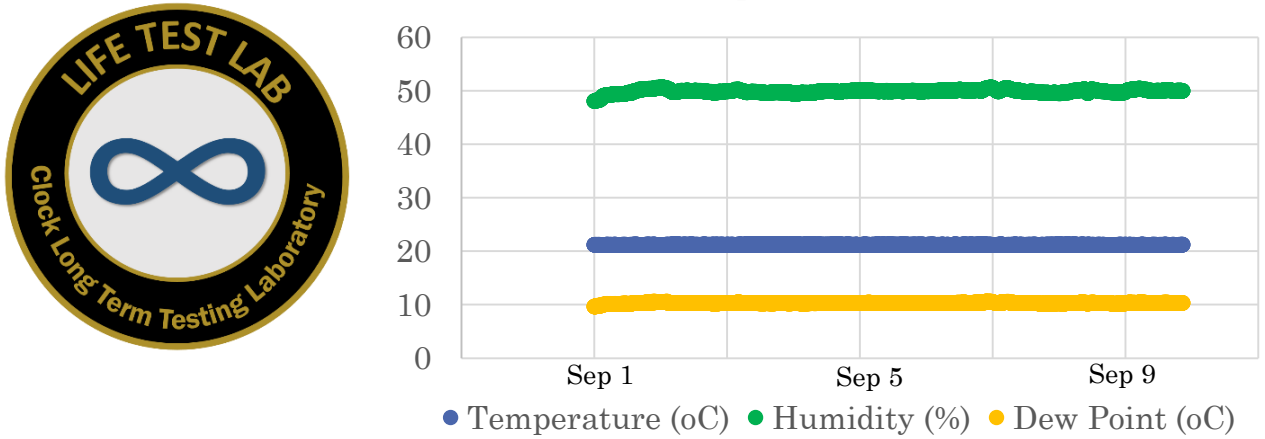
Other sites involved: APL, NIST

Main Contact:
Christine Hackman
Naval Research Lab

New Laboratory Spaces

NRL and NAVFAC have been engaging in updates to ageing facilities across the laboratory.

- Updated environmental controls
- Higher electrical amperage capacity and protection from city power outages
- Physical pilings to bedrock beneath building for better platform stability.



Future time and frequency measurement room.

Satellite Bus and Special Systems Lab

Engineering and Payload Development Section:

- Design and develop flight electronics and firmware to support various scientific payloads.
- Develop software to handle telemetry interfaces and data processing.
- Develop power supplies for various instruments.

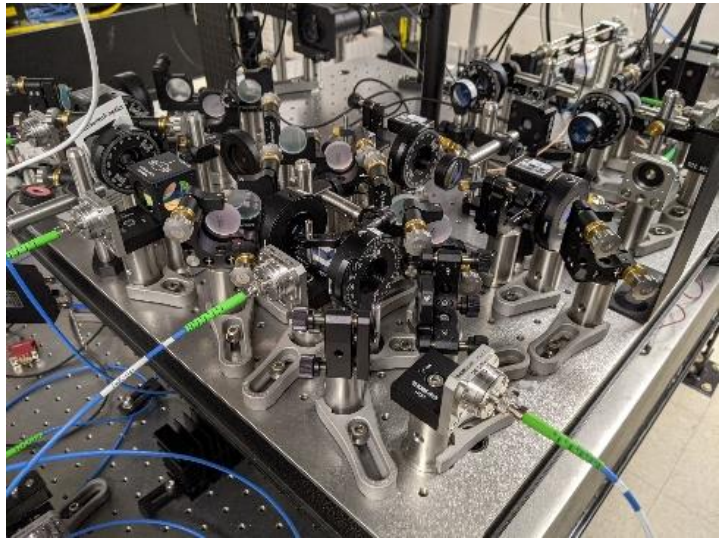
Support for various programs:

- **ECLIPSE**: Tomographic imaging of ionosphere using space based senor suite.
- **GLOTemp**: Studies atmospheric transport between troposphere and stratosphere.
- **LARADO**: Real-time on-orbit local object detection for situational awareness in space.

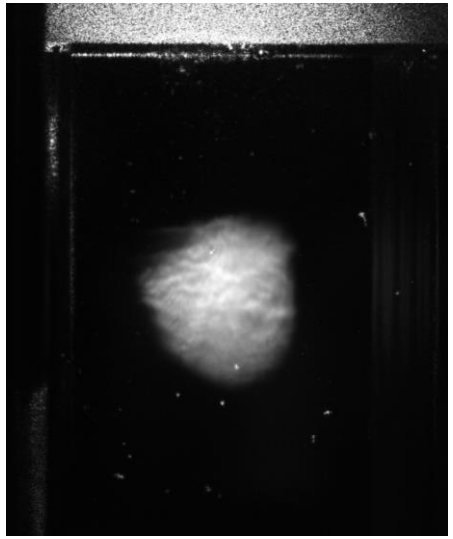
Space payload laboratory and clean room.

Cold Quantum / Laser Laboratory

Previous Laser Lab Work involved cold atom trapping of 87Rb.



Laser equipment in existing lab, to be moved to newer area with better environmentals.



Cold atom cloud in lab shown left.

Future Laser Lab.

ION / PTTI 2024 Meeting

Long Beach, CA

22 – 25 January 2024

Topics:

Activities at National Metrology Laboratories

Advanced and Future Clocks

Environmental Sensitivity of Clocks and Timing Systems

GNSS Timing Architectures and Capabilities

LEO Satellite Timing Requirements and Applications

Low SWaP Clocks and Oscillators for 5G and Beyond

Methods and Algorithms for Timing Applications and Timescales

Present and Future Clocks for Space

Time and Frequency Transfer Supporting 1E –18 Clock Comparisons

Time Transfer over Communications and Unconventional Methods

Timekeeping for Quantum Networking and Other Science Applications

Updates from Regulatory Agencies and Institutions

Dr. Daphna Enzer, Program Chair

Jet Propulsion Laboratory

Dr. Josef Vojtech, Tutorials Chair

Czech Education and Scientific Network (CESNET)

Abstracts Due: 04 October 2023