National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

The Deep Space Atomic Clock and Potential Scientific Applications

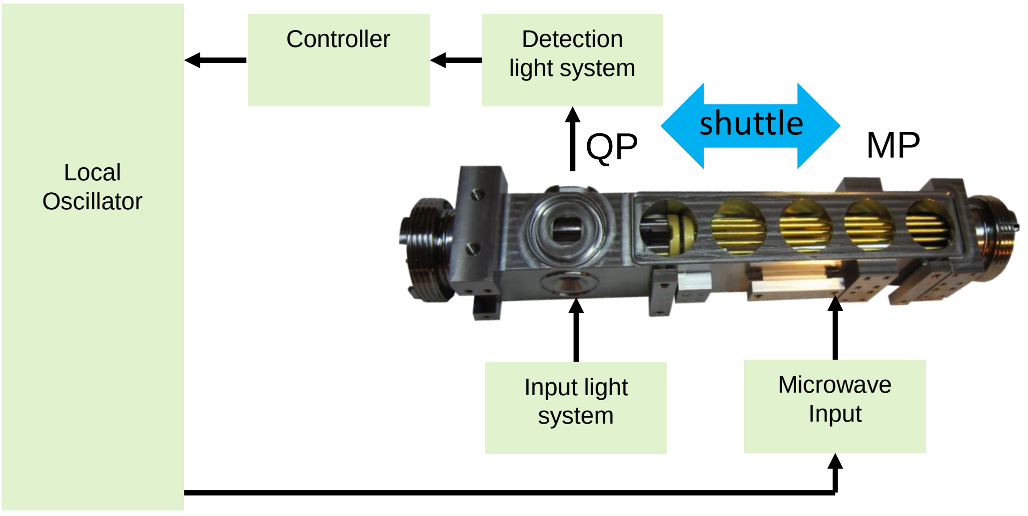
Eric Burt, John Prestage, Robert Tjoelker, **Eric Tardiff,** Daphna Enzer, Da Kuang, Dave Murphy, David Robison, Jill Seubert, Rabi Wang, James McKelvey, Vladimir Iltchenko, Andrey Matsko, and **Todd Ely**

Jet Propulsion Laboratory, California Institute of Technology

9th Symposium on Frequency Standards and Metrology

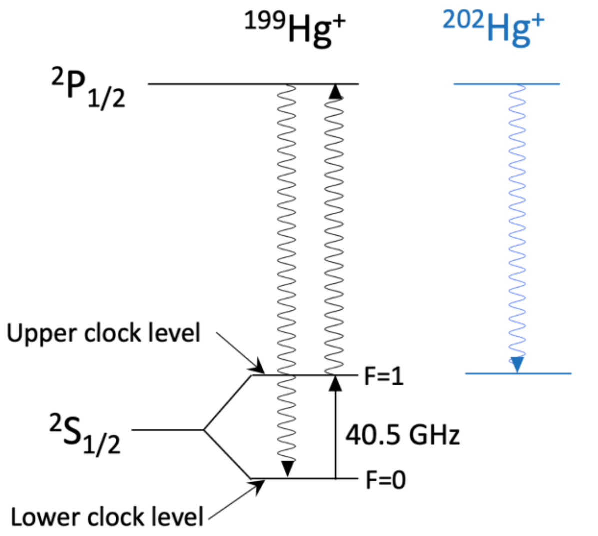
Joint funding for the DSAC project provided by the NASA offices of Space Technology Mission Directorate (STMD) and Space Communications and Navigation (SCaN)

JPL Trapped Ion Clock Overview



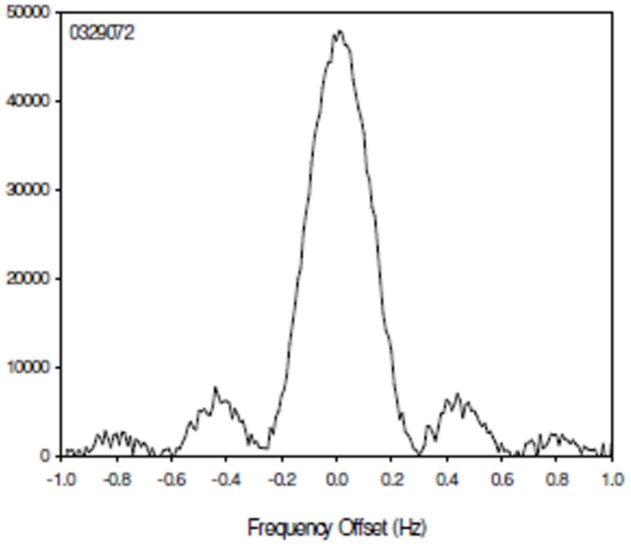
Key Performance Features:

- **10^6-10^7 $^{199}\mathrm{Hg}^+$ trapped ions**
  - No wall collisions, high Q microwave line
  - Buffer gas cooled to ~300K
  - Multi-pole ion trap – ***lower systematics***
- **State selection/detection:**
  - Optical Pumping from $^{202}\mathrm{Hg}^+$ lamp
  - 1-2 UV photons per ion per second scattered
- **High Clock Transition:**
  - 40,507,347,996.8 Hz – ***low magnetic sensitivity***
- **Adapts to variety of Local Oscillators - *flexible***



$^{199}\mathrm{Hg}^+$ clock ion level structure

$^{202}\mathrm{Hg}^+$ lamp ion level structure



Key Reliability Features: - ***practical***

- **No Lasers**
- **No Cryogenics**
- **No Microwave cavity**
- **No Light Shift**
- **Low Consumables**

199Hg Ion Clock Development Timeline

40.5 GHz transition in 199Hg+, optically pumped with 202Hg+ discharge lamp, buffer gas cooled

1993 $7\times10^{-14}/T^{1/2}$, long term drifts < 2×10^{-16}/day.

1996 $2 \times 10^{-14}/T^{1/2}$ advanced LOs: ***CSO, H-masers***

1999 Multi-pole ion trap reduction of 2nd Order Doppler Shift

2006 High temp bake-out -> sealed getter pump

2008 Compensated Multi-pole: UTC quality timekeeping with a single clock

- long term variations below < 3×10^{-17}/day.

2010GPSIII MAFS: 50W total power demonstrated.

2011 high bake sealed operation demonstrated

2010-16 Ultra-stable multipole ion trap reference clock

2016-present - Miniature clock development: 1 liter (next talk)

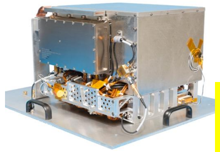
2019-2021 DSAC operates in LEO

2022 DSAC-2 – Low 30W, long-life concept for NASA & DoD

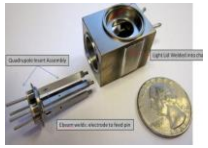
5th FSM

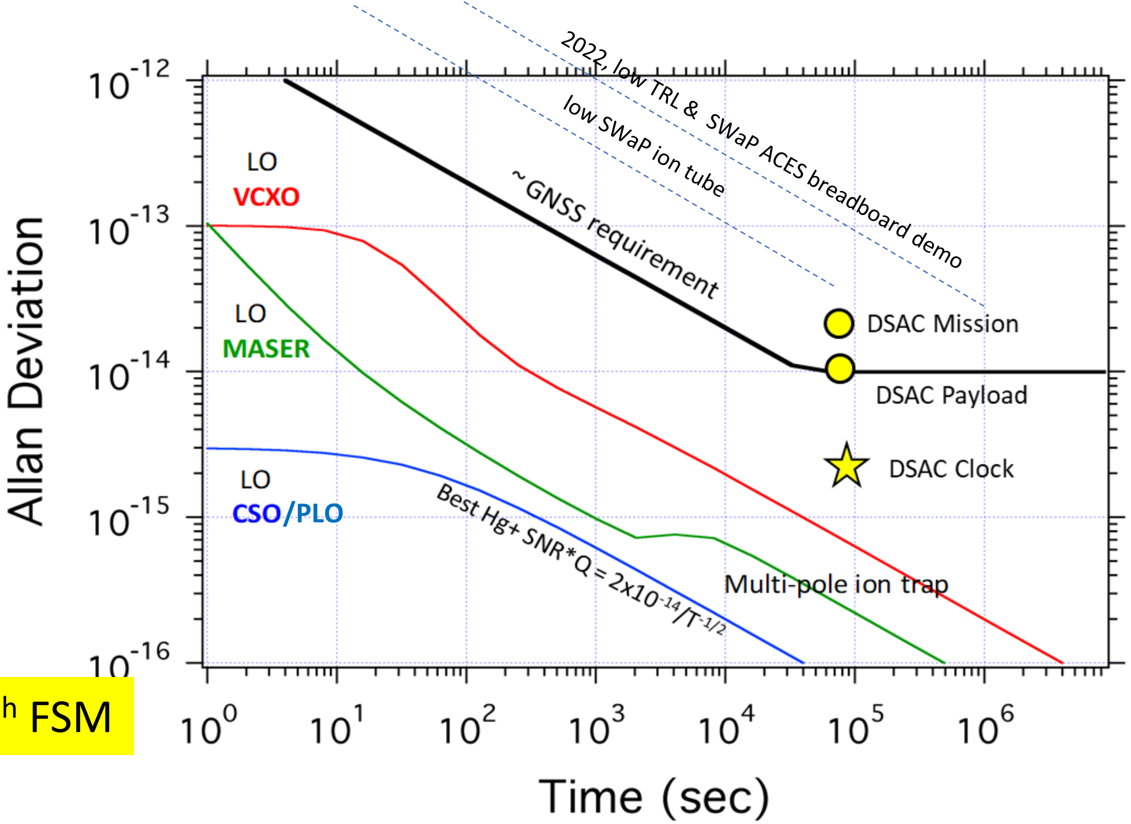
7th FSM

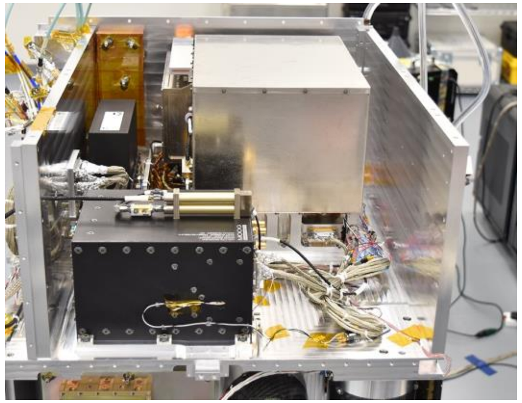
8th FSM



9th FSM

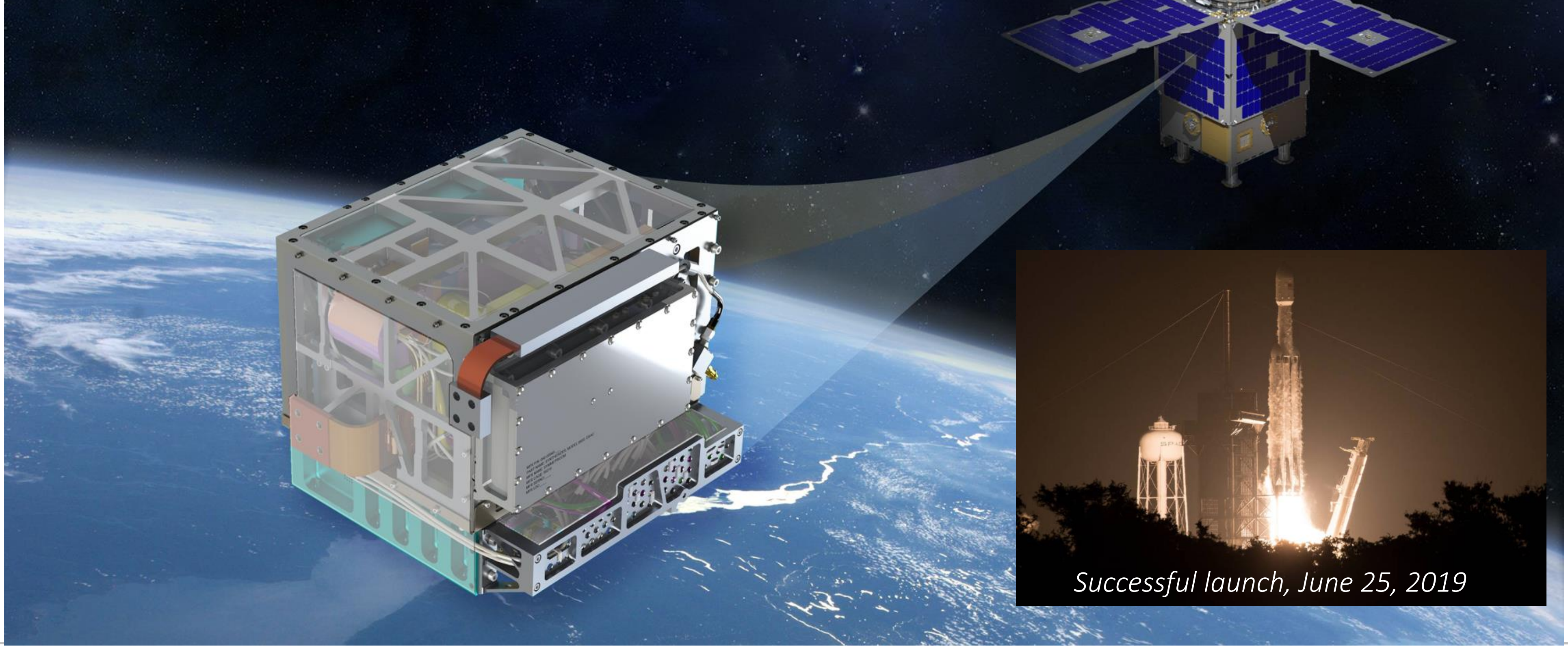






Deep Space Atomic Clock

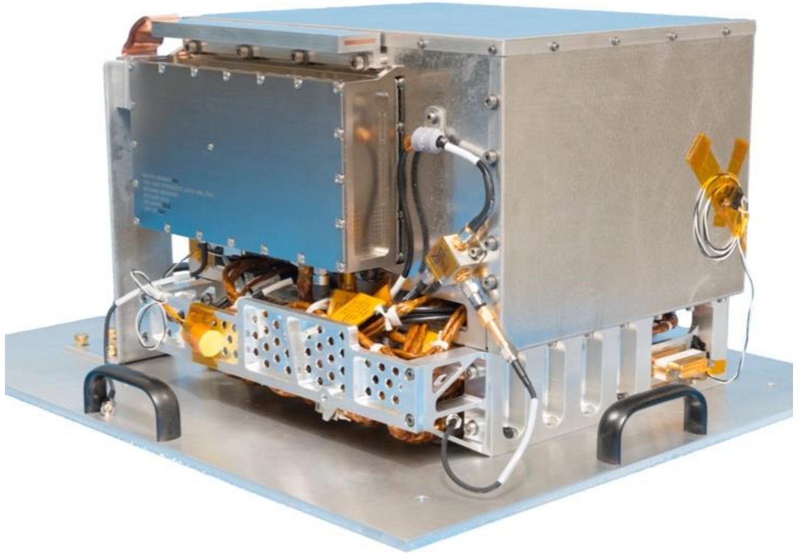
A Technology Demonstration Mission



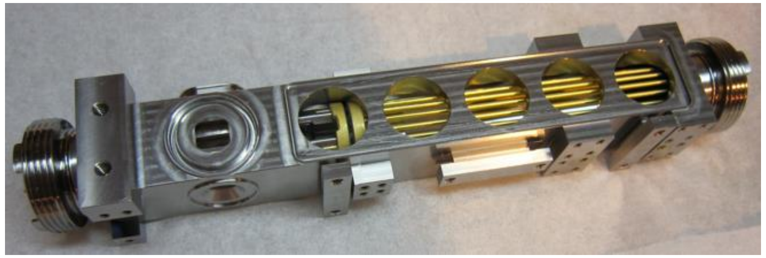
Successful launch, June 25, 2019

Some Primary Physics Package Subsystems

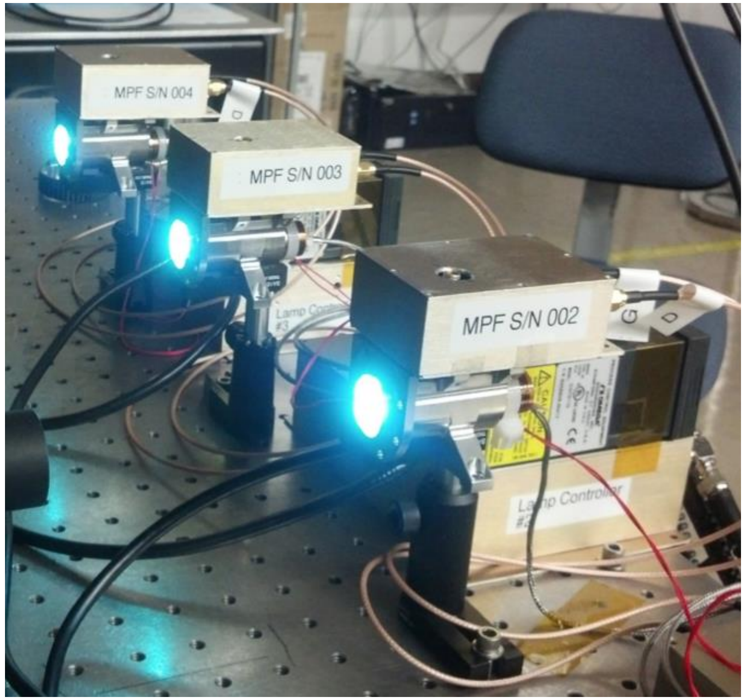
DSAC Demonstration Unit

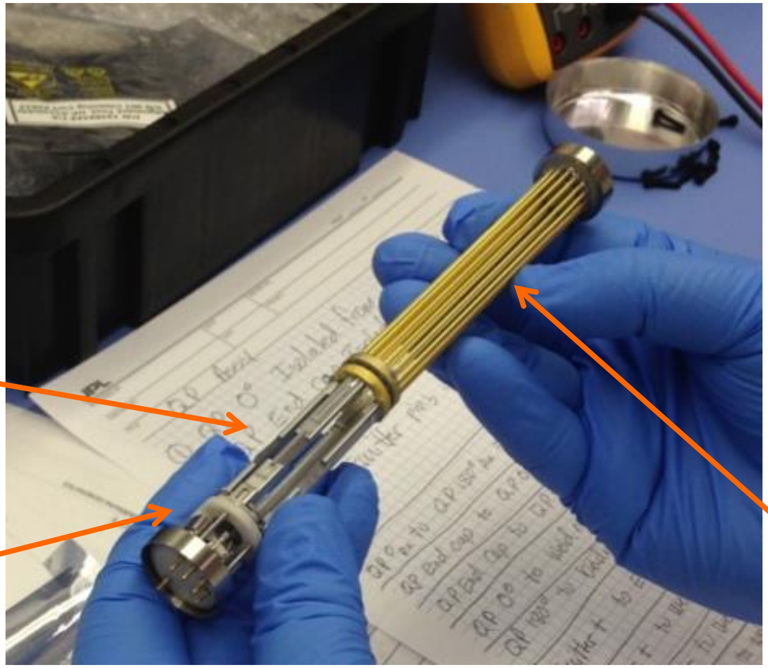


Titanium Vacuum Tube



Mercury UV Lamp Testing





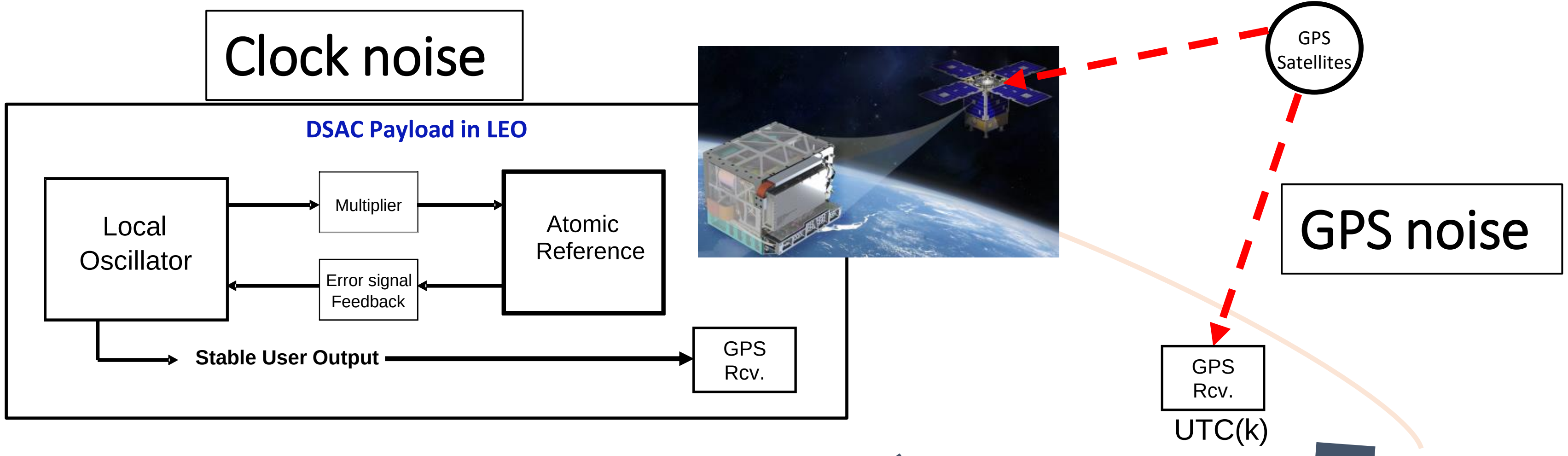
Quadrupole Trap Electrodes

Electron Emitter

Multi-pole Trap Electrodes

Challenges of measurements in space: Noise Sources

DSAC Frequency Stability Measurements vs UTC via GPS



Clock noise

DSAC Payload in LEO

Local Oscillator

Multiplier

Error signal Feedback

Atomic Reference

Stable User Output

GPS Rcv.

GPS Satellites

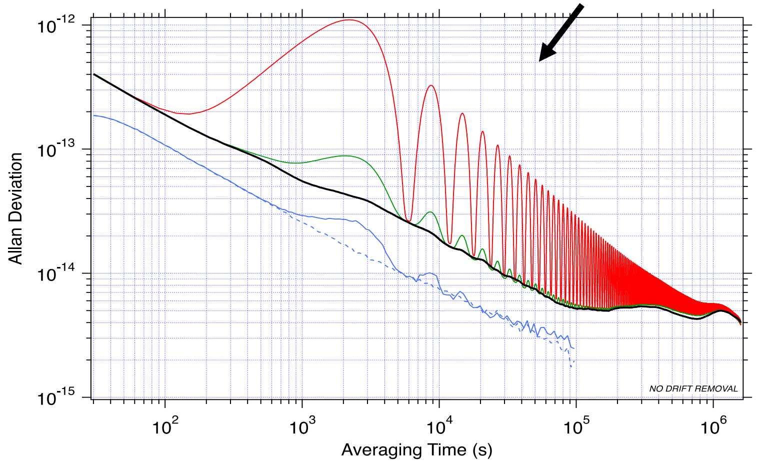
GPS noise

GPS Rcv.

UTC(k)

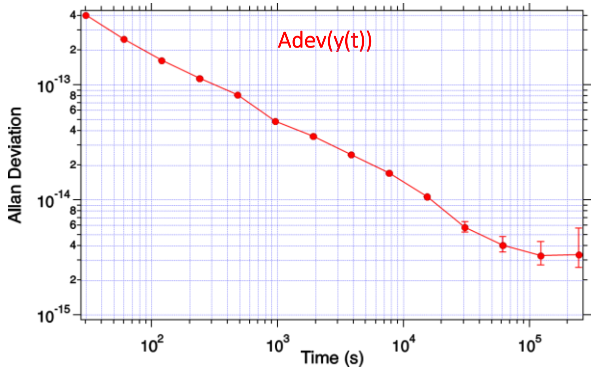
Require precise orbit determination to remove relativistic effects – need J2 corrections

OD



Final result: measure all three

Hg+ stability vs UTC (> ~20,000 s) via GPS time transfer:



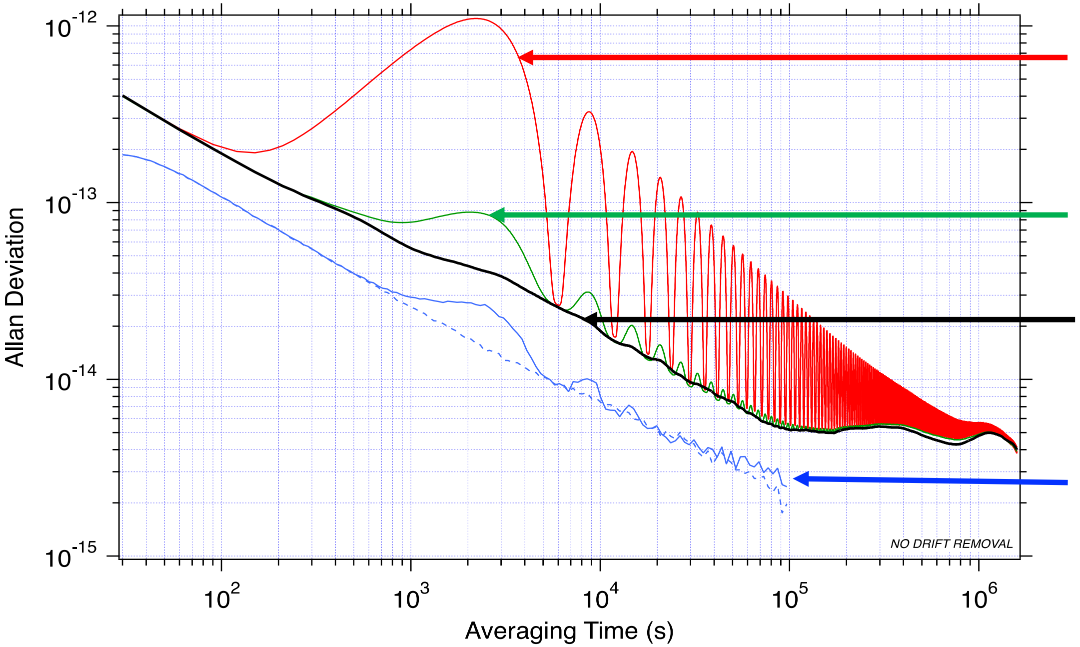
DSAC Results: Calibrating GPS Receiver and Relativistic Effects

GPS phase dynamically corrected for gravitational effects (red shift)

$$\tau_s = \int dt\left[1+\frac{\Phi(r)-\Phi_0}{c^2}-\frac{v^2}{2c^2}\right]$$

Must include higher order terms (J2) in the gravitational potential

$$\Phi(r) = -\frac{GM}{r}\left[1-J_2\left(\frac{a_1}{r}\right)^2\frac{(3z^2-r^2)}{2r^2}\right]$$



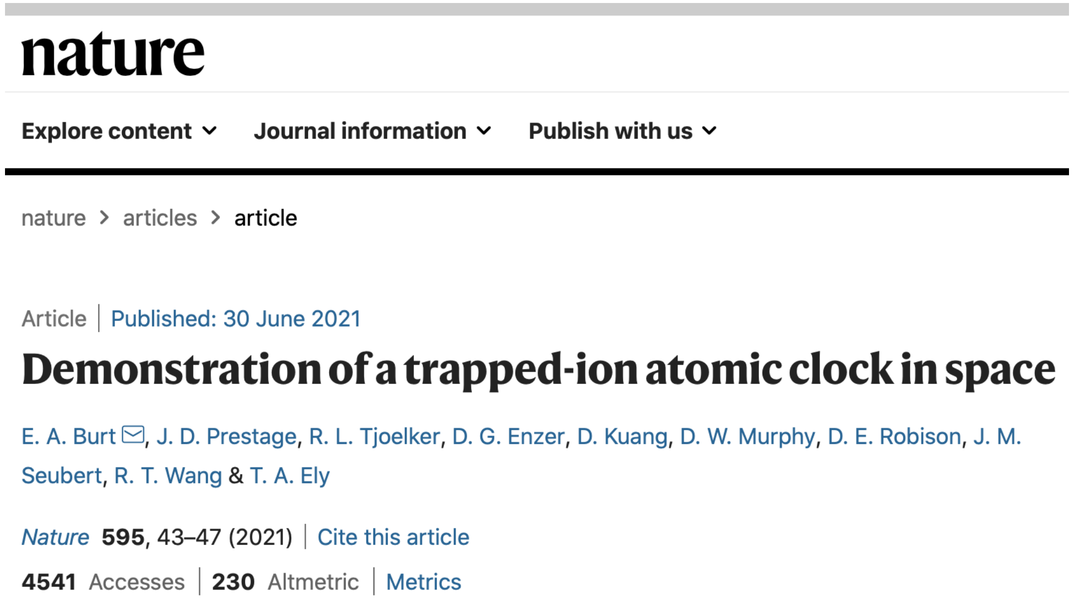
No corrections

Relativity corrections, but no GPSR temperature corrections

Measurement floor after relativity and GPSR temp correction

Estimated clock noise

DSAC Results



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Demonstration of a trapped-ion atomic clock in space

E. A. Burt, J. D. Prestage, R. L. Tjoelker, D. G. Enzer, D. Kuang, D. W. Murphy, D. E. Robison, J. M. Seubert, R. T. Wang & T. A. Ely

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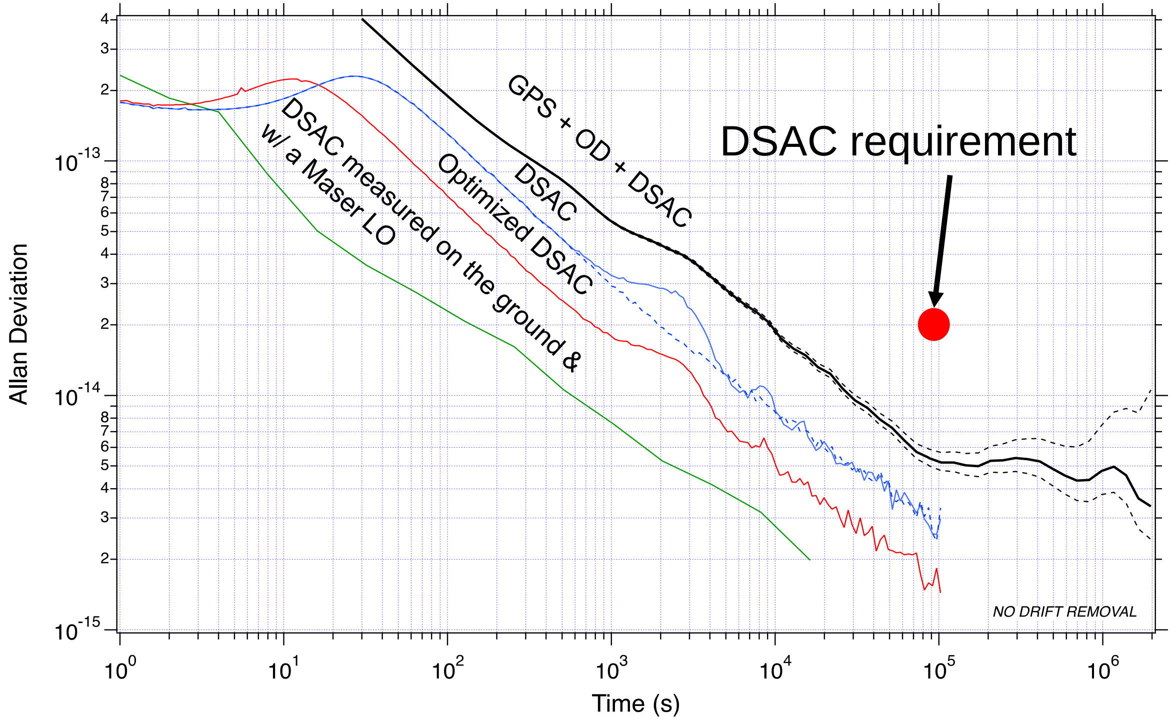
4541 Accesses | **230** Altmetric | Metrics



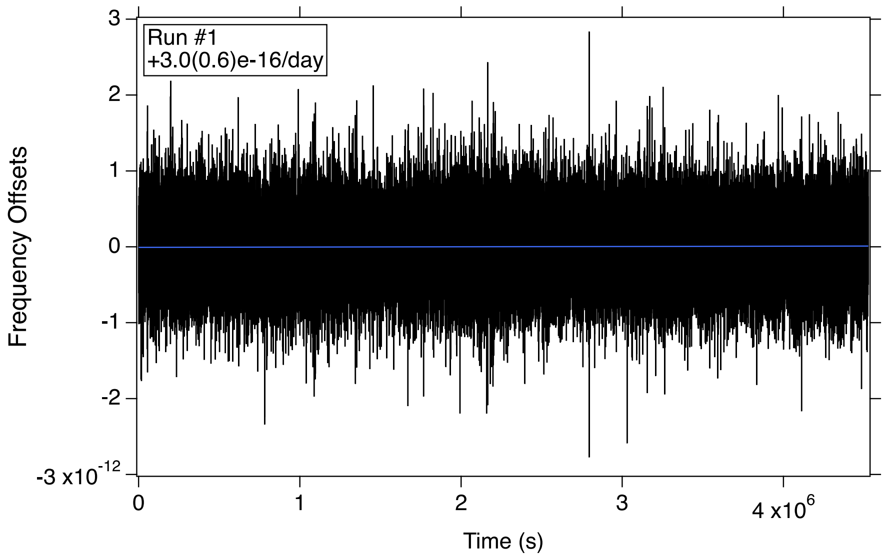
Stability at one-day of 3e-15

- ***significantly better than required 2e-14***

Drift of 3.0e-16/day

- ***establishes space clock record***

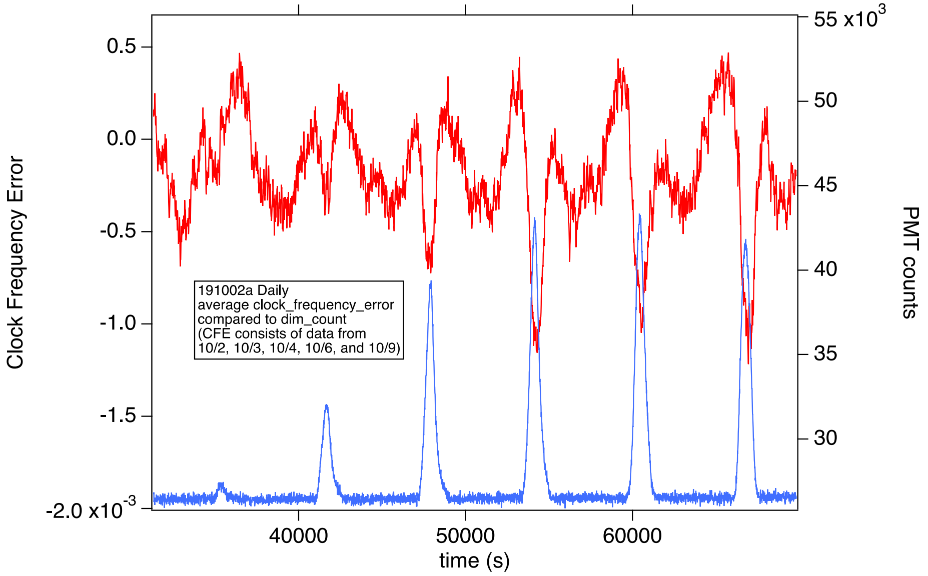
Two subsequent long runs had similar long term stability



Run #1 (late 2020):
+3.0(0.6)e-16/day

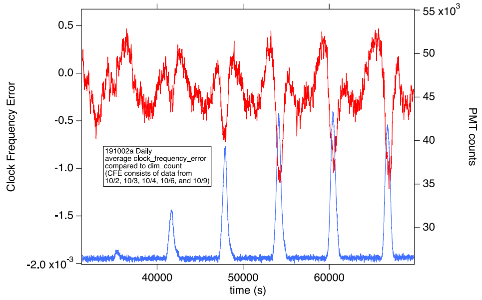
DSAC Environmental Sensitivities

Radiation: SAA-induced USO drift variations taken out by clock control loop



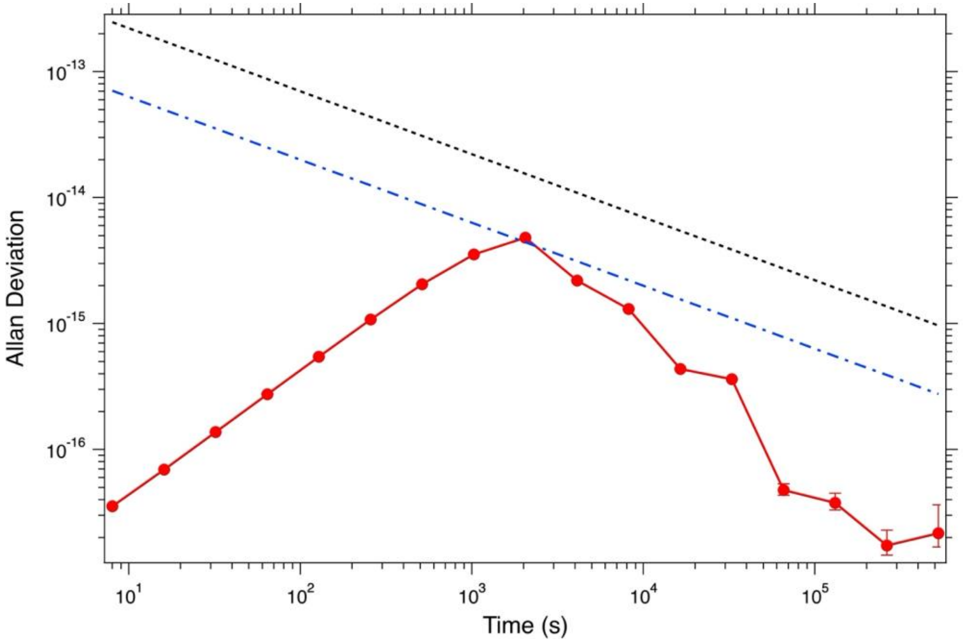
DSAC Environmental Sensitivities

Radiation



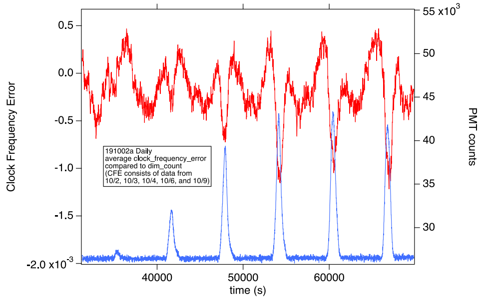
Magnetic Shifts: below measurement noise floor

- 250 mG/orbit - 100x lab!
- Strength of Hg+ technology

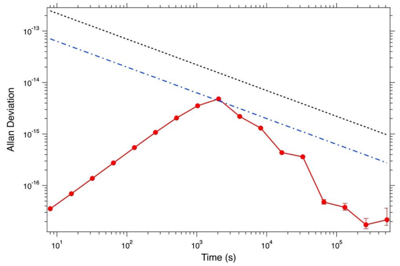


DSAC Environmental Sensitivities

Radiation

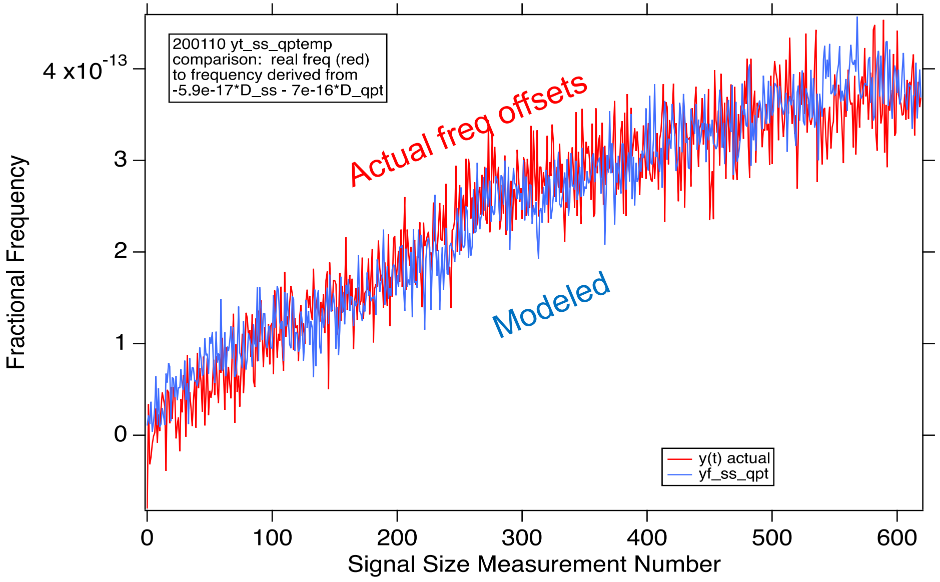


Magnetic Shifts

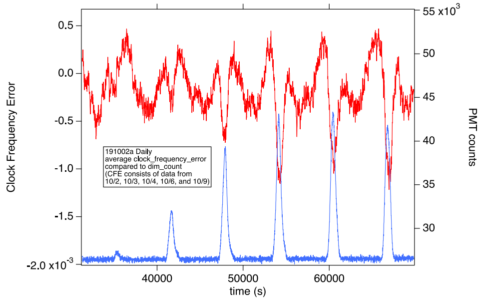


Ion number variations:

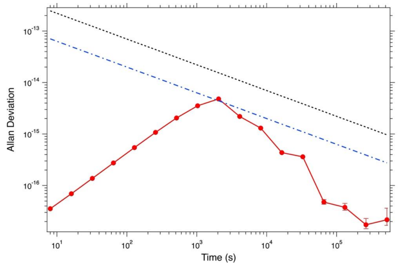
- Second order Doppler shifts
- Actual = model: well understood



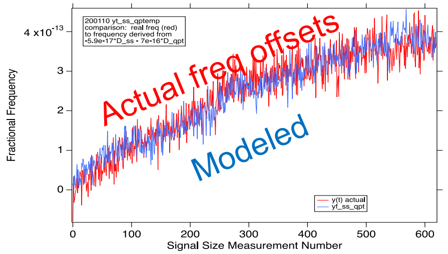
DSAC Environmental Sensitivities



Radiation



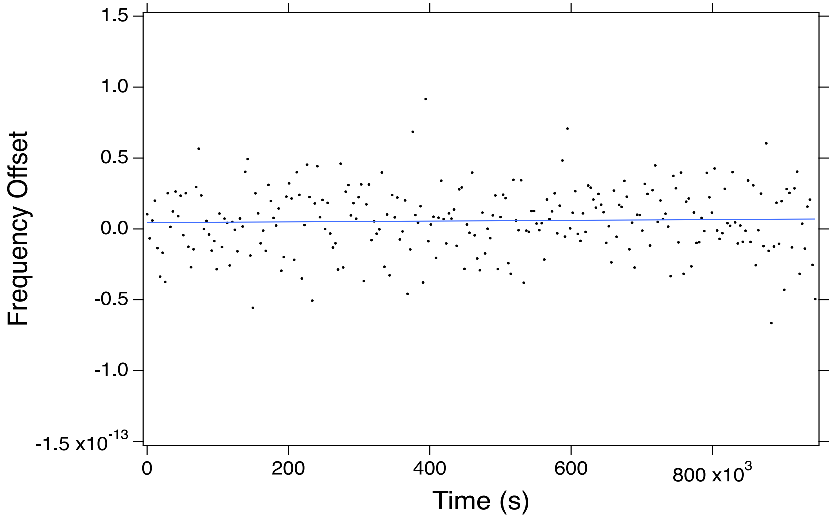
Magnetic Shifts



Ion number variations

Collision shifts

- Residual frequency offsets with other effects removed
- Stable at 4e-16/day level

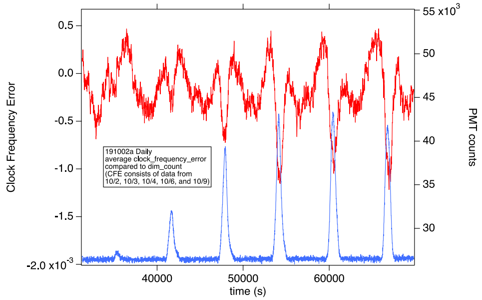


DSAC Environmental Sensitivities

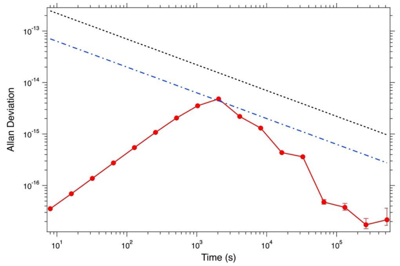
Temperature sensitivity:

- Not fundamental
- T-sensitivity of these
- **Overall: 1e-14/C with NO thermal regulation**
- **Path to unregulated 2e-15/C is known**

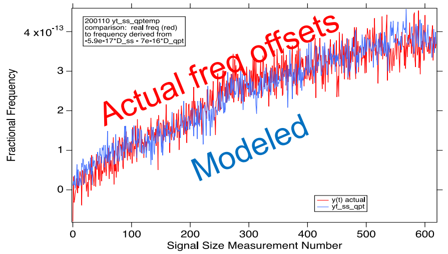
Radiation



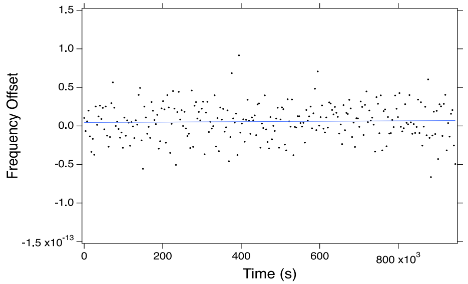
Magnetic Shifts



Ion number variations (second order Doppler)



Collision shifts (Background gas)



Light shifts: Not measured, but estimated at <3e-15 measurement noise floor

Fundamental systematic effects are well-understood and below the measurement noise floor

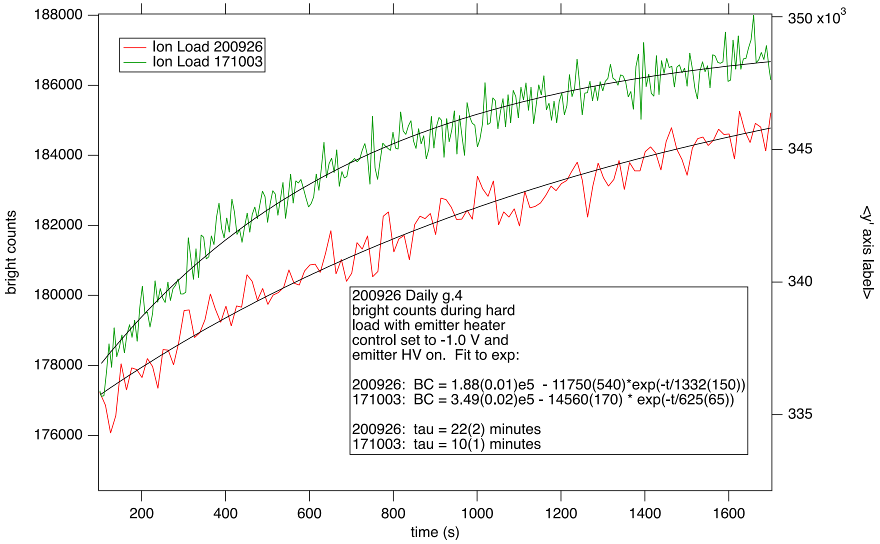
DSAC Clock lifetime: > 7 years

Vacuum Tube

Mercury vapor evolution

- **Extrapolate current trap load time: 7-year life**
- Likely explanation: Hg/Au amalgamation – gold will be removed in future versions

Trap load time variations



200926 Daily g.4
bright counts during hard
load with emitter heater
control set to -1.0 V and
emitter HV on. Fit to exp:

200926: BC = 1.88(0.01)e5 - 11750(540)*exp(-t/1332(150))
171003: BC = 3.49(0.02)e5 - 14560(170) * exp(-t/625(65))

200926: tau = 22(2) minutes
171003: tau = 10(1) minutes

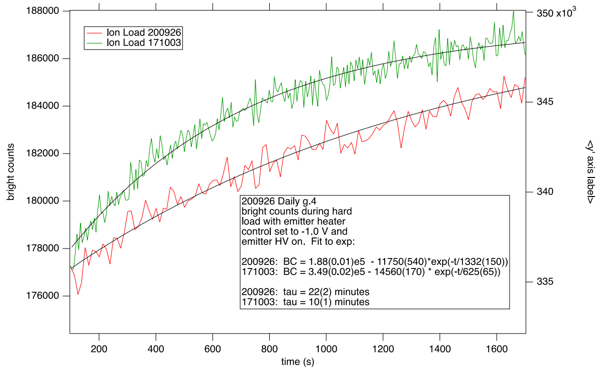
DSAC Clock lifetime: > 7 years

Vacuum Tube

Mercury vapor evolution

- **Extrapolate current trap load time: 7-year life**

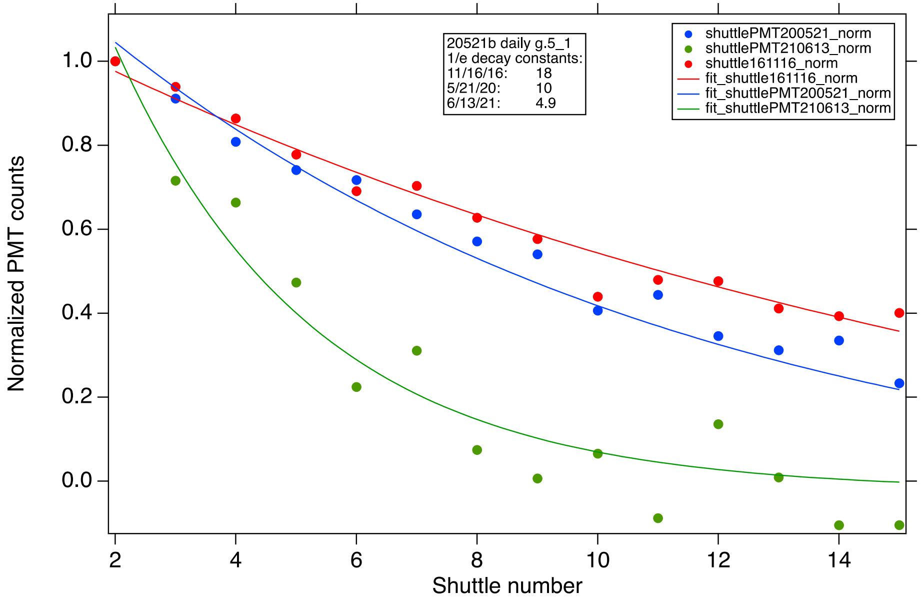
Trap load time variations



Neon evolution

- Shuttle decay measurements calibrated to neon pressure
- Extrapolate to > 8-year life
- Method to extend understood

Trap “shuttling” decay



Nov, 2016:
P = 4.7e-6 torr

May, 2020:
P = 2.6e-6 torr

June, 2021:
P = 1.3e-6 torr

DSAC Clock lifetime: > 7 years

Vacuum Tube

Mercury vapor evolution

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Neon evolution

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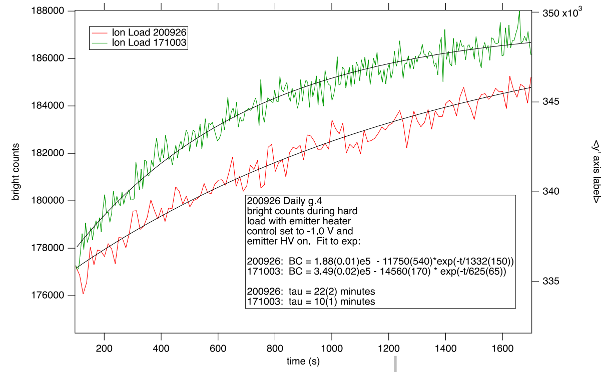
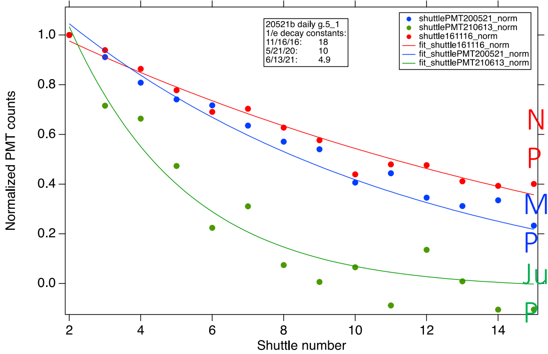
Trap load time variations



Trap “shuttling” decay

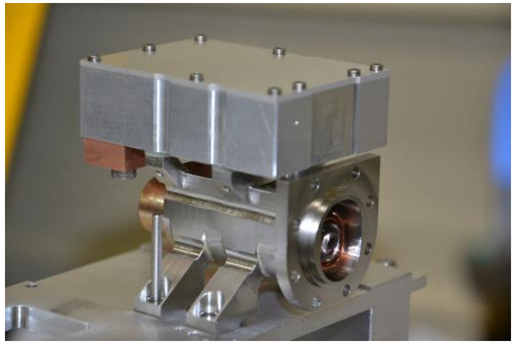


Nov, 2016:
P = 4.7e-6 torr

May, 2020:
P = 2.6e-6 torr

June, 2021:
P = 1.3e-6 torr

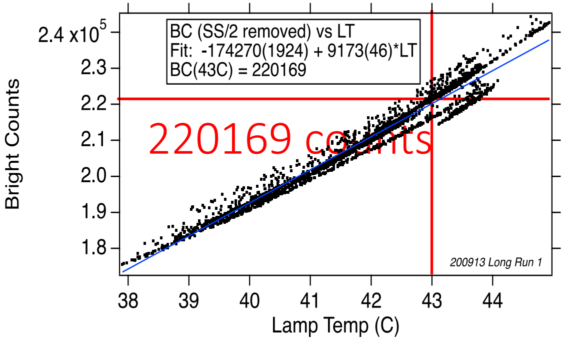
Lamp Assy.



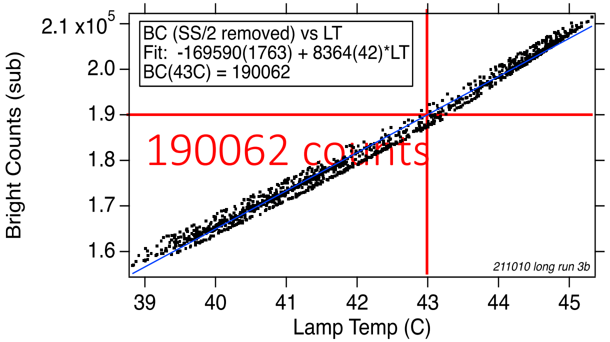
Optics aging

- 13.7% change in 13 months
- => > 7 years total life
- Most likely lamp

September 2020



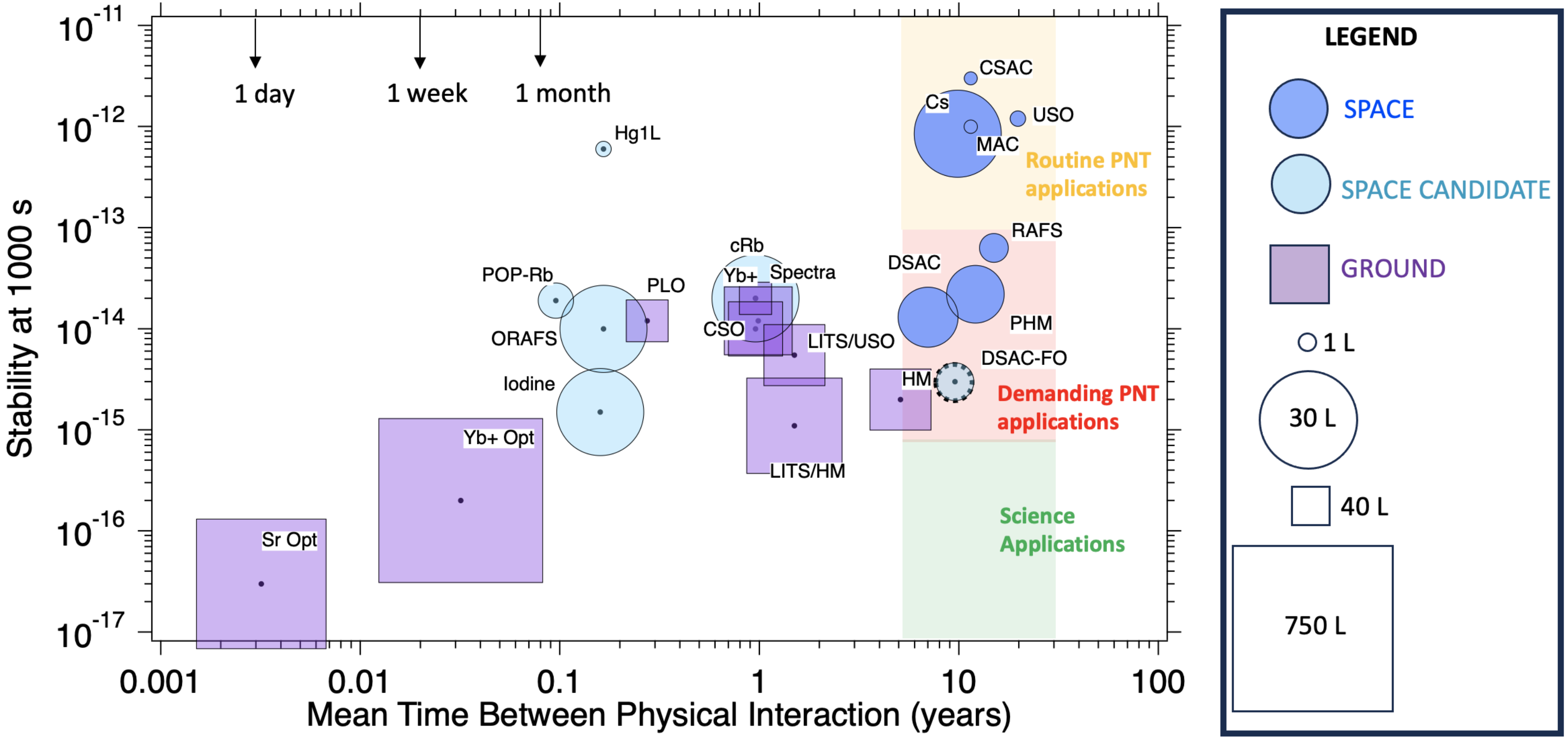
October 2021



Clock lifetime > 7 years with known methods to extend this

Future Position, Navigation and Timing Clocks

Position, Navigation and Timing (PNT) Clock Metrics



*Mean time between physical interaction is only estimated for these standards because this data was not reported

Takeaway: for PNT, need more than performance: SWaP and operability equally important

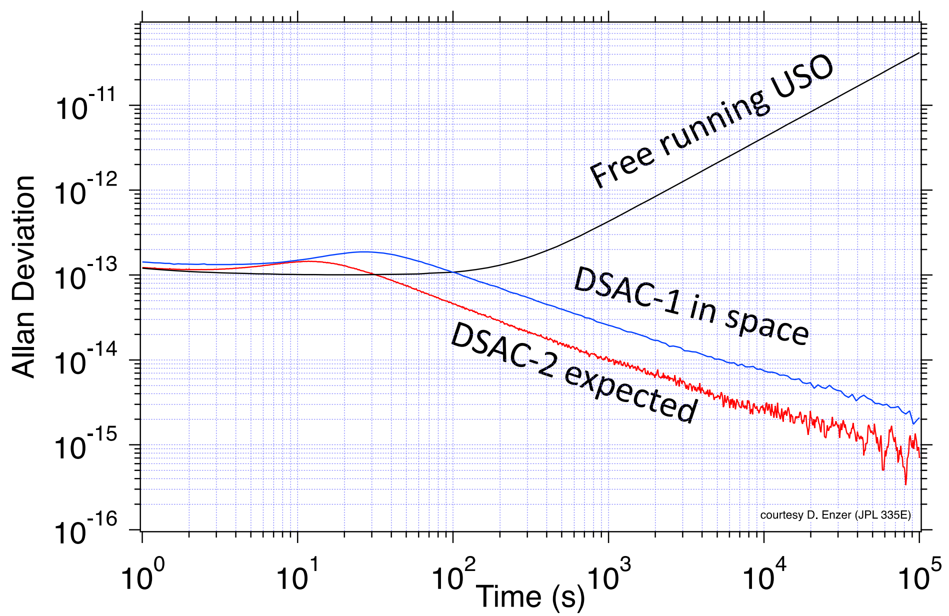
Technology Maturation Task (TMT)

Space and Ground Clocks – common performance properties

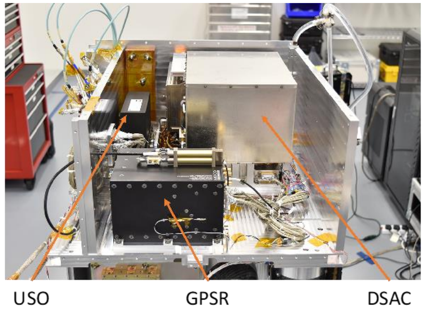
How much can we reduce SWaP and increase Life while maintaining maser-like performance?

- **Common requirements with broader market and commercial interest:**
  - **Ground Clocks:** H-maser (e.g. DSN, VLBI), Cs beam replacement (e.g. telecom)
  - **Space Clocks:** DSAC2, GPS & GNSS
- **Operability, reliability, and manufacturability paramount.**
- **Instrument Life: 5-10 years**
- **Frequency stability class:**
  - Local Oscillator = 1E-13 class USO
  - 1E-13 at 1 second, 2E-13/τ½ , 1E-15 at 1 day. Long term drift <5E-16/day
- **SWaP class volume driver:**
  - Space < GPS clock footprint
  - Ground < 5071 Cs chassis height (**5.25”**).

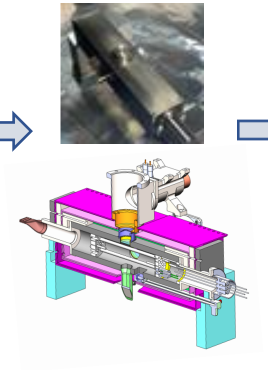
Frequency stability with Quartz USO as the LO



DSAC (STMD, SCaN)

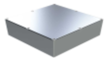


TMT (SCaN)

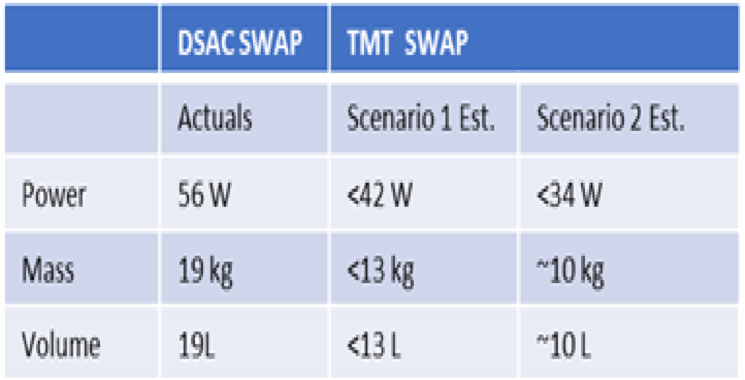


Flight Prototype

DARPA/ONR development
miniature, tactical
(1E-11/root tau)



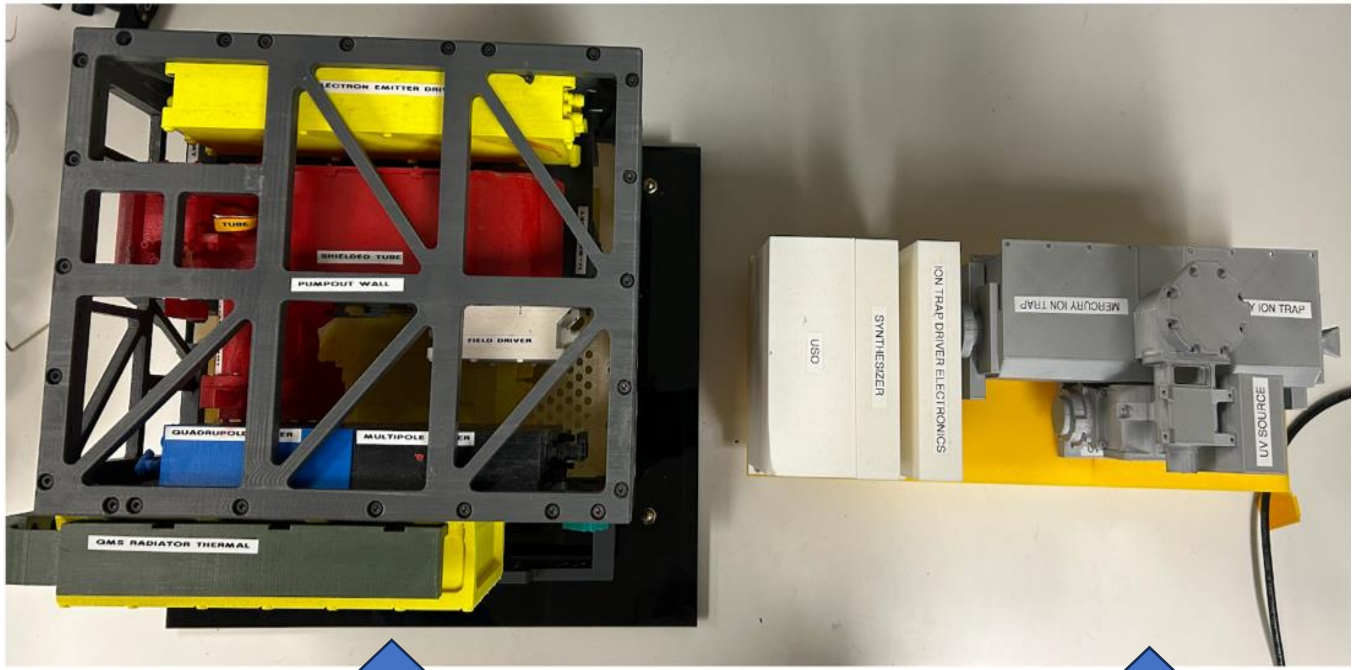
Ground Prototype



	DSAC SWAP	TMT SWAP	
	Actuals	Scenario 1 Est.	Scenario 2 Est.
Power	56 W	<42 W	<34 W
Mass	19 kg	<13 kg	~10 kg
Volume	19L	<13 L	~10 L

TMT

3D-models

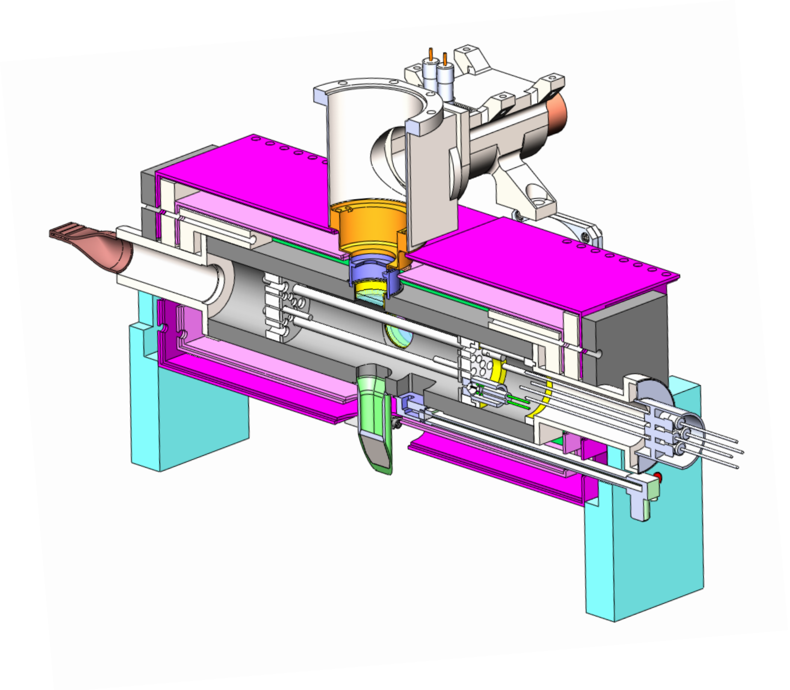


DSAC (+ USO and controller)

TMT (all-inclusive)

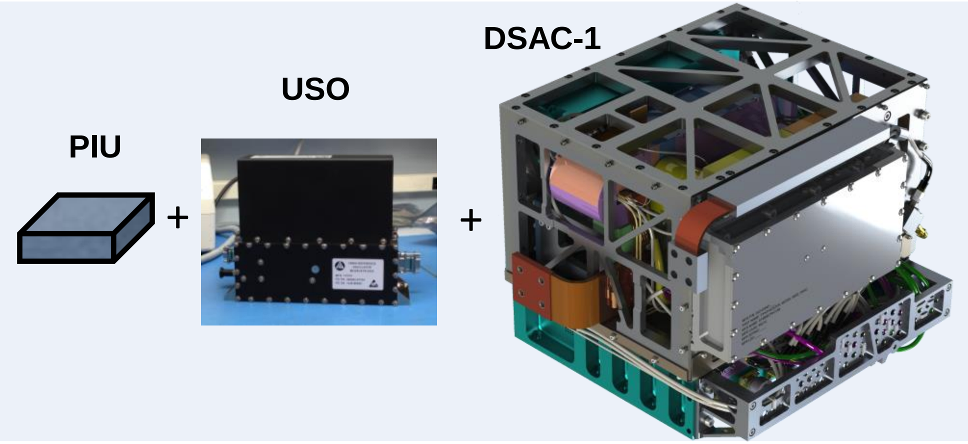
TMT approach

- Simplified trap architecture: QP-only
- Eliminate 1 trap driver
- Simplify controller architecture
- Integrate electronics
- Eliminate empty space
- Improve optics efficiency

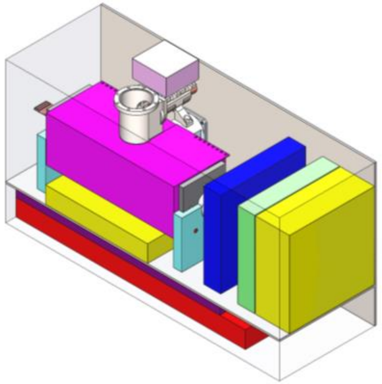


TMT Performance Goal

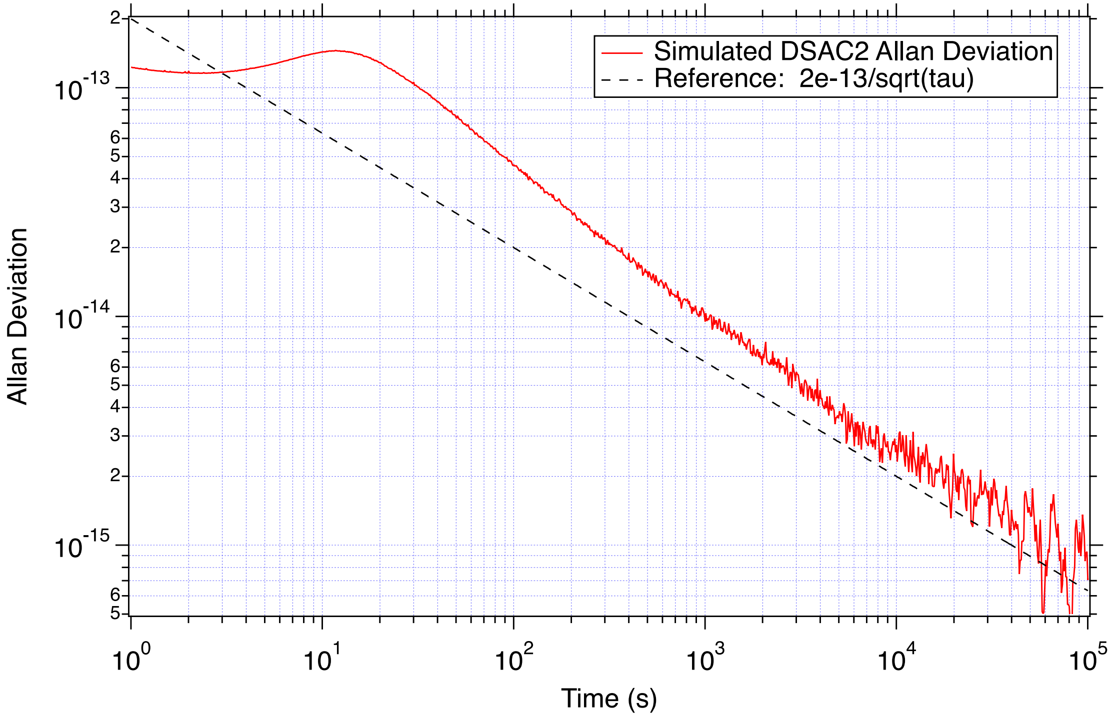
50 W, 19 kg

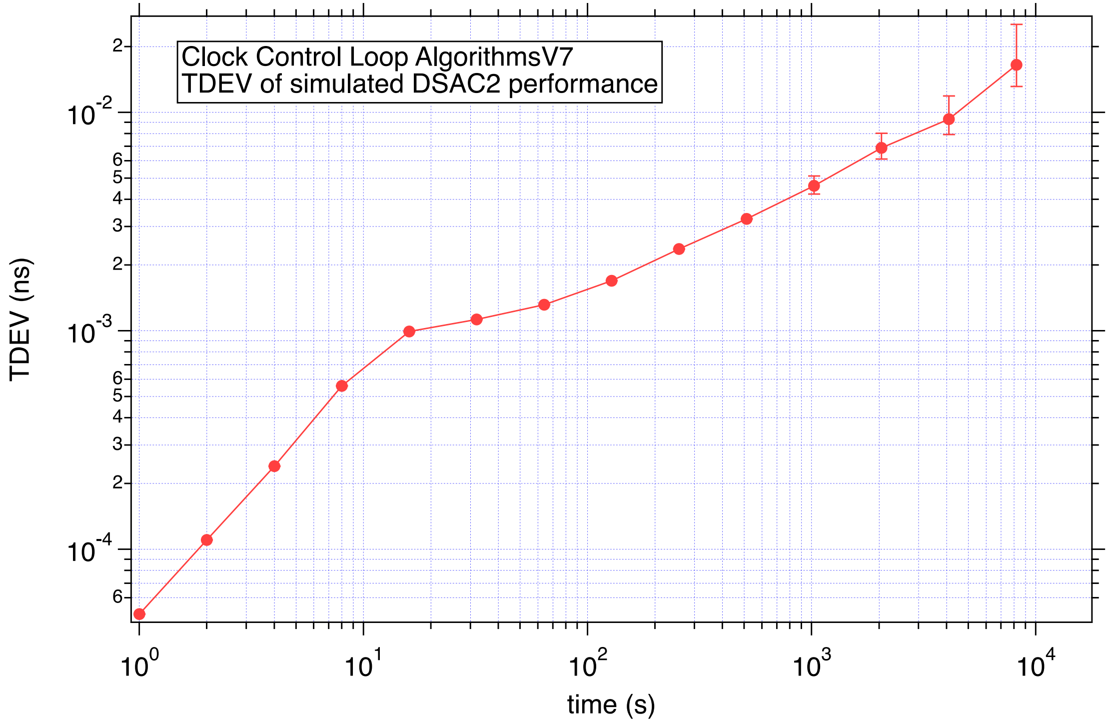


TMT Concept



34 W, 10 kg



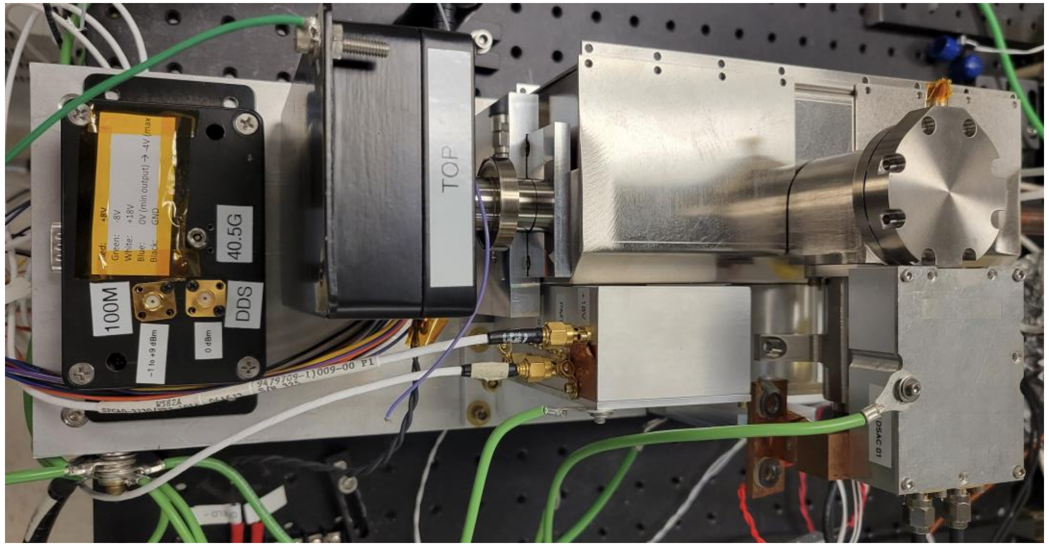


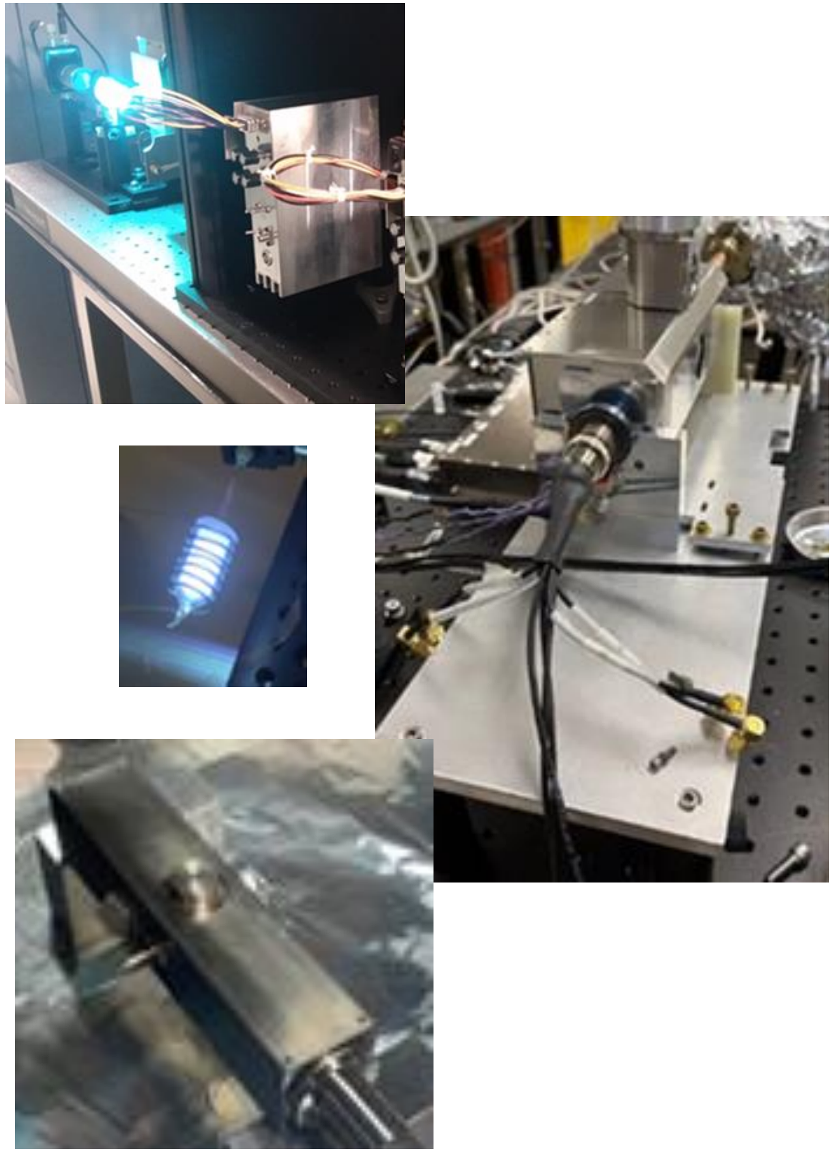
1e-13 at 1 s, <1e-15 at a day, ~50 ps at a day, 34 W, 10 kg

Prototype Build

3D Model

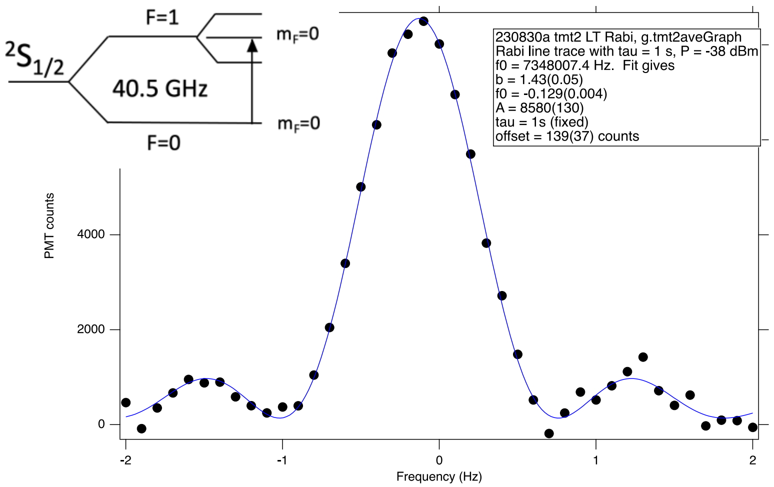
Prototype build with electronics



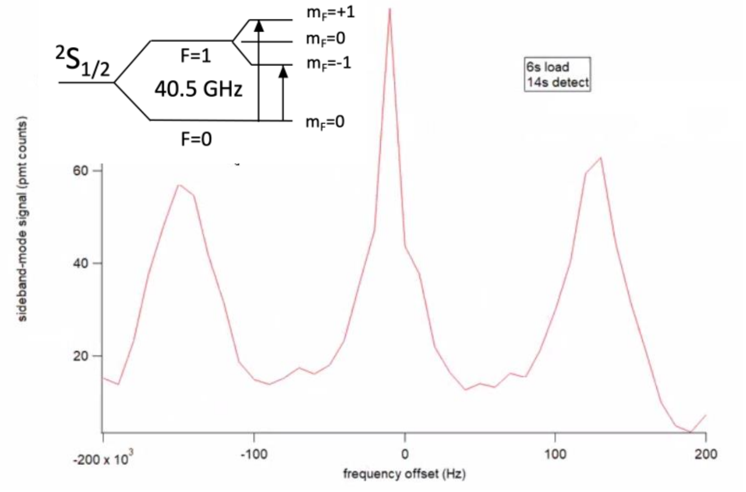


Prototype Initial Results

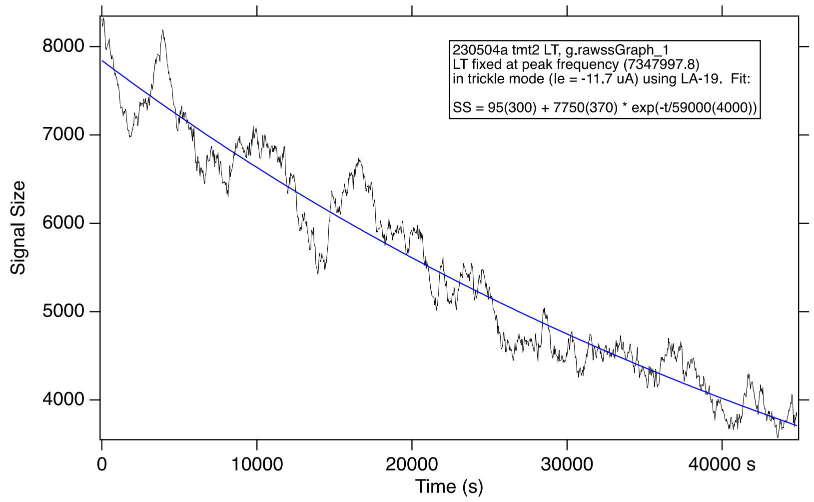
Clock transition spectroscopy



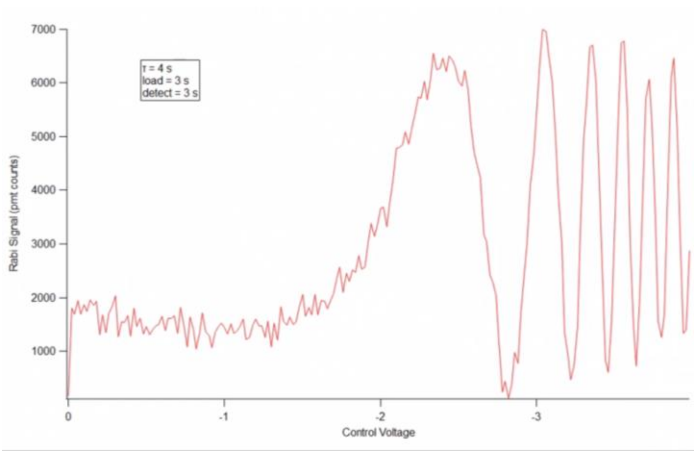
Zeeman spectroscopy



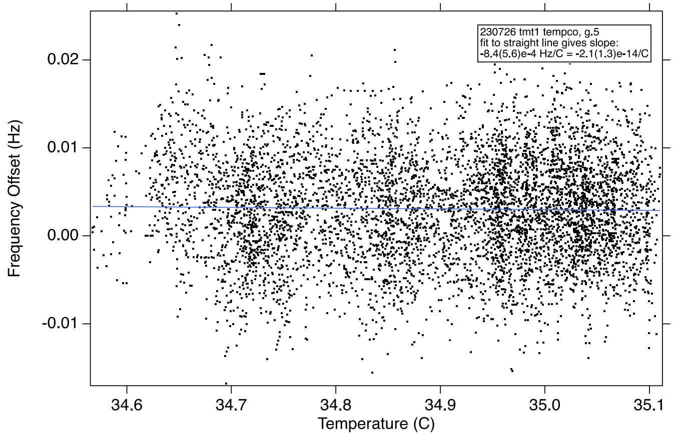
Trap lifetime ~ 1 day



Contrast with increasing microwave power => excellent coherence

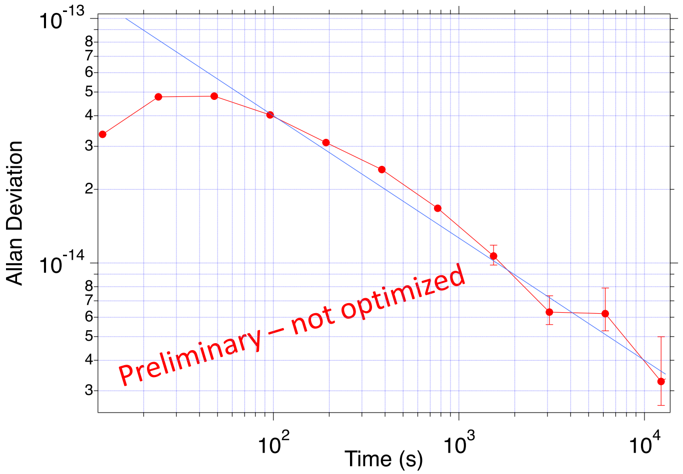


Initial temperature sensitivity: < 2e-14/C



Magnetic sensitivity: in progress

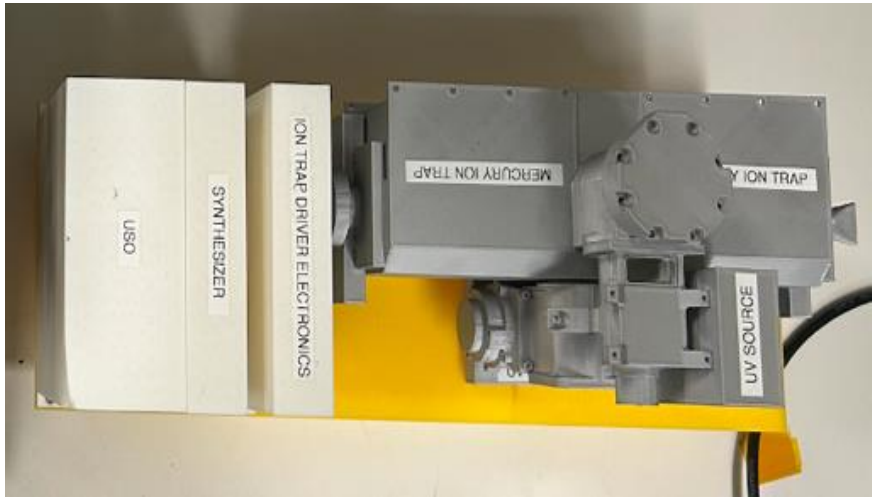
- 4e-13/sqrt(tau) (maser LO)
- Further optimization: SNR supports 3e-13/sqrt(tau)

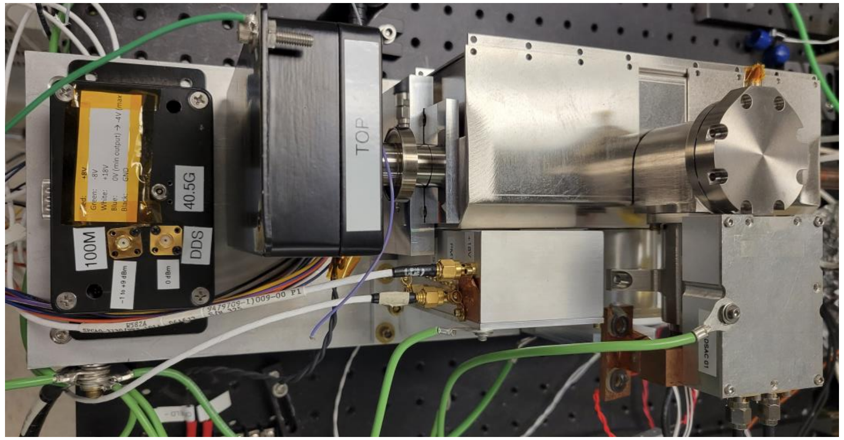


Prototype Electronics

DSAC
synth → Prototype

DSAC
trap/EED → Prototype

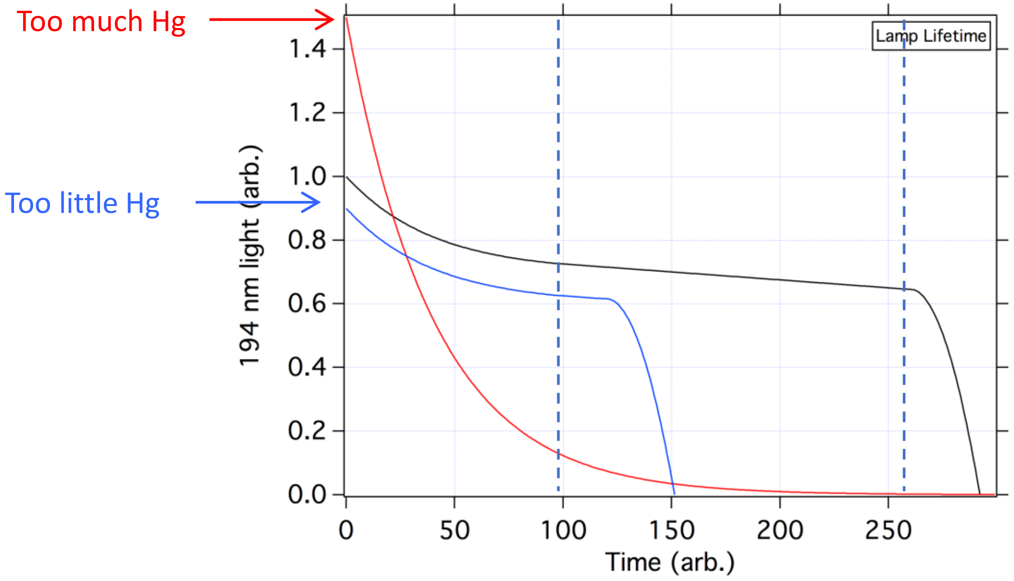




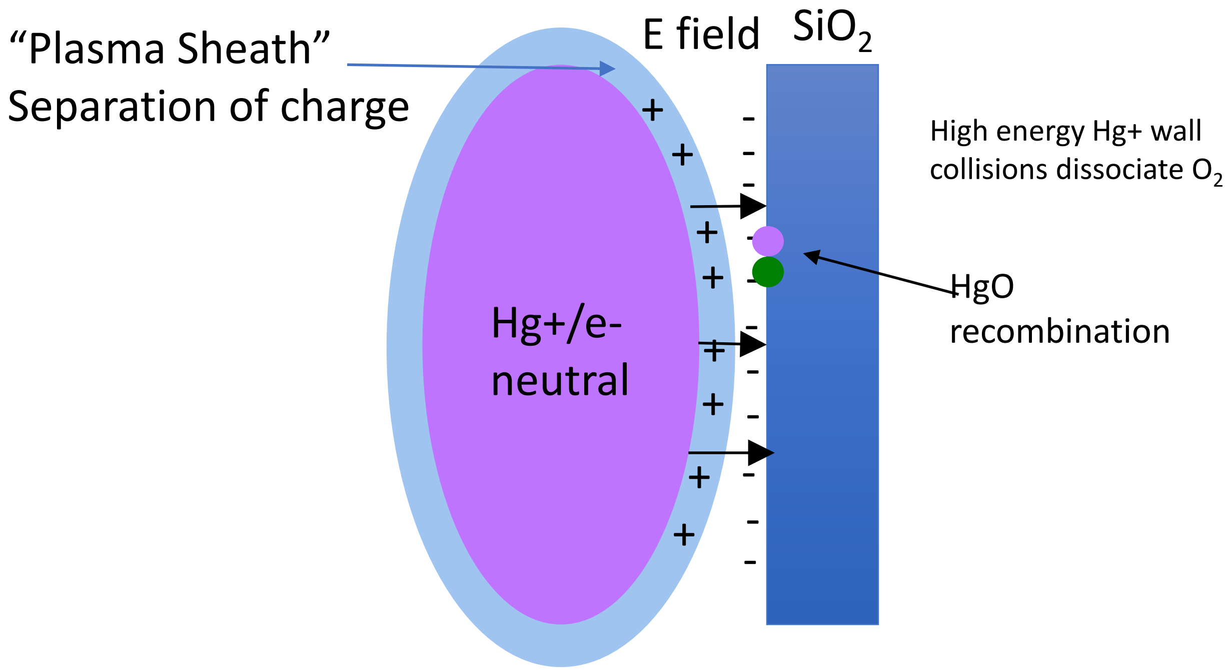
Light source aging

Need:

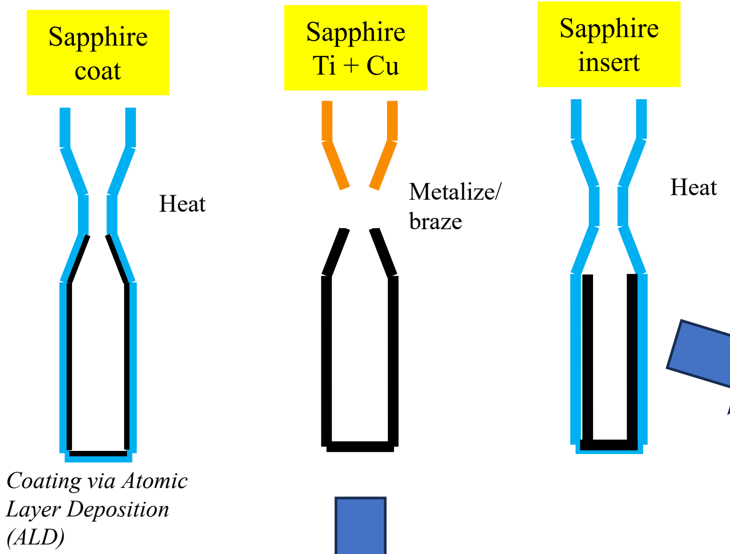
- Incorporate sapphire
- Methods to calibrate/quantify Hg



Mercury Oxide: where does the oxygen come from?



Plasma discharge light source development: Incorporating sapphire



Sapphire coat

Heat

Coating via Atomic Layer Deposition (ALD)

Sapphire Ti + Cu

Metalize/ braze

Sapphire insert

Heat

ALD sapphire coated

Bulk sapphire

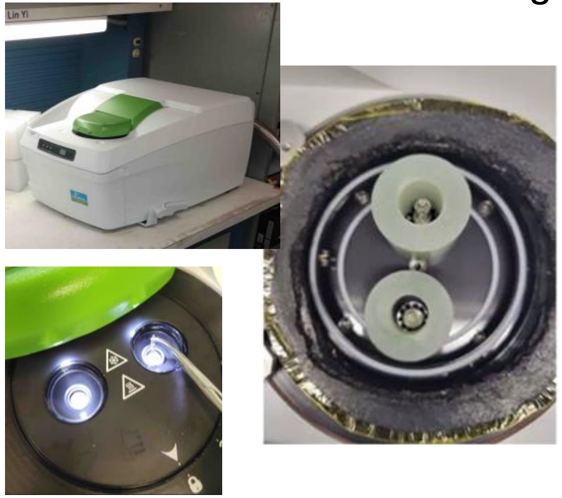
Sapphire insert

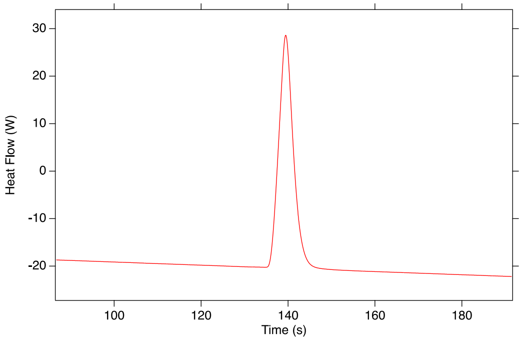
See next talk for another approach…

Lamp Life and Quantification

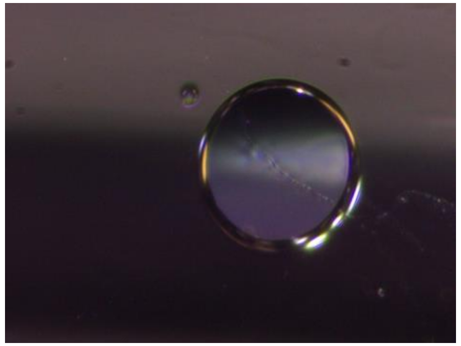
Lamp Content Quantification

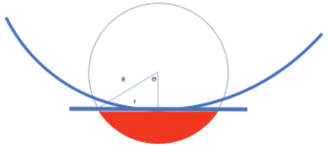
Differential Scanning Calorimetry (DSC)



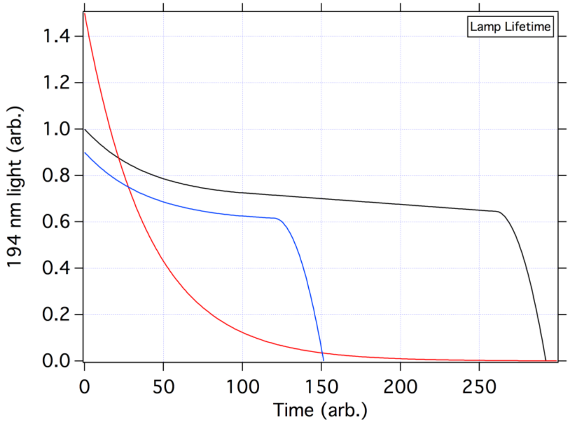


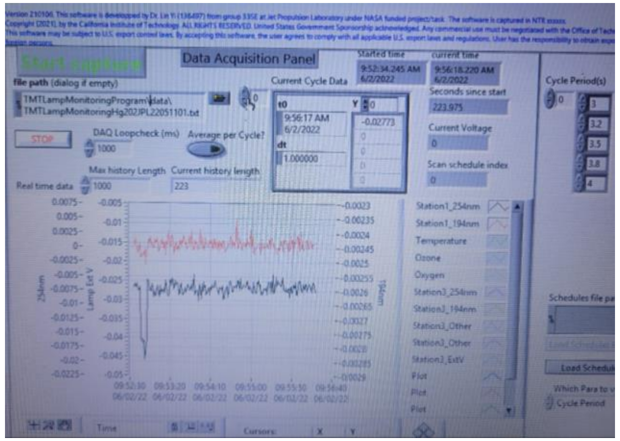
Optical Hg Drop Imaging





Long-term spectral & life monitoring





Data Acquisition Panel

Started time 9:52:34.245 AM 6/2/2022

current time 9:56:18.220 AM 6/2/2022

file path (dialog if empty) TMTLampMonitoringProgram\data\TMTLampMonitoringHg202JPL22051101.txt

Current Cycle Data

t0 9:56:17 AM 6/2/2022

dt 1.000000

Y 0

-0.02773
0
0
0
0

Seconds since start 223.975

Current Voltage 0

Scan schedule index 0

Cycle Period(s) 0

3
3.2
3.5
3.8
4

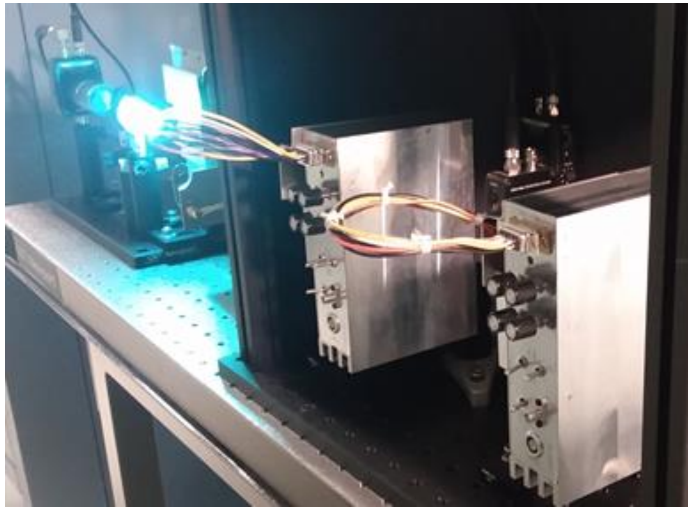
DAQ Loopcheck (ms) 1000

Average per Cycle?

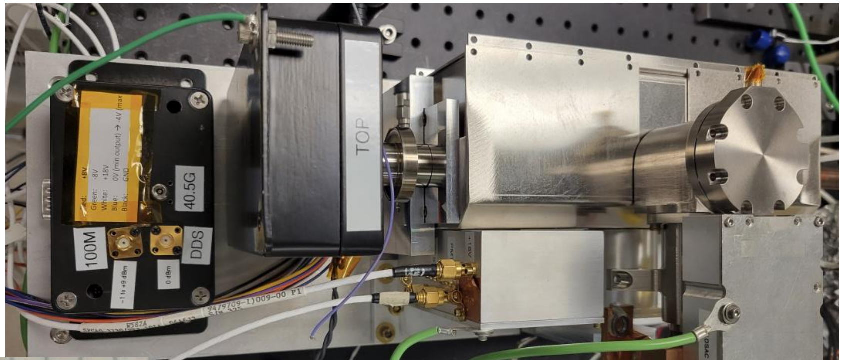
Max history Length 1000

Current history length 223

Ar and Hg discharge



TMT Summary



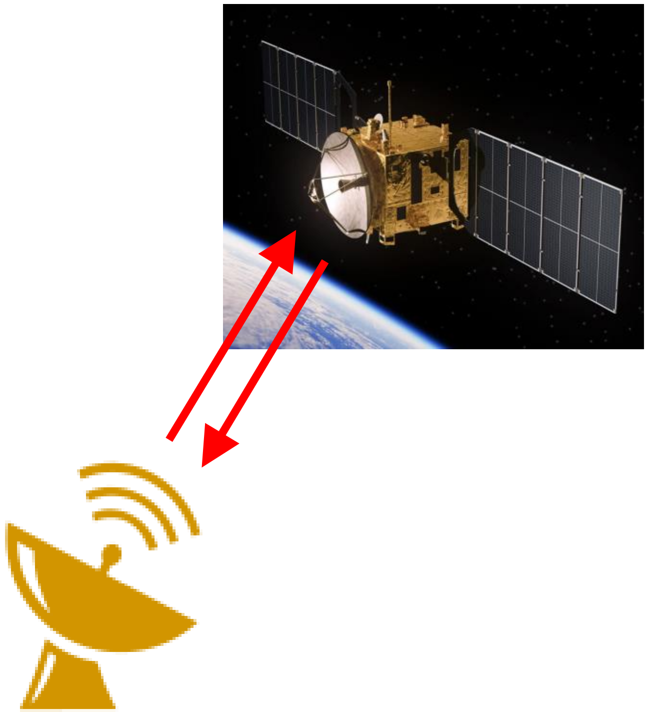
- **Performance:**
  - on track for 2e-13/sqrt(tau), 1e-15 at a day
- **SWaP:**
  - on track for 10 L / 34 W
- **Lifetime:**
  - have built a sapphire-coated lamp
  - Producing best clock signal
  - life testing in progress

Science Applications

Deep space navigation: a science enabler

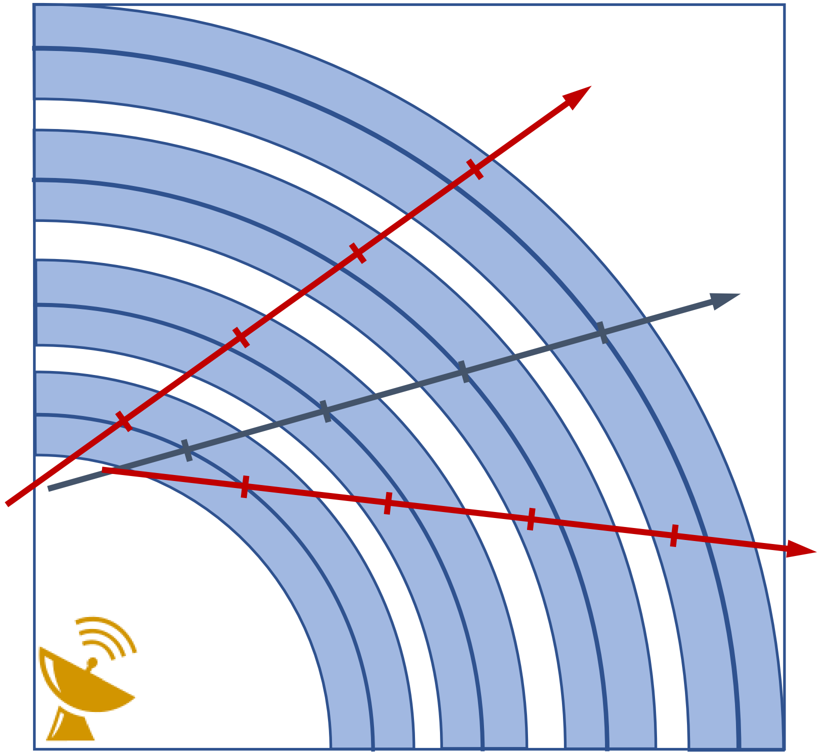
Deep Space Nav using 1-Way Range and a Spacecraft Clock

Two-way signals:
S/C is transponder, no clock
Distance + Velocity



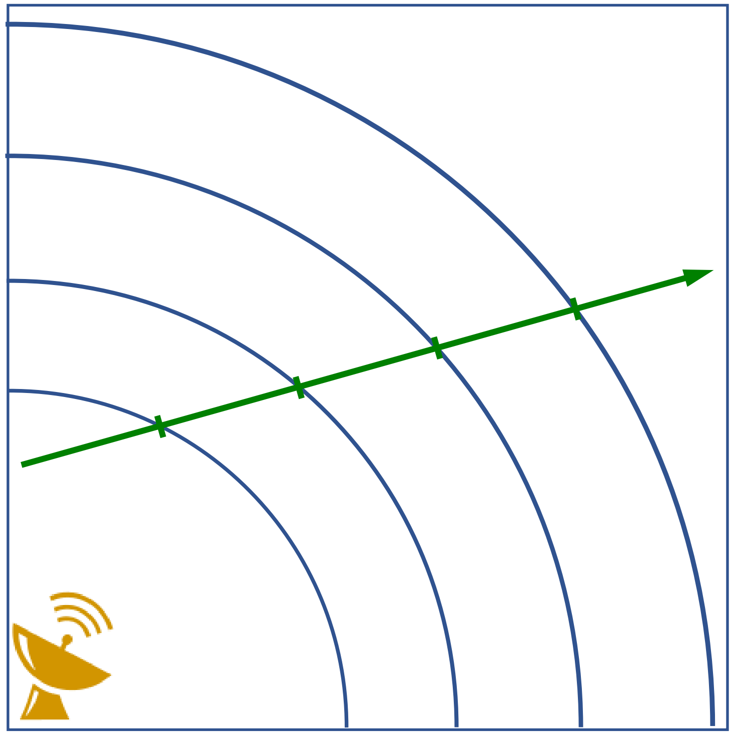
Precise, but not real time

One-way signal with bad clock:
Time delay + Doppler + Fit



Real-time nav, but imprecise

One-way signal with good clock:
Time delay + Doppler + Fit



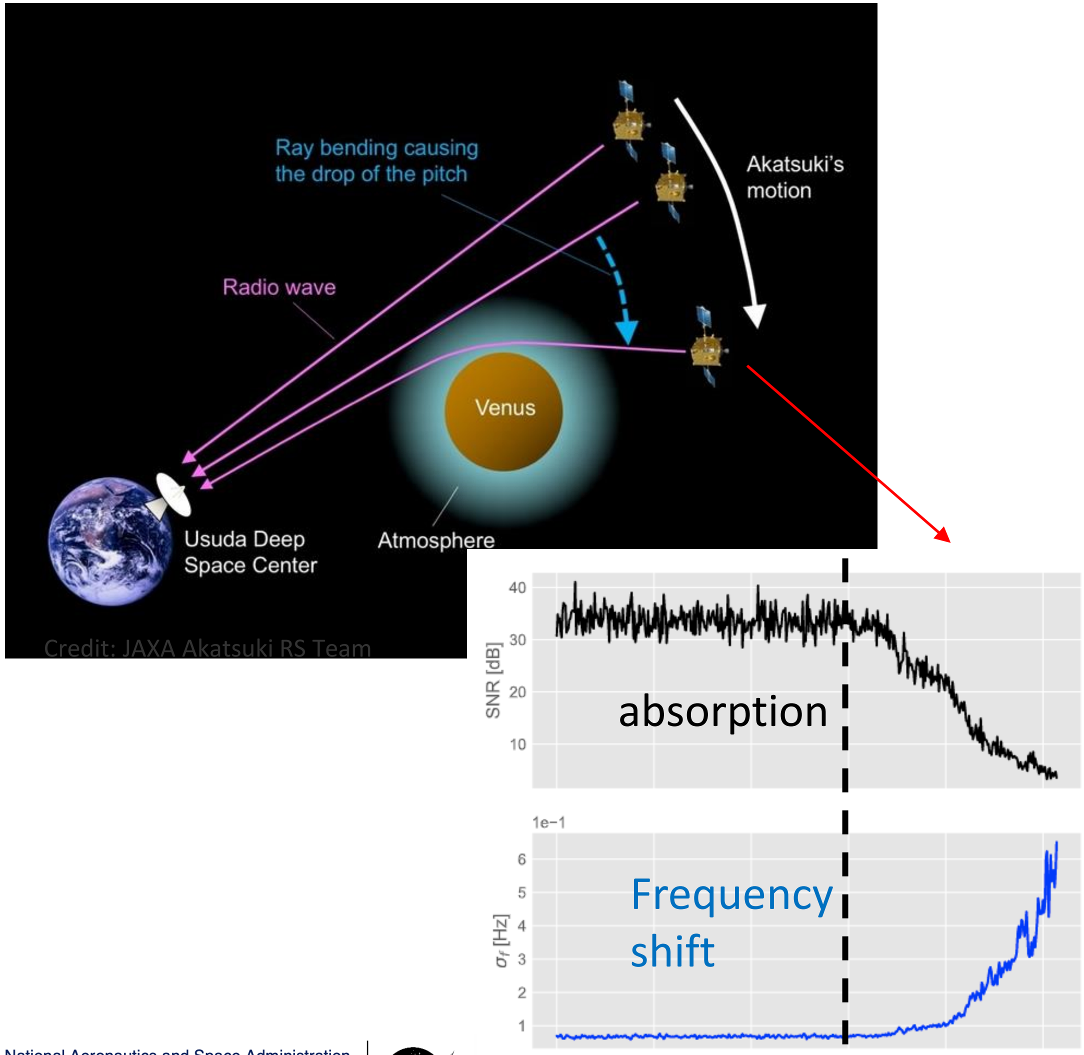
Real-time nav and precise

Radio Occultation

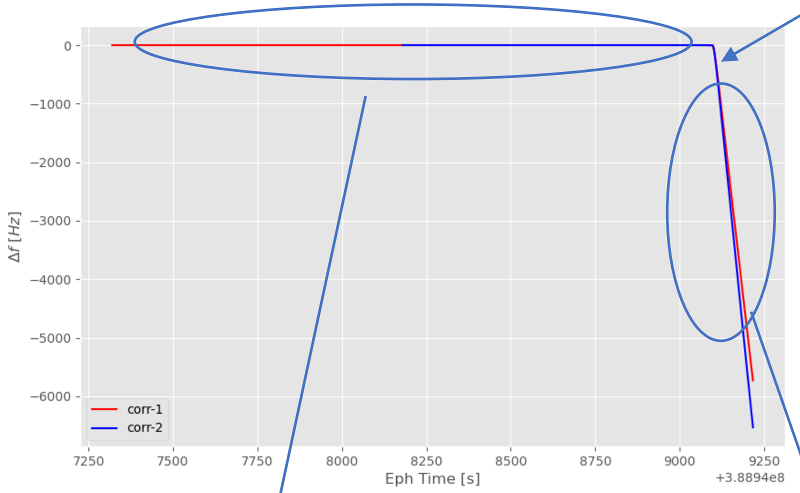
Courtesy Tatiana Bocanegra-Bahamon, JPL

- Must correct for USO drift
- Depends heavily on data used

RO Experiment Geometry

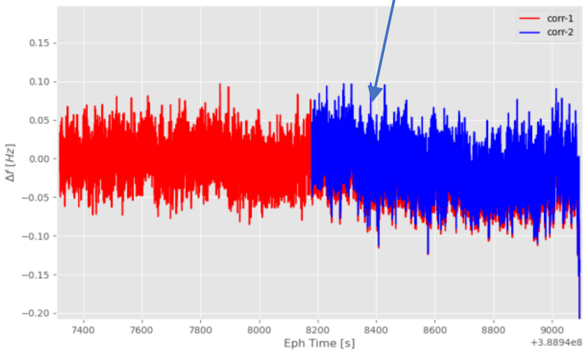


Ingress



Ingress point

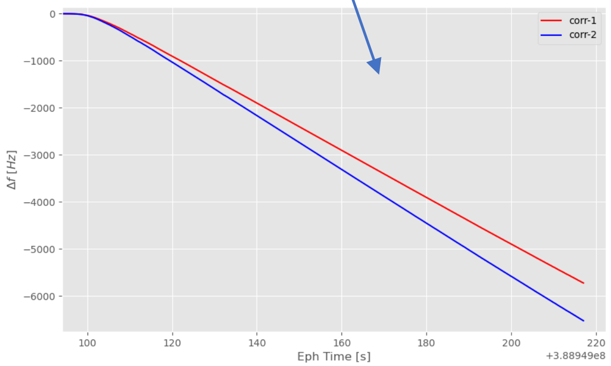
Occultation data



Data used for drift est.

Baseline mean:

- 7mHz (red), -2mHz (blue)

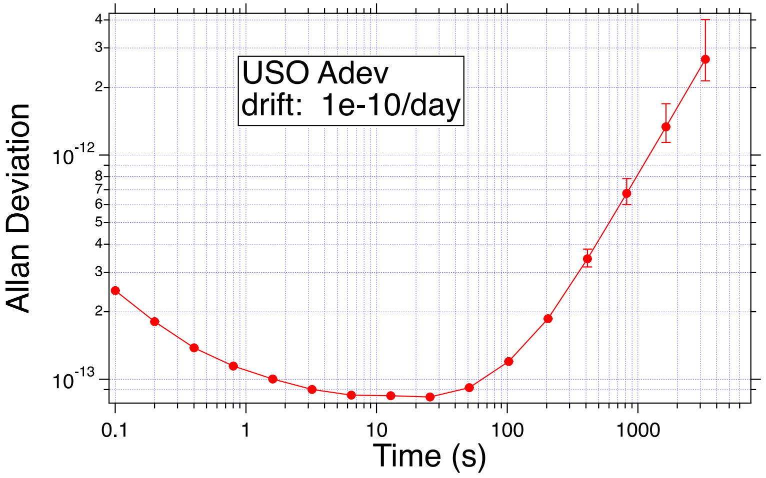


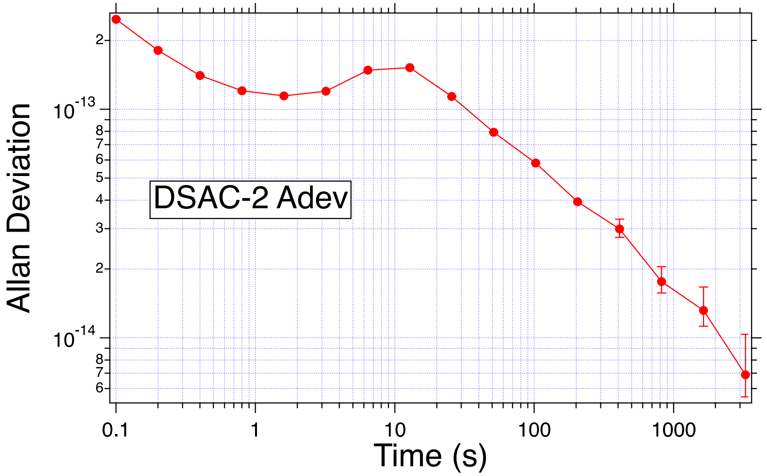
Uncertainty in RO result
due to USO drift estimate

RO Simulation: DSAC vs. USO

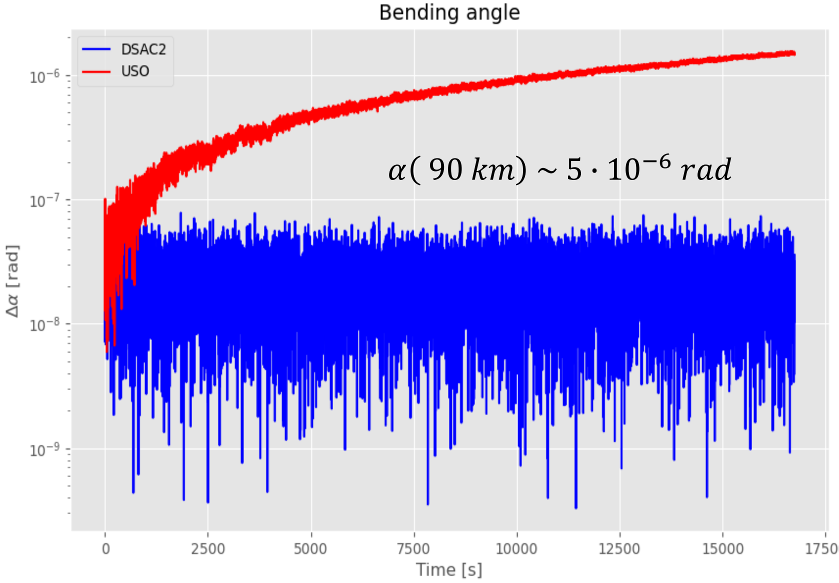
Effect of reducing the clock error

$$\sigma_f^2 = \frac{2BN_0/C}{(2\pi\tau)^2} + \sigma_{AD}^2 f_0^2$$

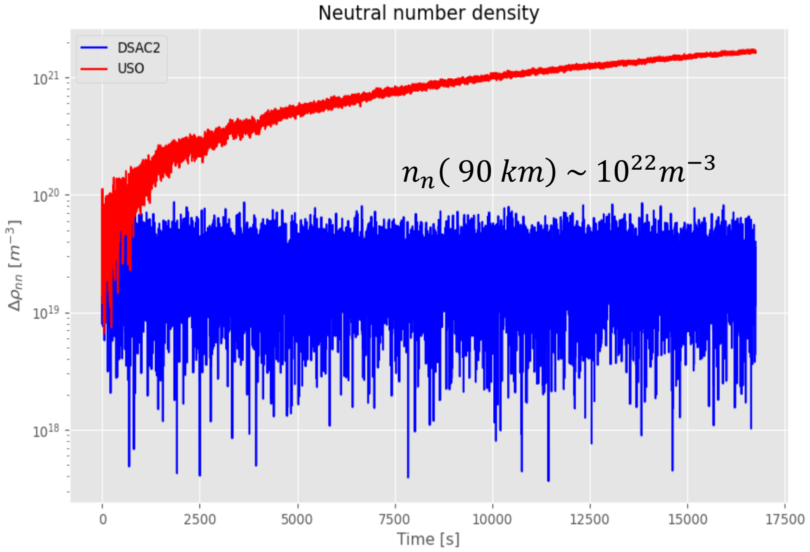




- Neglecting OD and transmissic errors
- propagate σ_f through the multivariate and multistage occultation measurement model using MC simulations.



1% vs. factor of 2



Part per 1000 vs. 10%

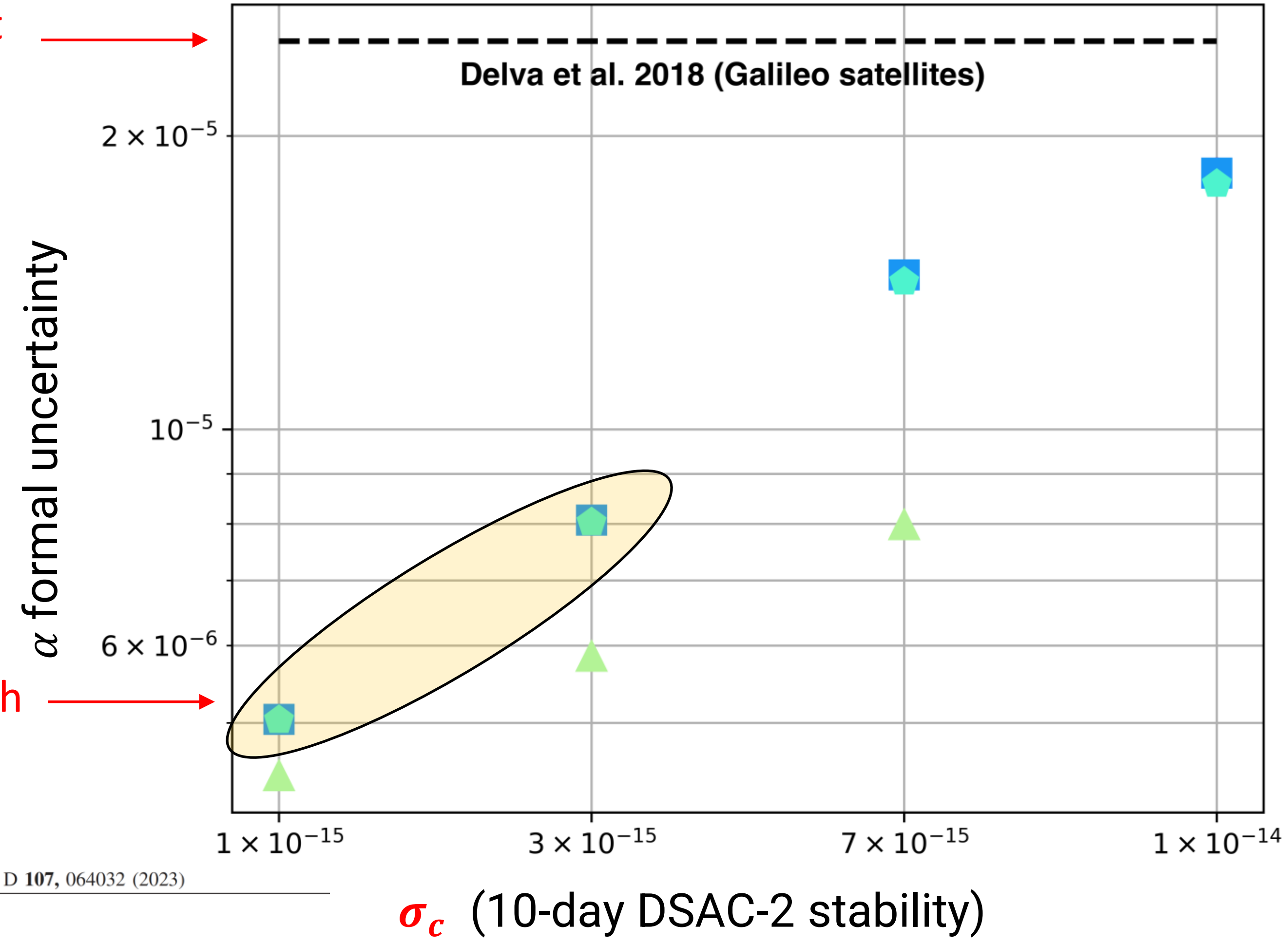
Courtesy Tatiana Bocanegra-Bahamon, JPL

Simulation Results for Venus Cruise LPI Measurement

Parametrization: α. LPI test with identical clocks (DSAC in space and on ground)

Multi-arc covariance analysis (using NASA-JPL MONTE software):

Current best

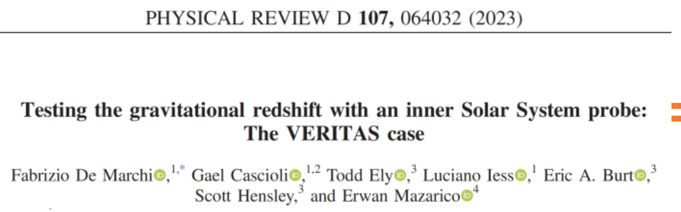


Possible with DSAC-2

σ_{init} : accuracy of initial frequency calibration (**i.e. expected to be $10^{-14} - 10^{-13}$**)

σ_c : expected 10-day frequency stability **DSAC-1 verified $\sigma_c < 5 \times 10^{-15}$**)

LPI/LLI slides courtesy of G. Cascioli, F. de Marchi, and L. Iess



PHYSICAL REVIEW D **107,** 064032 (2023)

Testing the gravitational redshift with an inner Solar System probe: The VERITAS case

Fabrizio De Marchi,[1,*] Gael Cascioli,[1,2] Todd Ely,[3] Luciano Iess,[1] Eric A. Burt,[3] Scott Hensley,[3] and Erwan Mazarico[4]

Summary

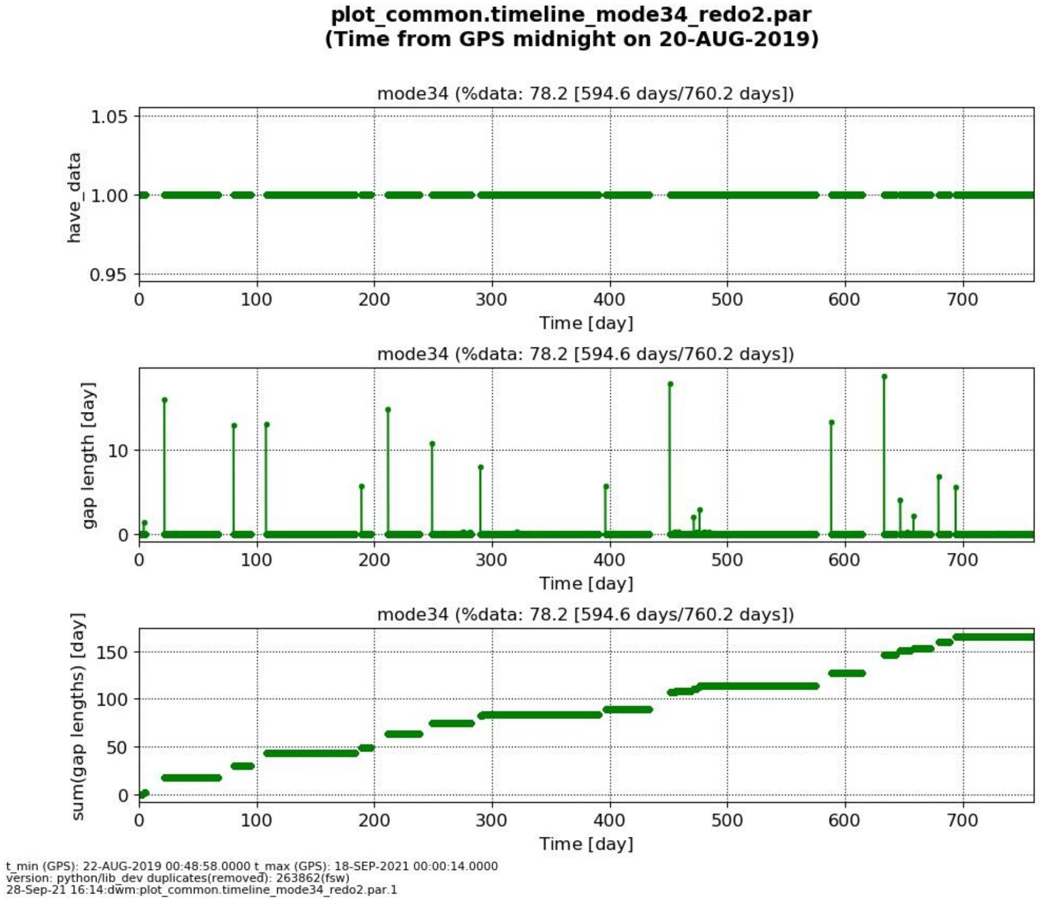
- DSAC: first trapped ion atomic clock in space
- < 3e-15 at 1 day, 3e-16/day drift, 300 ps at 1 day (meas. system limit)
- Lowest environmental sensitivities
- A lower SWaP breadboard prototype has been built
- Enables: deep space nav, science, and applications requiring autonomy
- Science examples: Relativity, Radio Occultation

Supporting Slides

DSAC 2019-2021 Operations Overview

- Mission operations from 8/20/2019 to 9/18/2021 for a duration of 760.2
- Operations periods include:
  - USO on: 84.6%
  - Clock on: 78.2%
  - GPS data: 74.9%
- 10 long runs (67 days longest)
- All run terminations due to S/C safe modes
- 2 known radiation-induced faults that impacted clock control – recovered
- No known clock hardware faults

Clock up time

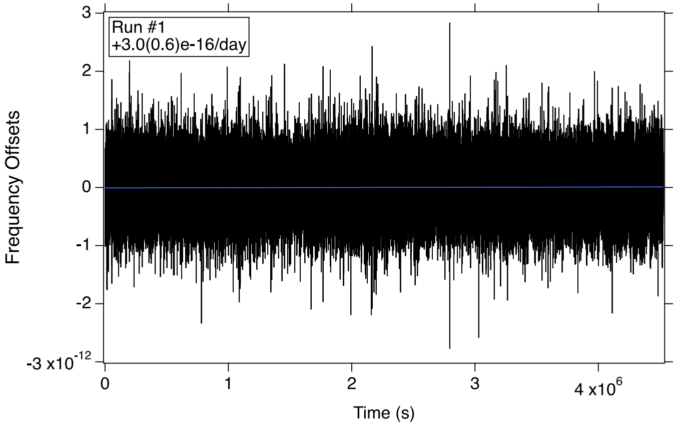


DSAC has proven to be very reliable and robust

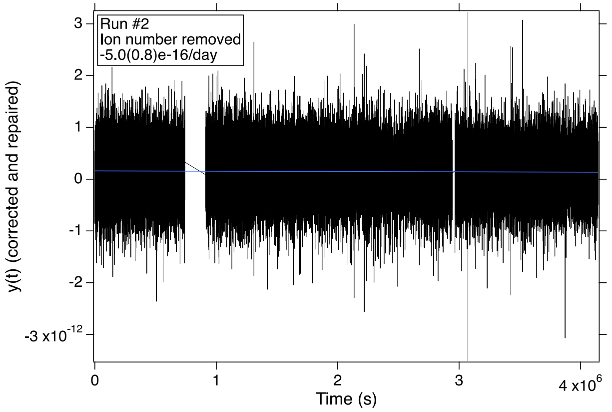
Long-Term Performance: Drift

- 3 long runs, each ~ 2 months

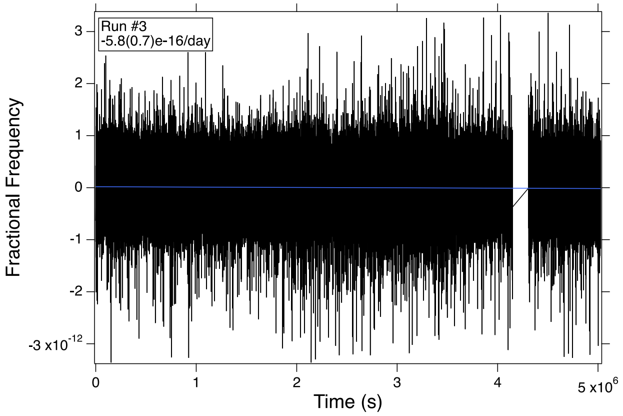
Run #1 (late 2020):
+3.0(0.6)e-16/day



Run #2 (early 2021):
Small ion cloud
correct for ion number
-5.0(0.8)e-16/day



Run #3 (late 2021):
Small ion cloud
-5.8(0.7)e-16/day



Confirmed:

- Systematic effects “corralled”
- Very little linear drift with no thermal regulation – two orders magnitude less than Rb
- Time keeping applications

Strength of trapped ion technology: long-term autonomous operations

Fundamental Science Enabled by DSAC

Gateway Provides Precision Time & Frequency for Science: measurements enabled by a precise clock

- 1/r^2 law of gravitation:
  - All measurements to date agree that the exponent is precisely “2”,
  - some theories of gravity predict a small deviation from this law.
  - Precise range of a drag-free spacecraft in deep space using a DSG clock together with laser ranging from the DSG to the moon could yield an improved limit on the correction [1].
- Cosmological constant (CC):
  - The CC is added to Einstein’s equations to explain an observed accelerating expansion of the universe.
  - Theoretical predictions disagree by many orders of magnitude with measured limits.
  - Ranging to a drag free spacecraft in deep space together with a DSG clock and laser ranging to the moon could improve limits on the cosmological constant. The measurement could also be enhanced by inferred outer planetary orbits as determined by nearby precise spacecraft ranging [1, 2].
- Dark Matter (DM):
  - DM in some form constitutes 90% of all matter and is required to explain the structure and dynamics of galaxies. So far unobserved.
  - Time variations in spacecraft ranging enabled by a DSG clock relative to a precisely known DSG orbit using laser ranging could be an indication of dark matter fluctuations on the spatial scale of the range [7].
  - Similar dark matter searches could also be carried out with a network of clocks, including one on the DSG and others on earth, on the spatial scale of the earth-moon distance.

Gateway Provides Precision Time & Frequency for Science: measurements enabled by a precise clock

- **Gravitational Red Shift (GRS):**
  - This general relativistic effect causes clocks deep in a gravitational potential to tick slower than those higher in the potential. All measurements to date agree with GR, however GR is known to be incomplete and some new theories predict variations in the GRS.
  - Due to it’s highly eccentric orbit, the DSG is an ideal platform to measure variations in the GRS by comparing a DSG clock to one on earth [5].
- **Lorentz Violation (LV)**:
  - Lorentz symmetry states that physics is the same regardless of relative orientation and speed of reference frames.
  - Some theories of quantum gravity predict a violation of this symmetry.
  - DSG orientation and speed constantly changing relative to Earth => DSG platform is ideal for looking for LV effects by comparing a DSG clock to one on earth.
  - Clock comparisons include changes in orientation (Michelson-Morley), velocity (Kennedy-Thorndike), and time dilation (Ives-Stilwell) [5, 6].
- **Quantum Entanglement (QE):**
  - correlating quantum states in systems separated by a space-like interval (not causally linked in a classical picture.)
  - Entanglement has been demonstrated out to 1200 km [8]. A DSG clock could extend this to earth-moon distance by using precise timing to improve signal to noise in an entangled state measurement apparatus.
- **Quantum Clock Synchronization (QCS):**
  - An algorithm to synchronize remote clocks using quantum entanglement.
  - Not yet fully demonstrated on the ground

Gateway Provides Precision Time & Frequency for Science

Test	Observable	Instrument	Current Best	DSAC on DSG
Space VLBI	230+ GHz microwave signals from SMBH's	Multiple antennae + clocks + …		
- $1/r^2$ **- cosmological constant** **- DM vs. MOND[1][1]**	S/C range	DSG clock + drag free S/C + DSG-Moon laser range[2]	10^{-6} at 100 AU	$5x10^{-8}$ at 100 AU[2]
Cosmological constant [2]	Planetary orbit from S/C range	DSG clock + drag free S/C + DSG-Moon laser range[3]	$\Lambda < 10^{-36}$	$\Lambda < 10^{-39}$
Cosmological constant	Perihelion precession[4]	Ranging between DSG and the moon	$\Lambda < 10^{-36}$	Unlikely to be competitive, but needs more study[9]
Gravitational Red Shift	Clock compare: DSG to earth	DSG clock	Clock: $2.5x10^{-5}$ [3a] AI: $7x10^{-9}$ [4]	$>3x10^{-6}$ [5] ~5e-6 (VERITAS)
Lorentz Violation	Clock compare DSG to earth in different reference frames	DSG clock	$1.1x10^{-8}$ [6]	$>1x10^{-7}$ [5]
Local Position Invariance	Compare two isotopes in- situ in space with elliptical orbit	Dual ^{199}Hg+/^{201}Hg+ clock	TBD	TBD
Dark Matter	Clock compare	network of clocks[7]	Energy scale > 10^5 TEV for a 100 km defect size [7]	$>10^6$ TEV [8]

Gateway Provides Precision Time & Frequency for Science

Test	Observable	Instrument	Current Best	DSAC on DSG
Quantum Entanglement	Entangled photon polarization correlations [8]	DSG clock + high precision clock elsewhere + entangled photon source[10]	Demonstrate entanglement over 1200 kilometers	Extend to Earth-moon distance scale
Quantum Clock Synchronization	Time synchronization of two remote clocks	2 DSG clocks + 1 remote clock + set of entangled qbits + method for transferring qbit phase to clocks[11]	Not yet fully demonstrated	

Gateway Provides Precision Time & Frequency for Science

Notes:

[1] DM = Dark Matter, MOND = Modified Newtonian Dynamics

[2] There is already a proposal to do 1-meter ranging with the DSN on a drag-free S/C at the outer planets (minimal solar gravitational potential). There is also a proposal to do laser ranging from the DSG to the moon at the mm level. If these two were already present, ranging from the gateway might be done at the sub-meter level, thereby improving on the DSN-based measurement.

[3] This is similar to the previous experiment and uses the same set up, but by virtue of the measured precision drag free satellite range, a planet position is inferred. The planetary orbit would place a limit on the cosmological constant.

[4] Use the DSG clock to do ranging from the DSG to the moon. The large eccentricity of the DSG orbit is predicted to result in a large perihelion precession as predicted by GR and could be used to place a limit on the cosmological constant. However, laser ranging should be far more precise than that using a clock.

[5] Might be better than existing clock comparisons, which are led by GPA, but not competitive with atom interferometer (AI) experiments.

[6] Willams et al., estimate that a Lorentz violation measurement could be improved by 2 orders of magnitude using the DSG highly eccentric orbit and an on board optical clock. A DSAC clock would provide 3 orders of magnitude worse stability, so the effect would be measured with 10x less precision than is already done.

[7] Cross correlation between two clocks is performed in situ or between remote clocks. For a given time scale, there should be no correlation (random noise).

[8] This is very speculative. The highly eccentric orbit may increase sensitivity to certain defect size scales not currently available.

[9] Current best measurements are based on perihelion advances of Earth and Mars. The perihelion advance of the DSG is likely to be less well known, but this needs more study.

[10] Quantum entanglement experiments send pairs of photons with their polarization states entangled, between two remote sites. Often the signals are greatly attenuated by the transmission distance. Precise timing on both ends enables very weak signal retrieval using narrow band detection.

[11] Quantum Clock Synchronization protocols synchronize remote clocks using measurements on quantum systems with shared prior entanglement. A quantum measurement on one element of a pair in one location causes a wave function collapse in the other remote partner and subsequent synchronized phase evolution. However virtually all such protocols depend on having a common phase origin in the two separated systems, which is equivalent to already synchronized clocks. More recent protocols attempt to address this loophole, however it is not clear how this could be implemented in an actual DSAC-like clock. The mechanism must be demonstrated in the laboratory using real clocks before attempting a demonstration on the DSG platform.

Gateway Provides Precision Time & Frequency for Science

References:

[1] B. Buscaino, et al., "Testing long-distance modifications of gravity to 100 astronomical units," PRD 92, 104048 (2015)

[2] M. Sereno, and P. Jetzer, "Solar and stellar system tests of the cosmological constant," PRD 73, 063004 (2006).

[3] R. Vessot et al., PRL 45, 2081 (1980)

[3a] S. Herrmann, et al., PRL 121, 231102 (2018)

[4] H. Muller, A. Peters, and S. Chu, "Precision measurement of the gravitational red shift by the interference of matter waves," Nature 463, 926 (2010).

[5] J.A. Williams and N. Yu, Deep Space Gateway Science workshop (2018)

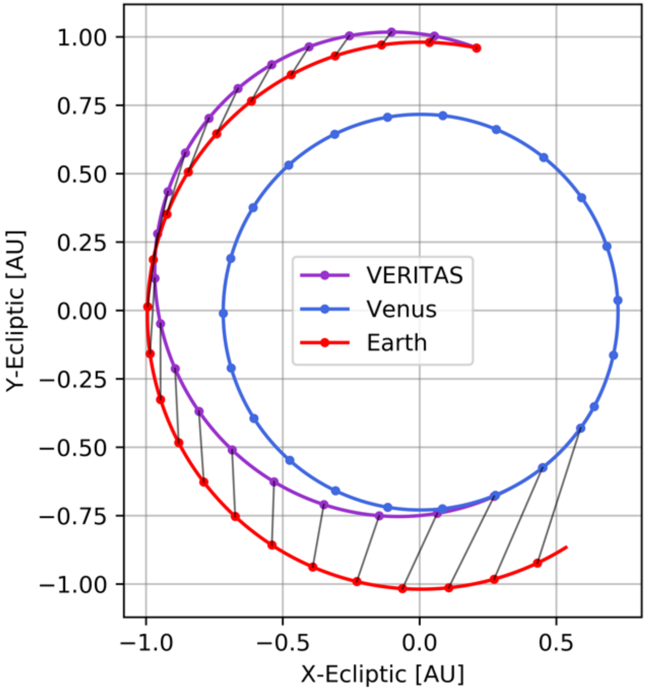
[6] P. Delva et al., PRL 118, 221102 (2017)

[7] P Wcislo et al., "Experimental constraints on dark matter detection with optical clocks," Nature Science 1, 0009 (2016).

[8] J. Yin, et al., "Satellite-based entanglement distribution over 1200 kilometers," Science 356, 1140 (2017)

Measuring the GR gravitational red shift using DSAC on VERITAS

- Measuring the GRS: Engineering vs. science
- GRS currently known at 1e-5 level
- Use depends on which is more precise: knowledge of GRS OR knowledge of OD, potential, and clock
- For instance:
  - DSAC orbit varied by 2e4 m altitude for each 100 minute orbit => GRS = 2e-12
  - **In DSAC orbit, GRS could only be measured at 1e-3 level – engineering**
- BUT, in deep space, potential change can be much larger
- Eg., in cruise phase to Venus, sample *solar* potential over 4e10 meters!
- Earth-Venus GRS ~ 1e-9 (solar effect at Venus is ~1e-19/m)
  - **Venus cruise GRS could be measured at 1e-6 level - science**



F. De Marchi, et al., "Testing the Gravitational Redshift with an Inner Solar System Probe: The VERITAS Case." Physical Review D 107, no. 6 (March 13, 2023): 064032. https://doi.org/10.1103/PhysRevD.107.064032.

LPI/LLI slides courtesy of G. Cascioli, F. de Marchi, and L. Iess

LLI – LPI on VERITAS: Iess et al. analysis

$$\frac{\Delta\nu}{\nu_{sc}}(\alpha_{sc},\alpha_{st},\epsilon_{sc},\epsilon_{st}) = \underbrace{(1+\alpha_{sc})\frac{\overset{\substack{\text{Space craft}\\ \text{GRS}}}{\overset{\downarrow}{U_{sc}}}}{c^2} - (1+\alpha_{st})\frac{\overset{\substack{\text{Station}\\ \text{GRS}}}{\overset{\downarrow}{U_{st}}}}{c^2}}_{\textbf{Local Position Invariance (LPI)}} + \underbrace{(1+\epsilon_{st})\frac{\overset{\substack{\text{Station } 2^{\text{nd}}\\ \text{order}\\ \text{Doppler}}}{\overset{\downarrow}{v_{st}^2}}}{2c^2} - (1+\epsilon_{sc})\frac{\overset{\substack{\text{Space craft}\\ 2^{\text{nd}}\text{ order}\\ \text{Doppler}}}{\overset{\downarrow}{v_{sc}^2}}}{2c^2}}_{\textbf{Local Lorenz Invariance (LLI)}}$$

This parametrization can be simplified under certain assumptions:

- If the two clocks are **identical or based on the same kind of atomic transition**:

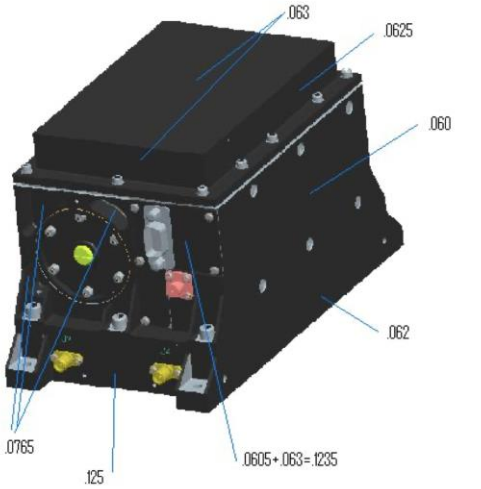
$$\alpha_{sc} = \alpha_{st} = \alpha \qquad \epsilon_{sc} = \epsilon_{st} = \epsilon$$

- LPI violation only (e.g. Delva et al. 2018):

$$\alpha_{sc} = \alpha_{st} = \alpha \qquad \epsilon_{sc} = \epsilon_{st} = 0$$

LPI/LLI slides courtesy of G. Cascioli, F. de Marchi, and L. Iess, University of Rome, VERITAS science team

RO Timing Methods



- **USO:**
  - Traditional approach
  - High TRL
  - Large drift
- **2-way Ka-band microwave link to ground maser**
  - Emerging approach
  - Maser-like stability
  - May not always be possible
  - Resynch overhead (“lock up time” = 2x light travel time to Earth)
- **DSAC**
  - Near-maser stability in-situ
  - Vs. USO and other clocks: Lowest environmental sensitivity
  - Vs. USO: No drift
  - Vs. 2way: 2x lower resynch time (1-way vs. 2-way)
  - Vs. 2way: Better localization (compared to 2-way)
  - Vs. 2way: Reduction of solar plasma effects by 2x