Trapped ion atomic clock development for space and ultra-stable ground applications

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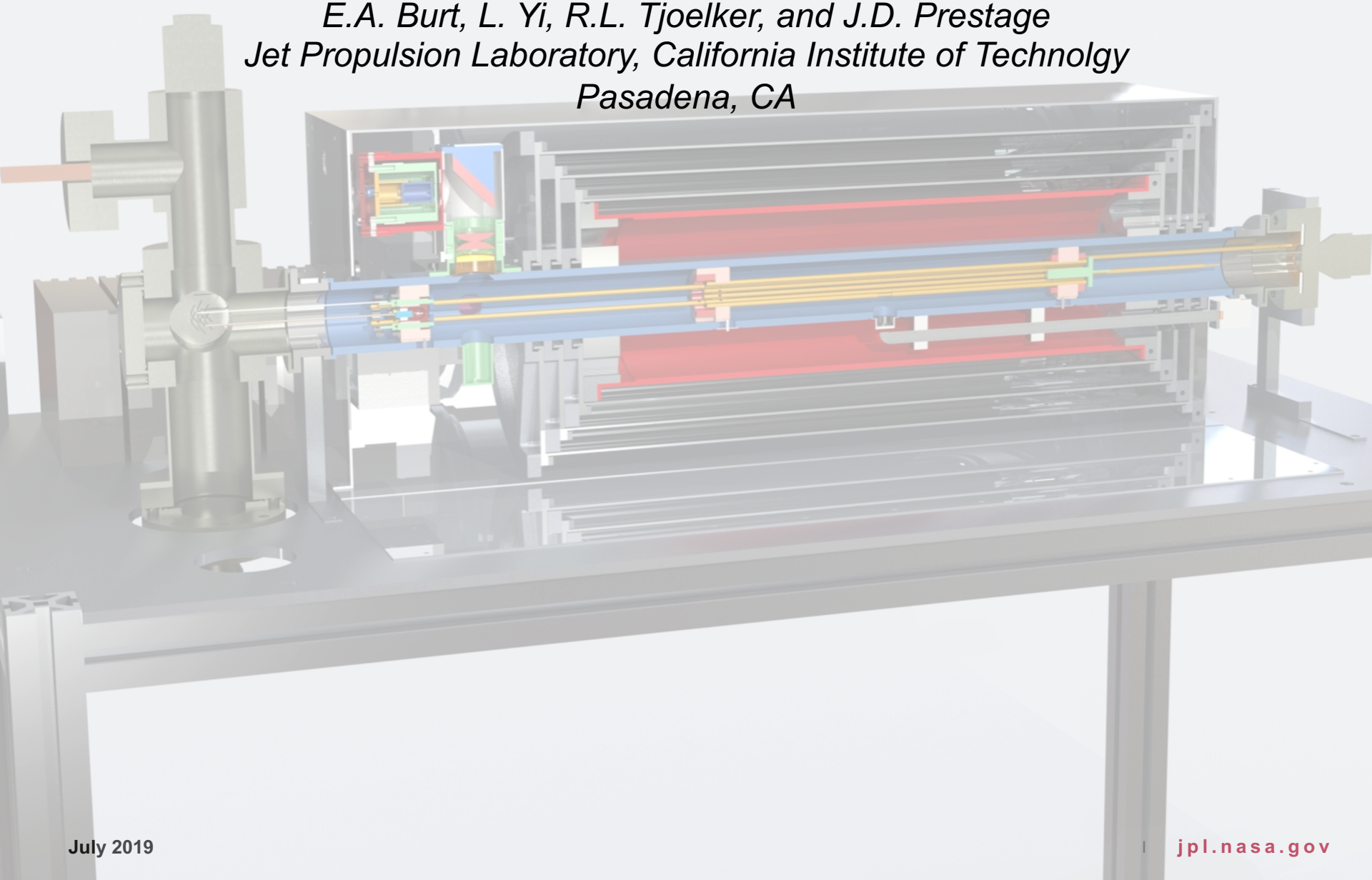
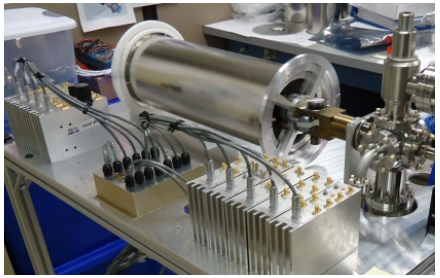


NASA/JPL Context: Mercury Trapped Ion Clocks

- **Long life, continuous, high stability operation**
- **Mercury Linear Ion Clock Paths and Applications:**

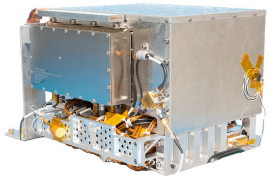


Ultra stable ion clock

1. Ultra-Stable Performance: UTC timescales

"Compensated" Multi-pole ion clock technologies:

- 10^{-16} at 1 to 10 days, drift ≤ 10^{-17}/day.
- 10^{-15} short term stability (~1 sec) via super LO's.



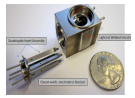
DSAC

2. Space: DSAC Technology Demonstration Mission (TRL 5-7)

- NASA Deep Space: ~ 20W and 5 kg goal
- GNSS (MAFS) : ~ 1×10^{-13} short term, 10^{-15} at 1 to 10 days
- Science and other apps….

3. Miniature, low power

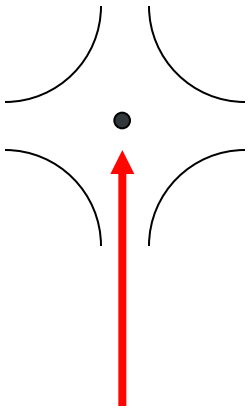
- cm^3 scale ion trap
- Miniature UV light sources and LO's
- Alternative ions



<3 cm^3

The Multi-pole Ion Trap

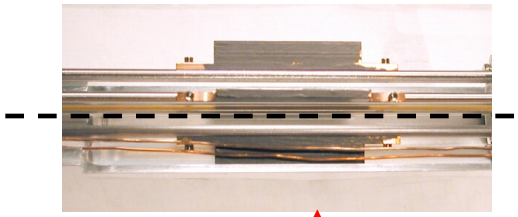
Spherical Quadrupole RF Trap



Field-free region at one point in center of trap

H.G. Dehmet, Bull. Am. Phys. Soc. 18, 1521 (1973)

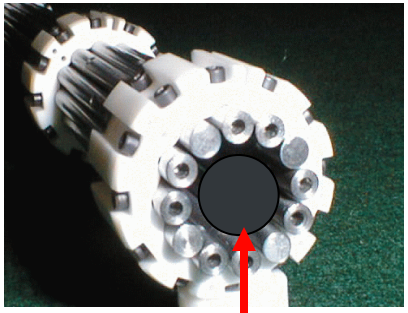
Linear Quadrupole RF Trap



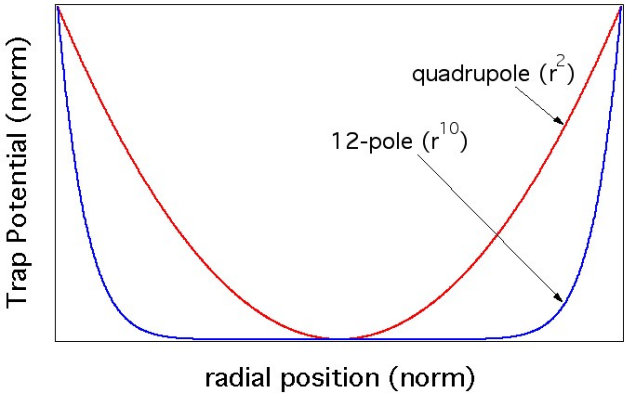
Field-free region on a line

J.D. Prestage, G.J. Dick, and L. Maleki, J. Appl. Phys. 66, 1013 (1989)

Multi-pole (12) RF Trap



Field-"free" Region in a volume



J.D. Prestage, R.L. Tjoelker, and L. Maleki, Proceedings of the 1999 Joint EFTF-FCS

Ion density in a MP trap

Boltzmann density distribution with pseudo potential V(r):

$$n(r) = n(0)exp^{-\left(V(r)+q\phi(r)\right)/kT}$$

Poisson's equation:

$$\nabla^2\phi(r) = -qn(r)/\epsilon_0$$

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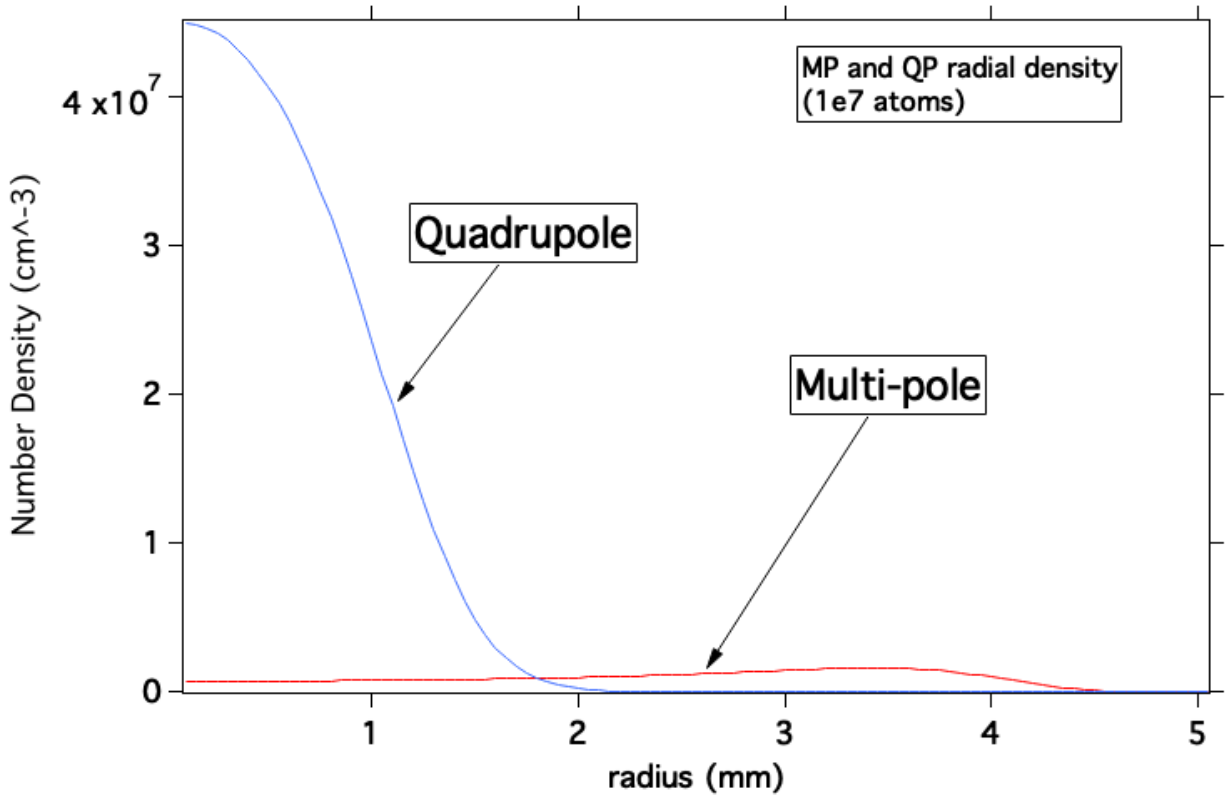
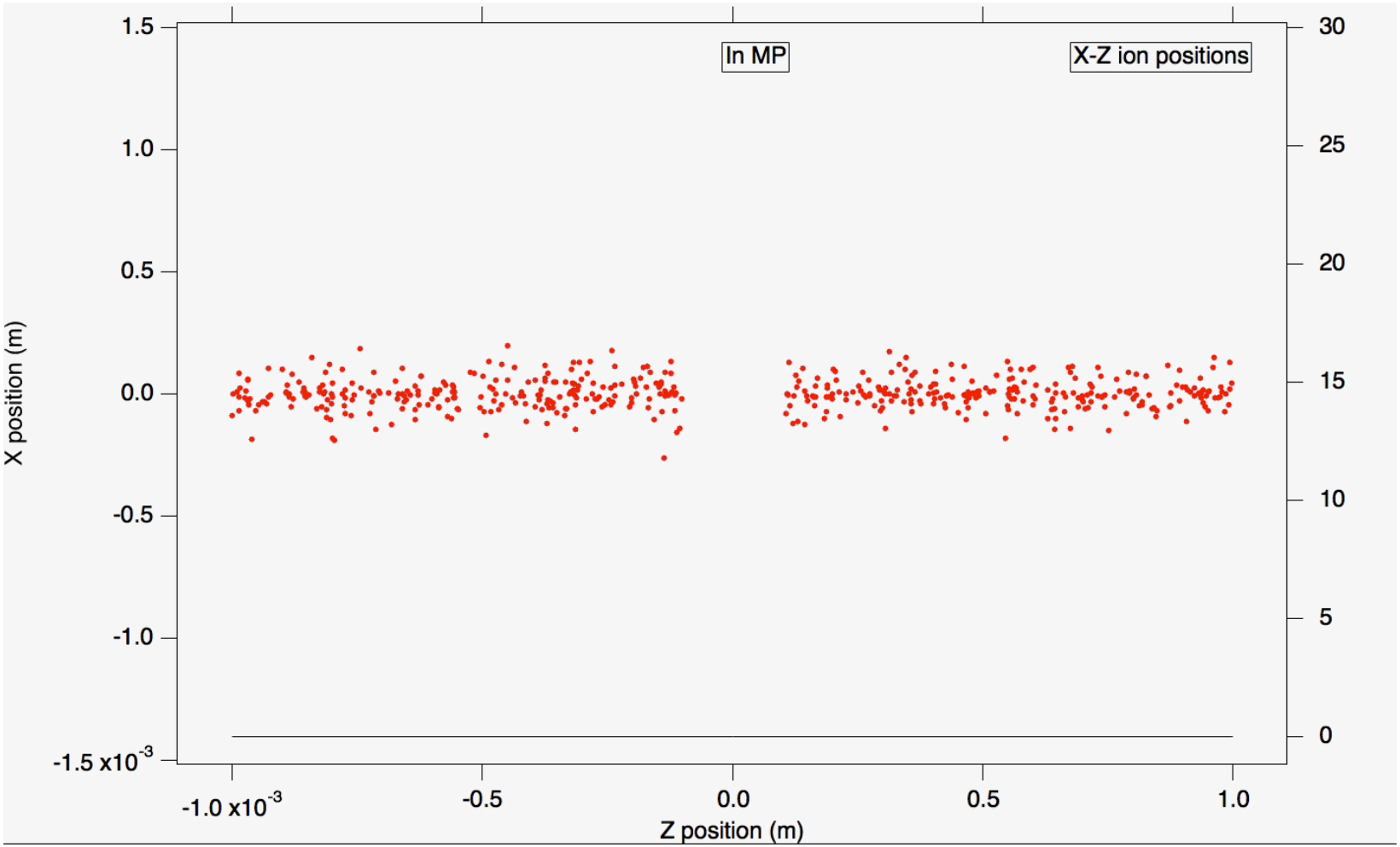


J.D. Prestage, et al., Proceedings of the 2000 IEEE IFCS, p. 706 (2000)

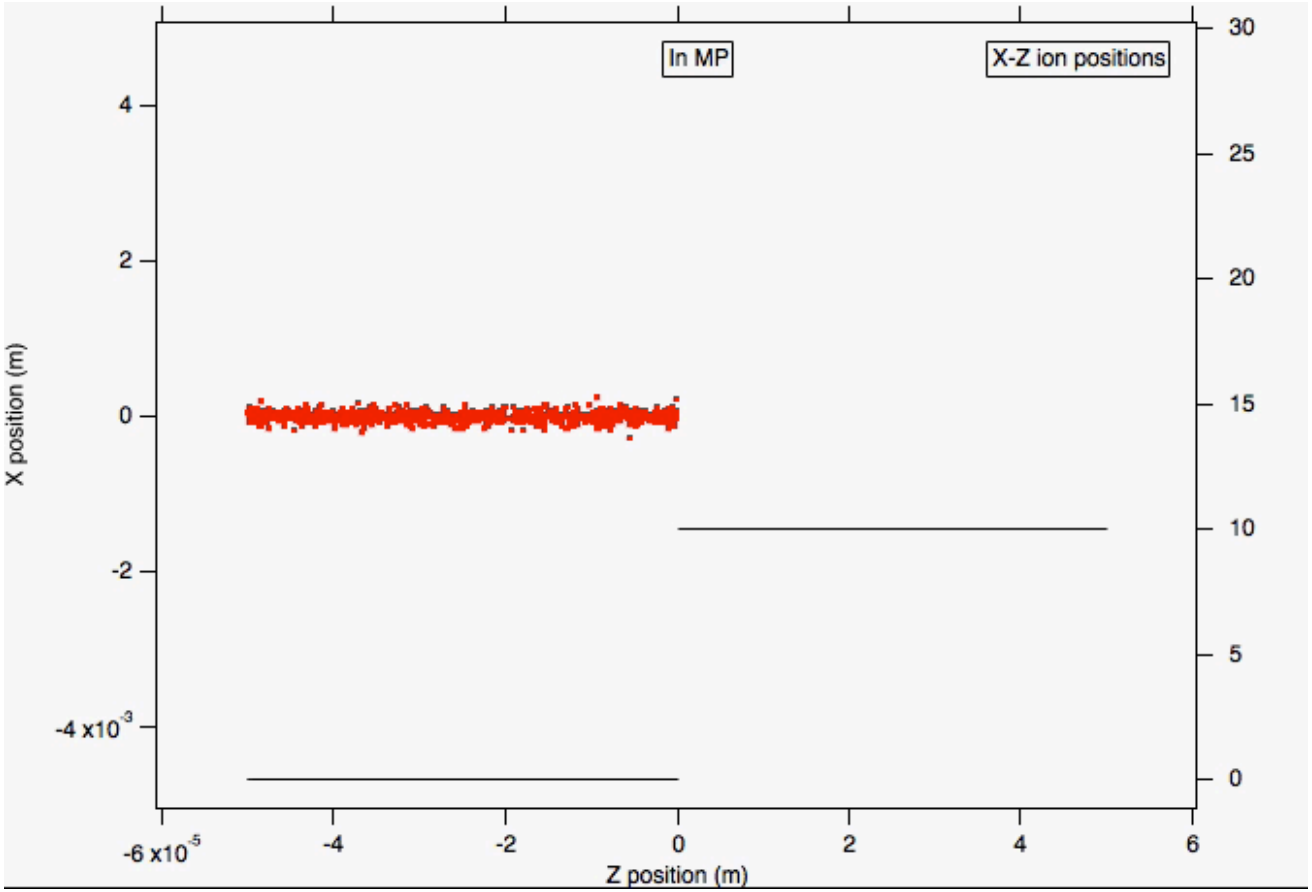
Room temperature trapped ion technology

- Quadrupole/multi-pole trap comparison

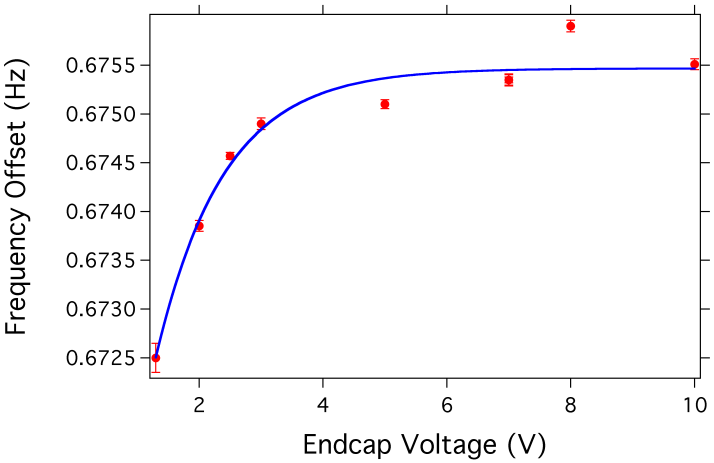


Room temperature trapped ion technology

- Shuttle simulation



Second order Doppler shift (time dilation) compensation
How it works



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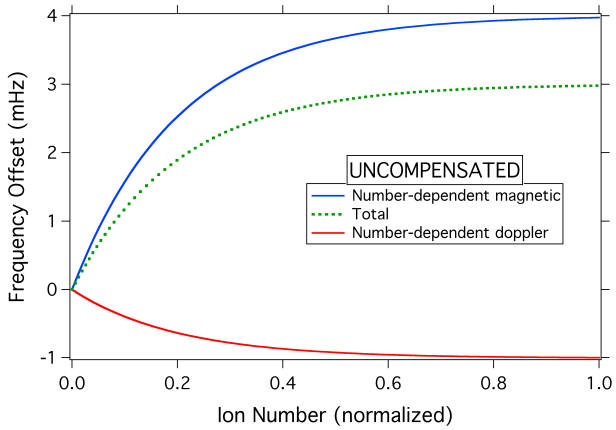
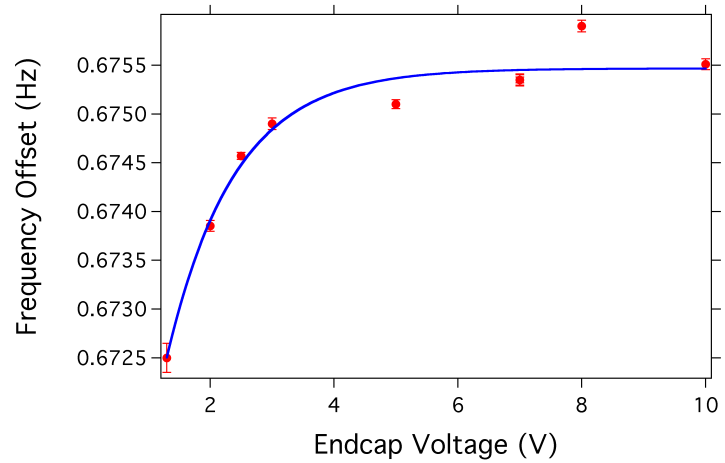
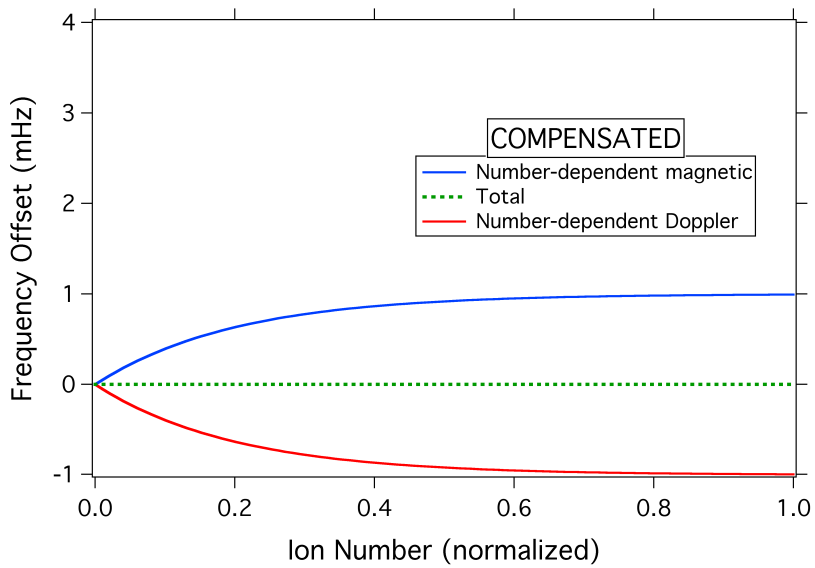
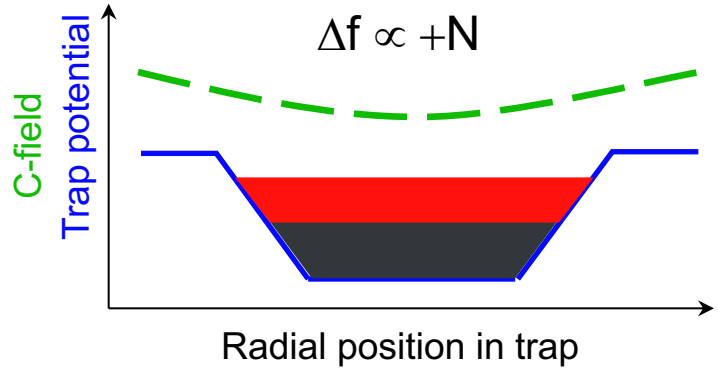


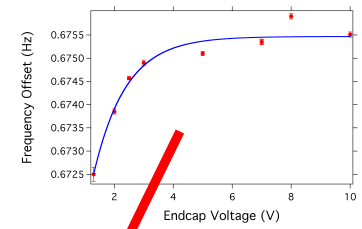




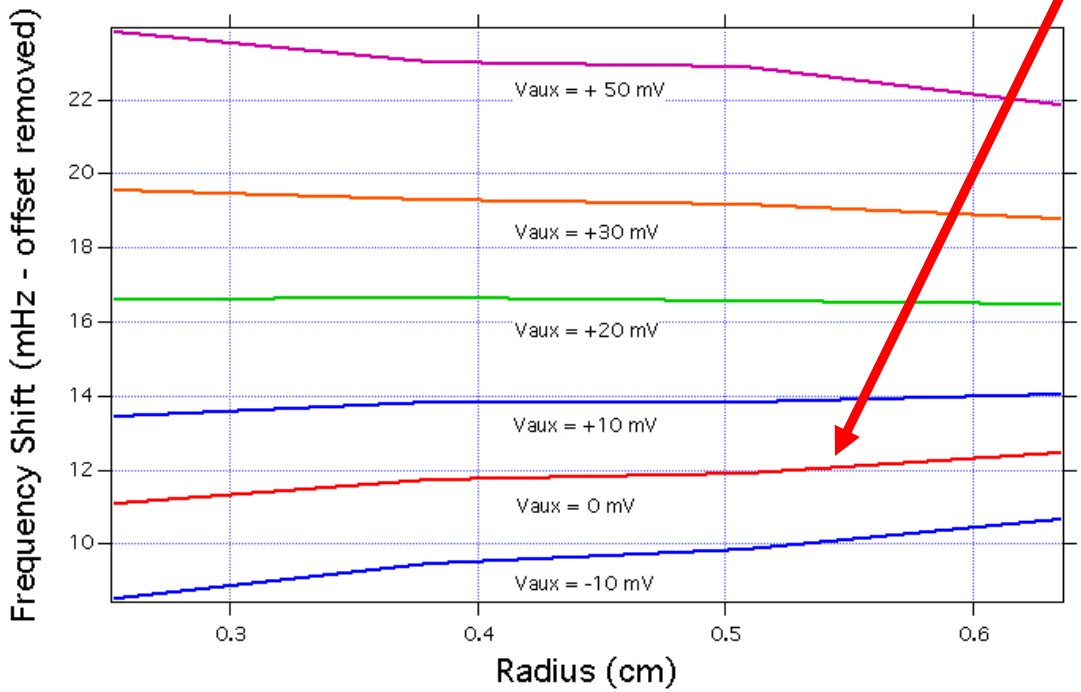
Model of Field Inhomogeneity Effect

Schematic



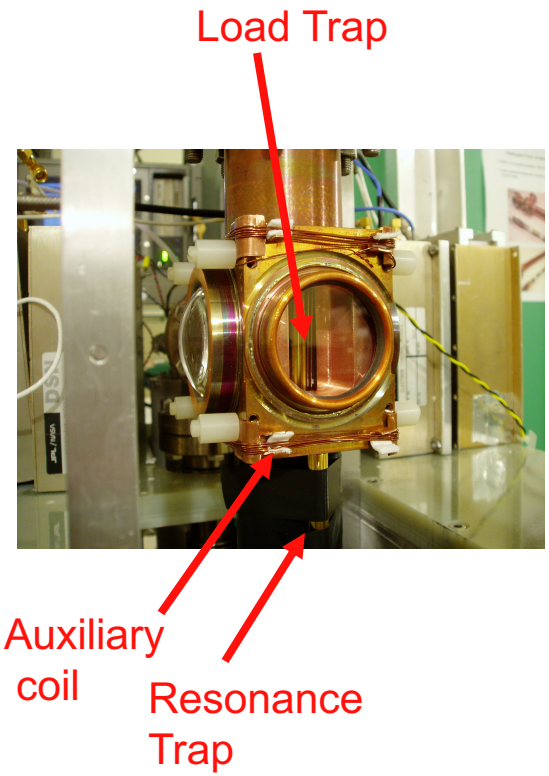


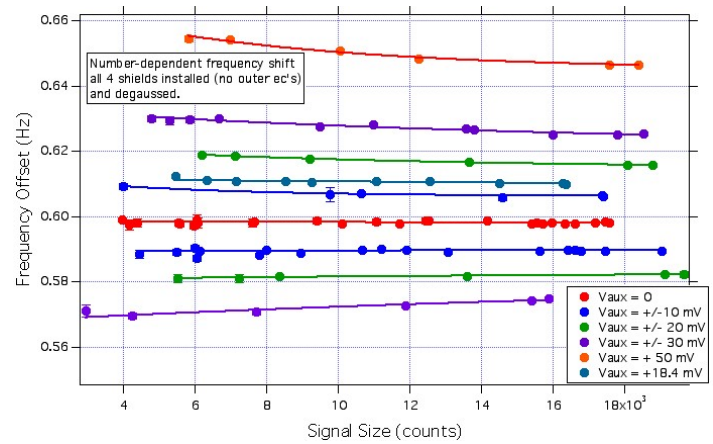
Finite Element Model of radial frequency dependence

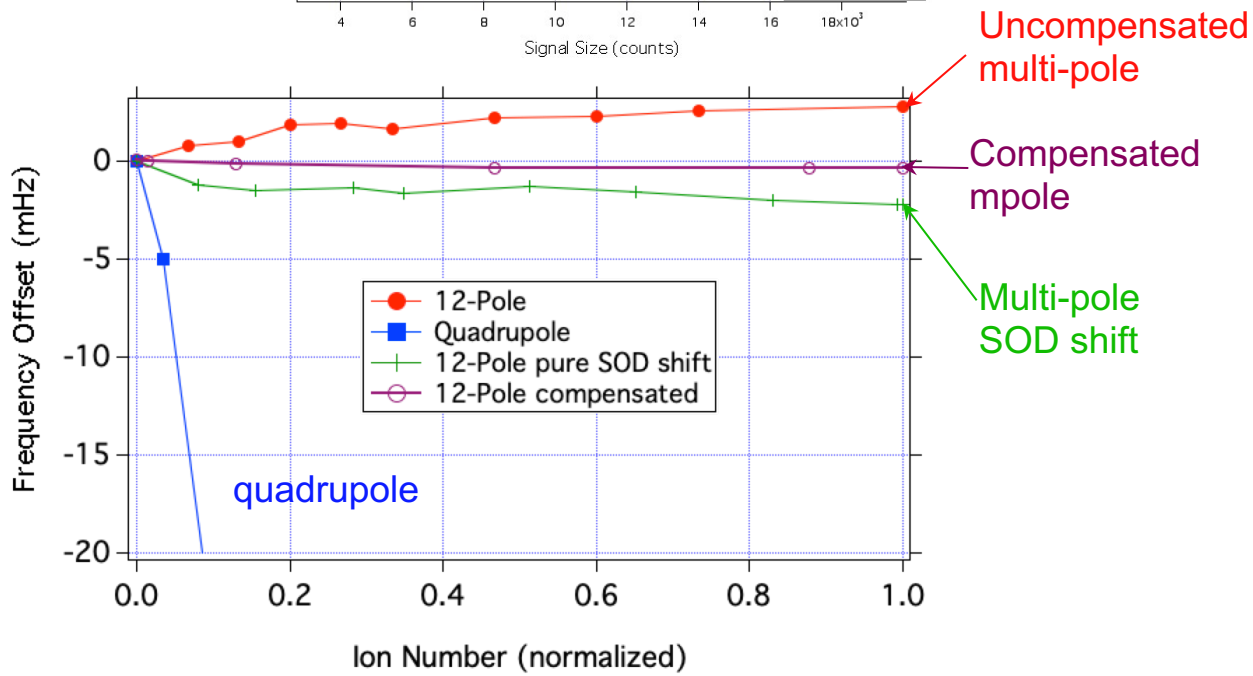


Larger ion number => larger radius

Second order Doppler shift compensation



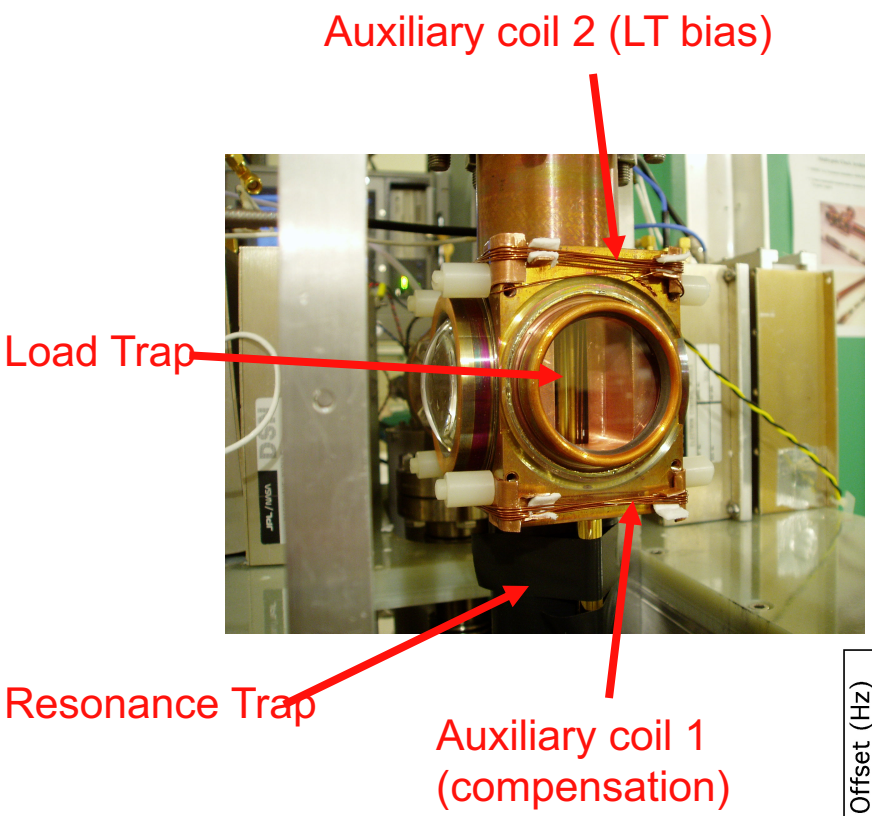




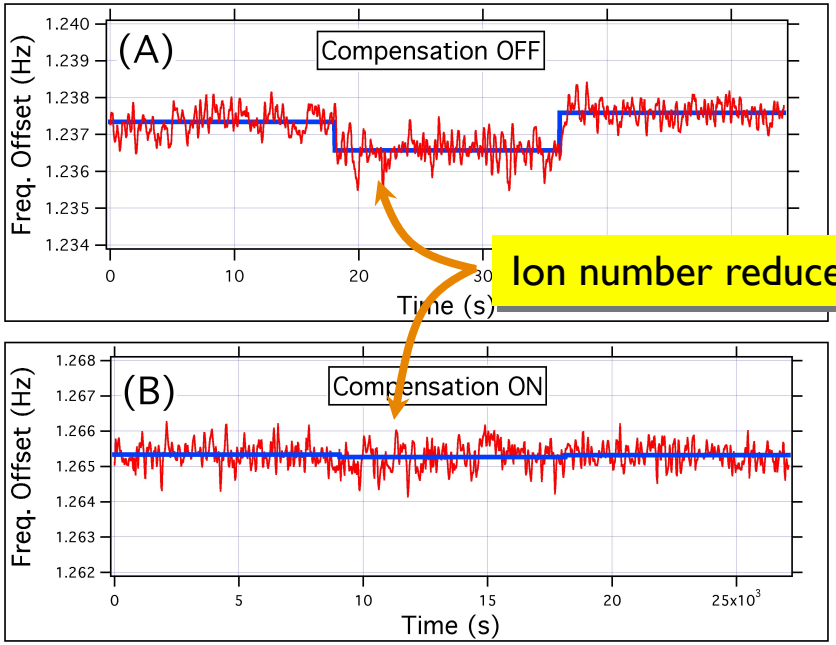
E.A. Burt and R.L. Tjoelker, Proceedings of the 2005 joint IEEE FCS/PTTI

1% change in ion number now results in < 5×10^{-17} (previously 1×10^{-15})

Second order Doppler shift Compensation: *Result*



Ion number dependence, once the largest systematic, is now barely detectable



Ion number reduced by 20%

E.A. Burt, W.A. Diener, R.L. Tjoelker, Proceedings of the 2007 Joint EFTF-IFCS

Ultra-stable ion clock development: Current generation

Fundamental shifts on the 40.5 GHz hyperfine transition in $^{199}Hg^{+}$

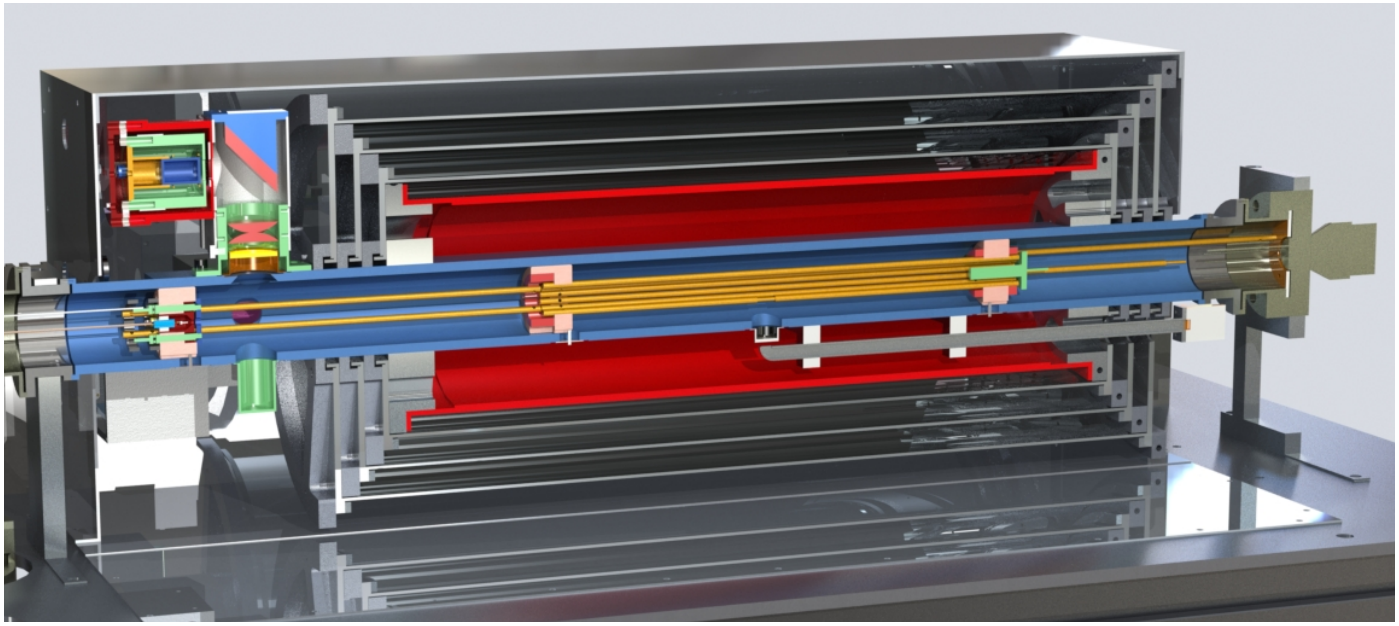
1. *Magnetic Shifts*
2. *Doppler Shifts (Thermal and Motional Doppler effects)*
3. *Collision Shifts (residual gases)*

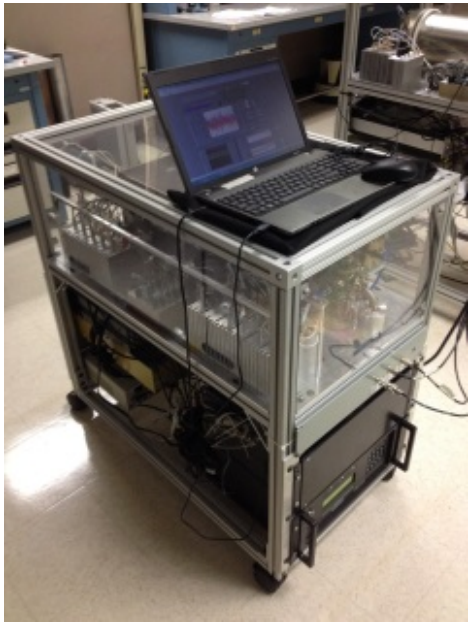
sensitivity minimized via

choice of ion + shielding > 1e5

compensated multi-pole linear ion traps

high T bakeout -> XHV (<1e-11 torr)



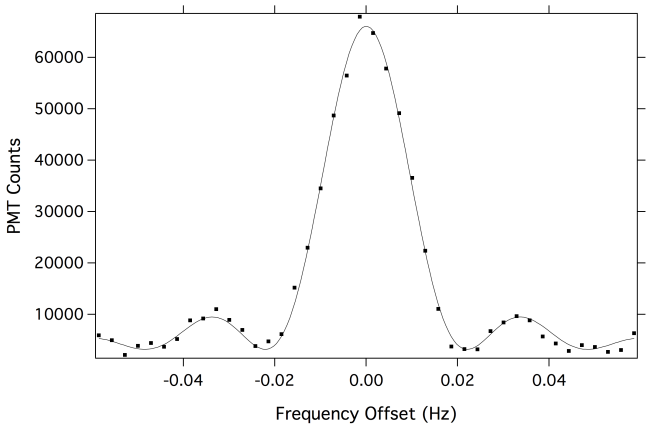


*E.A. Burt, L. Yi., B. Tucker, R. Hamell, and R.L. Tjoelker; "JPL Ultra-Stable Trapped Ion Atomic Frequency Standards," IEEE TUFFC **63**, 1013 (2016).*

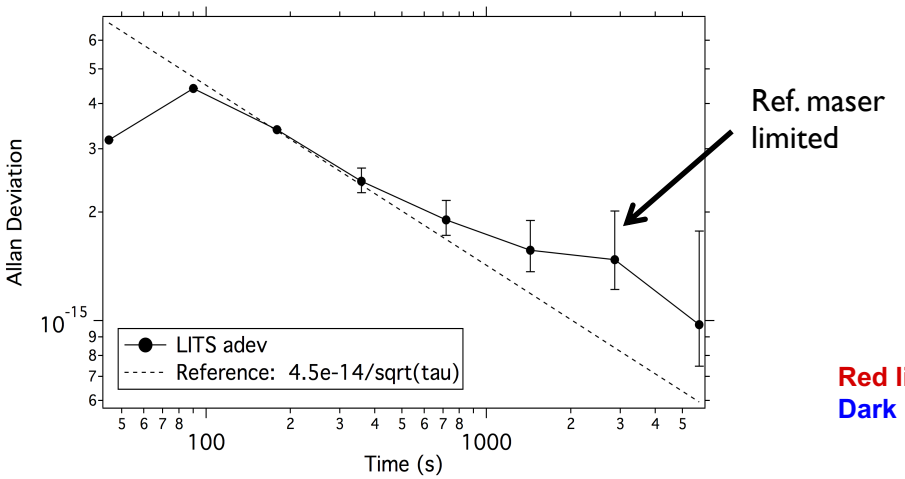
Ultra-stable ion clock performance

High Q operation with maser LO

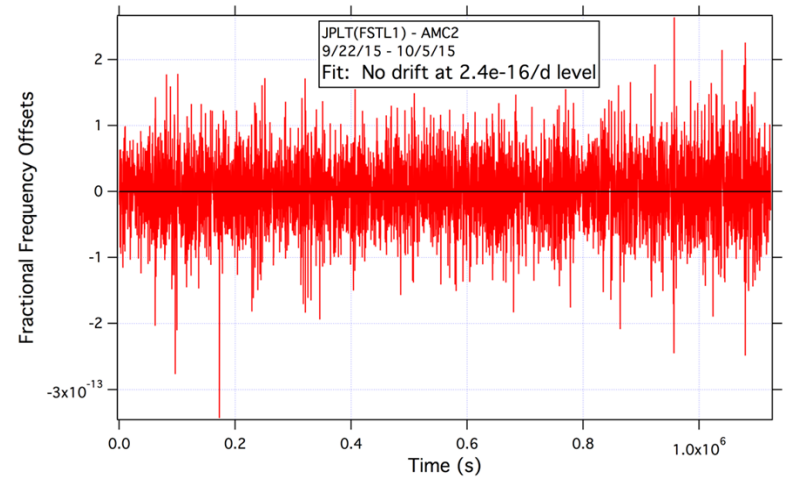
Local Characterizations vs H-maser

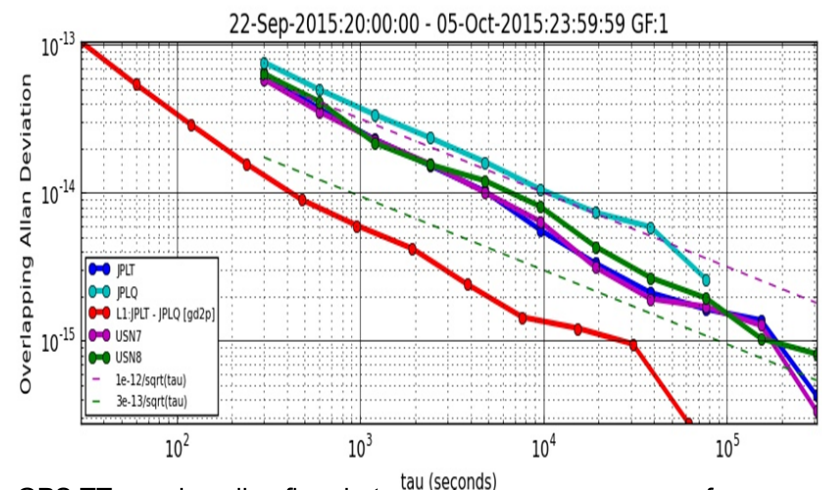


- **40 second Rabi Interrogation**
- **Q ~ 1.6E+12**
- **SNR*Q ~ 4.5E-14/sqrt(tau)**



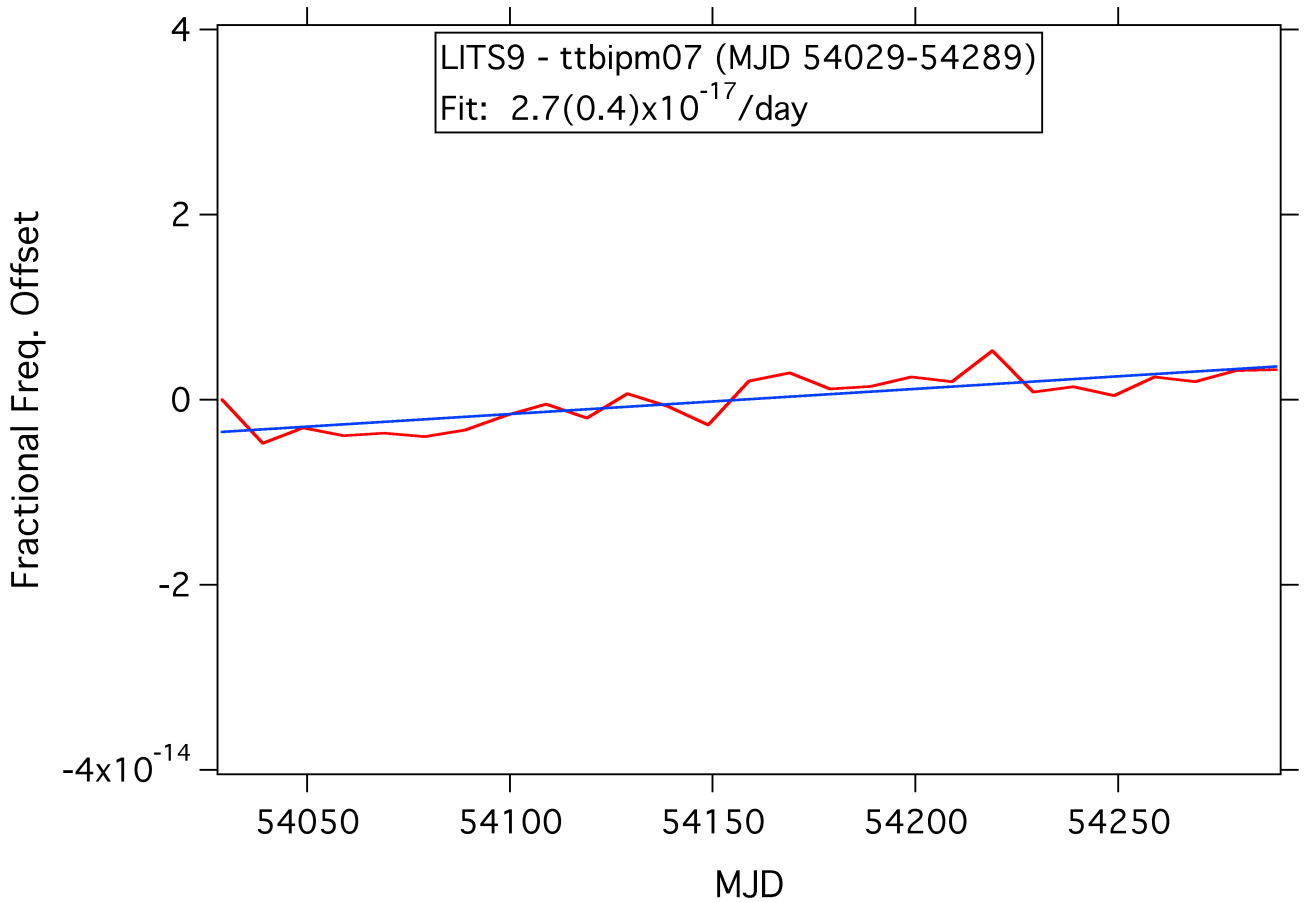
GPS TT characterizations vs UTC





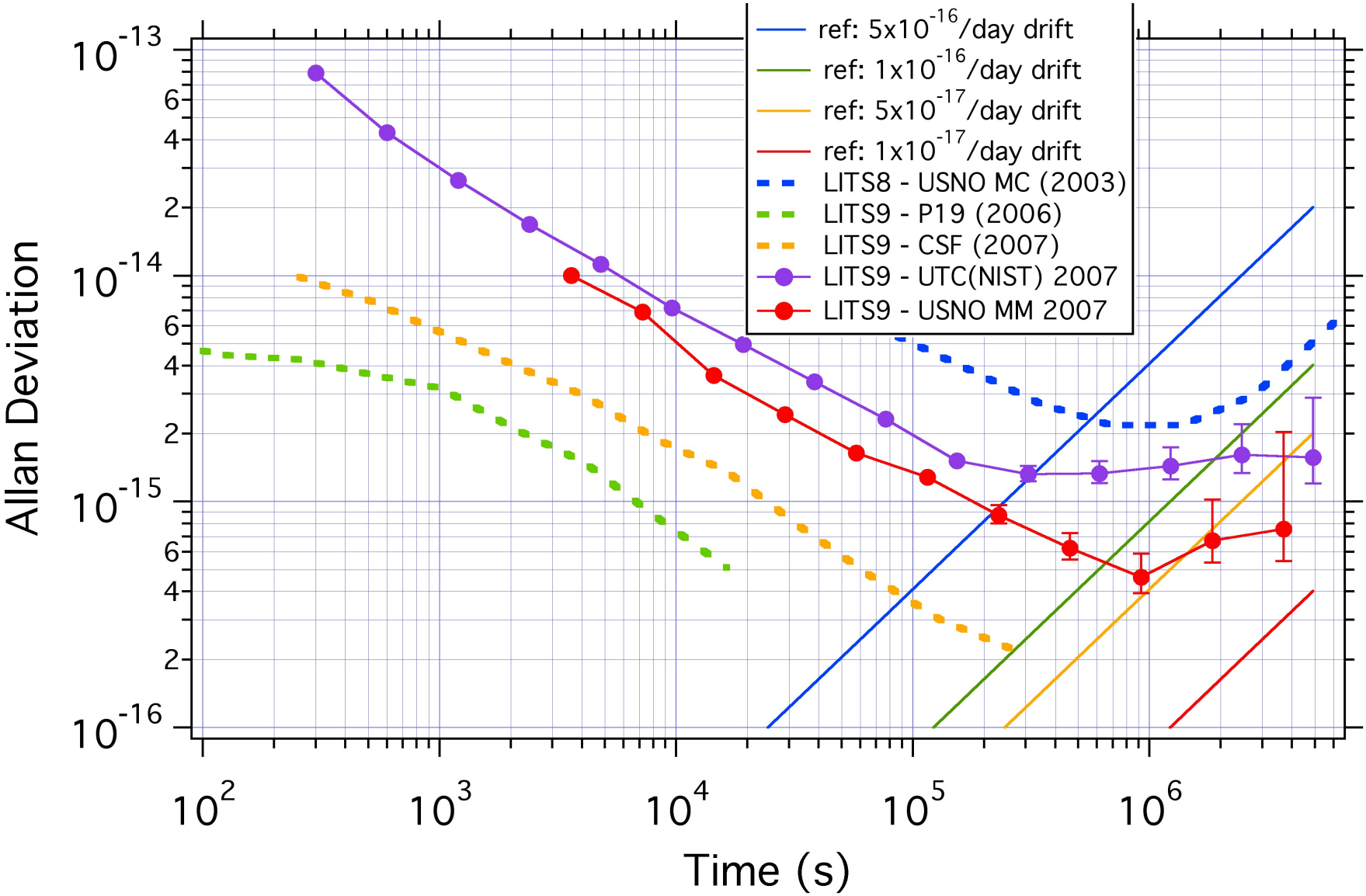
Red line: GPS TT zero baseline floor between two rcvrs, common reference.
Dark Blue: FSTL Hg1/SAO reference vs USNO AMC2 (i.e. GPS time)
$<10^5$ s dominated by GPS time transfer noise.
$>10^5$ s representative of the Hg standard stability over 14 day interval.

9-Month Stability



- Clock operated continuously for 9 months: MJD54023 to MJD54296
- Clock was completely free-running during this interval - no intervention
- Drift of $+2.7(0.4)\times10^{-17}$/day relative to LC primary stds and TTBIPM

Compensated Mpole LITS Long-Term Stability

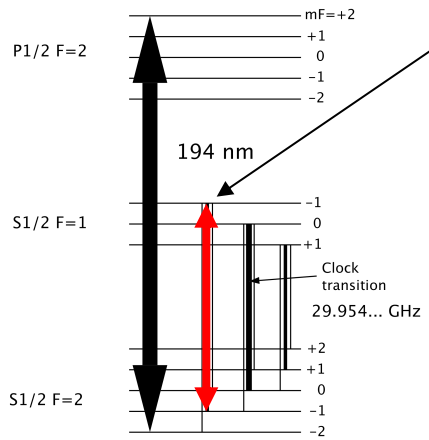


Comparison to the USNO maser mean shows a floor of 4.5×10^{-16}, and very low drift

(Usno maser mean data supplied by D. Matsakis and J. Skinner)

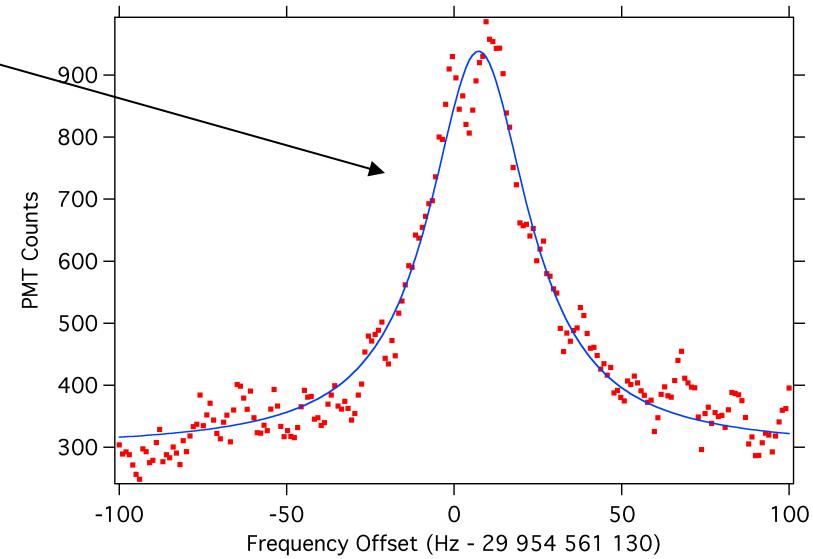
A 201Hg+ clock and isotope comparisons

Doppler-Free Field-Sensitive Spectroscopy



F=1, m_F=-1 to F=2, m_F=-1

$\Delta m_F = 0$

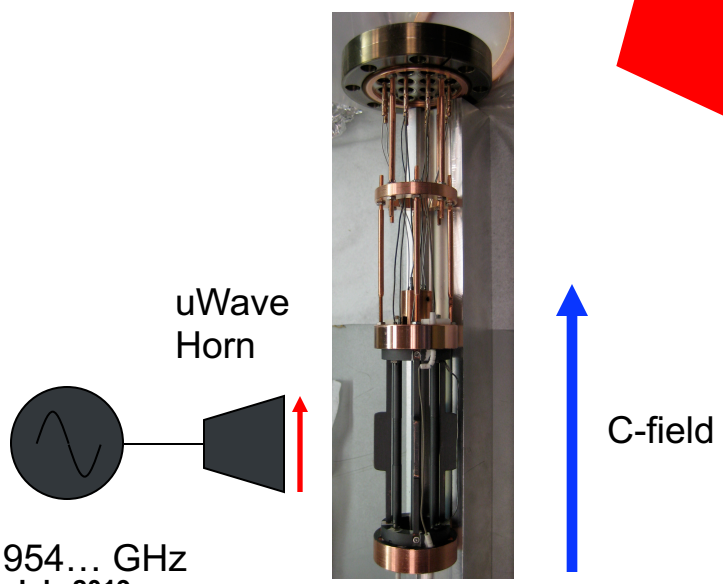


$f_{-1,-1}$ = 29 954 561 137(30) Hz

B_0 = 139.341(42) mG

Δf = +195 kHz

Residual broadening due to C-field current source instability



29.954… GHz

- space applications
- $^{201}Hg^+$ magnetometer for $^{199}Hg^+$

Evaluation of Clock Frequency

Effect	Shift (Hz)	Error Estimate (Hz)
Second-order Zeeman	+2.5471	0.0005
Second-order Doppler (T)	-0.013	0.013
Second-order Doppler (N)	-0.04	0.04
Pressure shift (He)	+0.0037	0.0003
Pressure shift (CH_4)	-0.0011	0.0011
AC Stark shift	+0.002	0.045
Total Shift	+2.499	0.062
Statistical Uncertainty	-	0.171
Derived Accuracy	-	0.01

$$f_0 = 29.954\,365\,821\,130(171)(62)(10)\ GHz$$

statistical

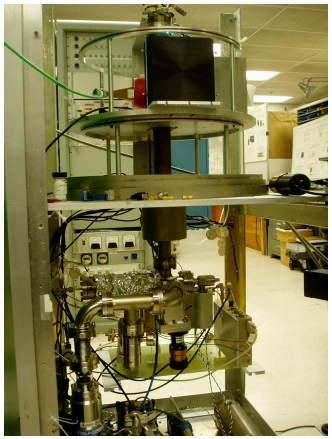
systematic

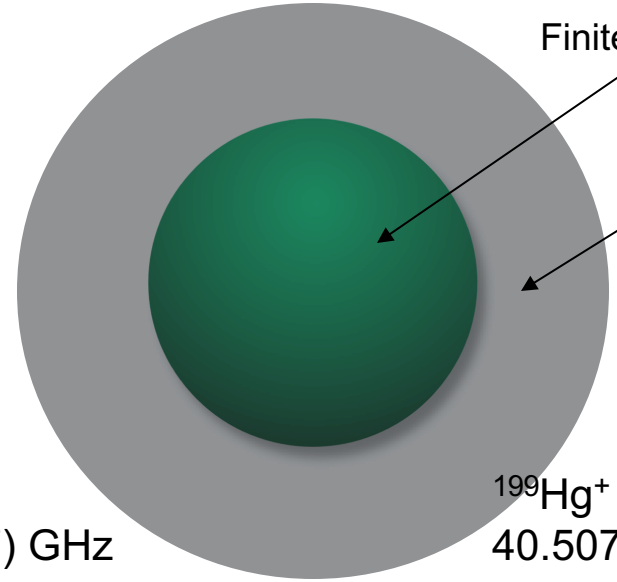
Derived accuracy

8 orders of magnitude improvement over previous result

*E.A. Burt, S. Taghavi-Larigani, and R.L. Tjoelker, PRA **79**, 062506-1 (2009)*

Hyperfine Anomaly (Bohr-Weisskopf Effect*)





$^{201}Hg^{+}$ HF clock:
29.9543658213(17) GHz

(this work)

$^{199}Hg^{+}$ HF clock:
40.5073479968415 9(41) GHz

(D.J. Berkeland, et al., PRL 80, 2089 (1998))

Point nucleus:

$$\frac{\Delta f_1}{\Delta f_2} = \left(\frac{\mu_{I1}/I_1}{\mu_{I2}/I_2}\right)\frac{F_1}{F_2}$$

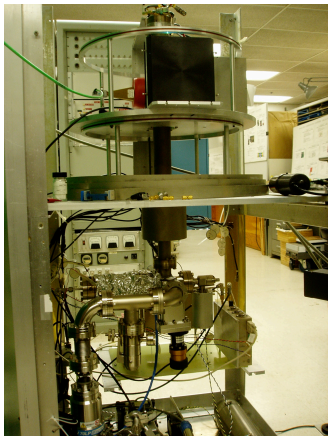
Finite nucleus:

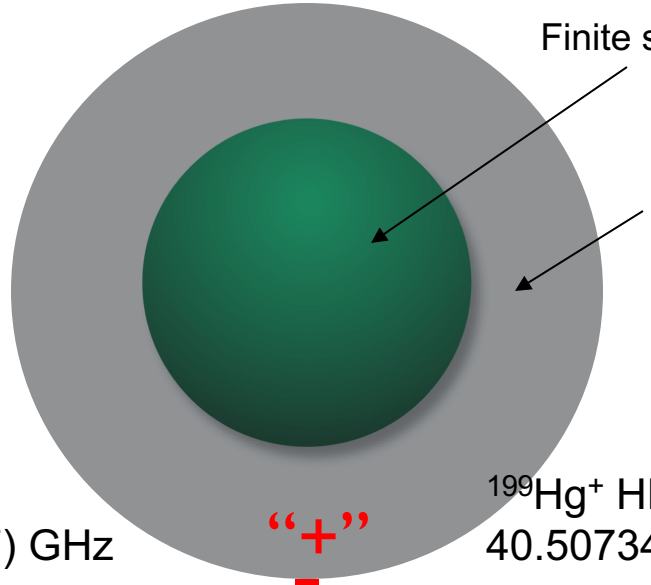
$$\frac{\Delta f_1}{\Delta f_2} = (1+\Delta)\left(\frac{\mu_{I1}/I_1}{\mu_{I2}/I_2}\right)\frac{F_1}{F_2}$$

HF anomaly

A. Bohr and V.F. Weisskipf, PR 77, 94 (1950)

Hyperfine Anomaly





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(D.J. Berkeland, et al., PRL 80, 2089 (1998))

$$\frac{\Delta f_1}{\Delta f_2} = (1+\Delta)\left(\frac{\mu_{I1}/I_1}{\mu_{I2}/I_2}\right)\frac{F_1}{F_2} \qquad \frac{f_{201}}{f_{199}} = -0.739479805(37)$$

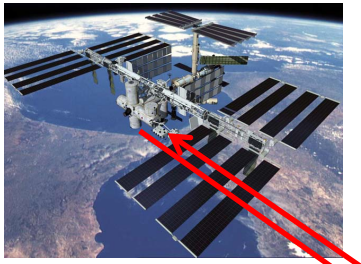
$$\Delta\left(S_{1/2}, 199Hg^{+}, 201Hg^{+}\right) = -0.001\,625\,7(5)$$

*E.A. Burt, S. Taghavi-Larigani, and R.L. Tjoelker, PRA **79**, 062506-1 (2009)*

Previous values Hg: -0.001627(19), *(Reimann and McDermott, PRC 7, 2065 (1973))*
Hg^{+}: -.0034 to +0.0056 *(Grandinetti, et al., (1986))*

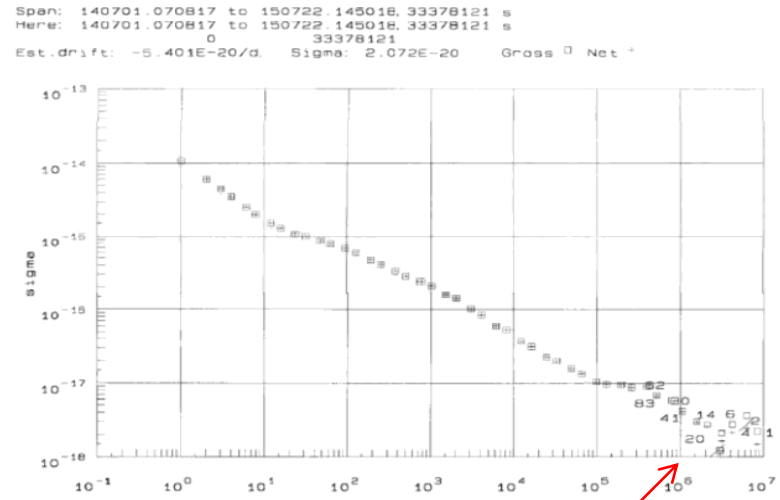
- Value now limited by knowledge of μ_I
- Agrees with neutral value: valence screening has minimal effect

Atomic Clock Ensemble in Space Mission (ACES)- JPL reference

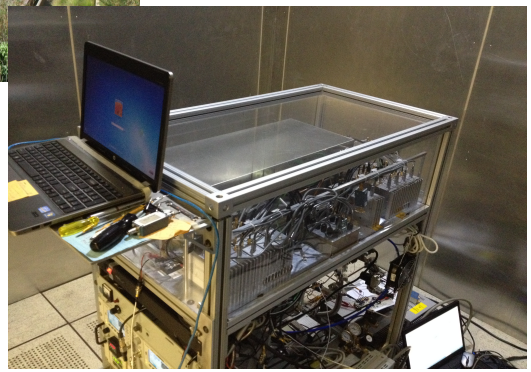


ISS clocks

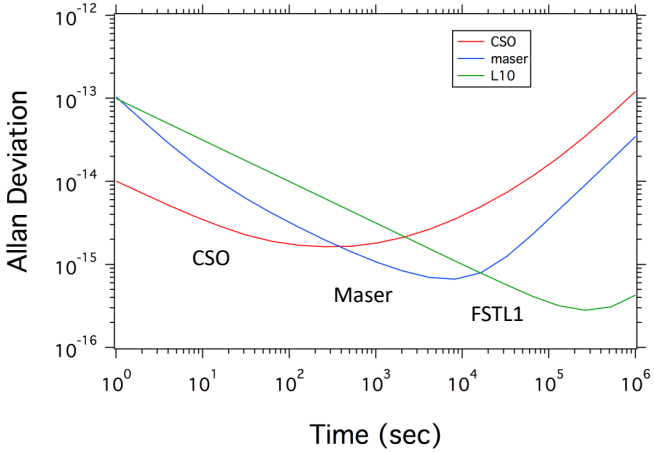
ACES
ground terminal



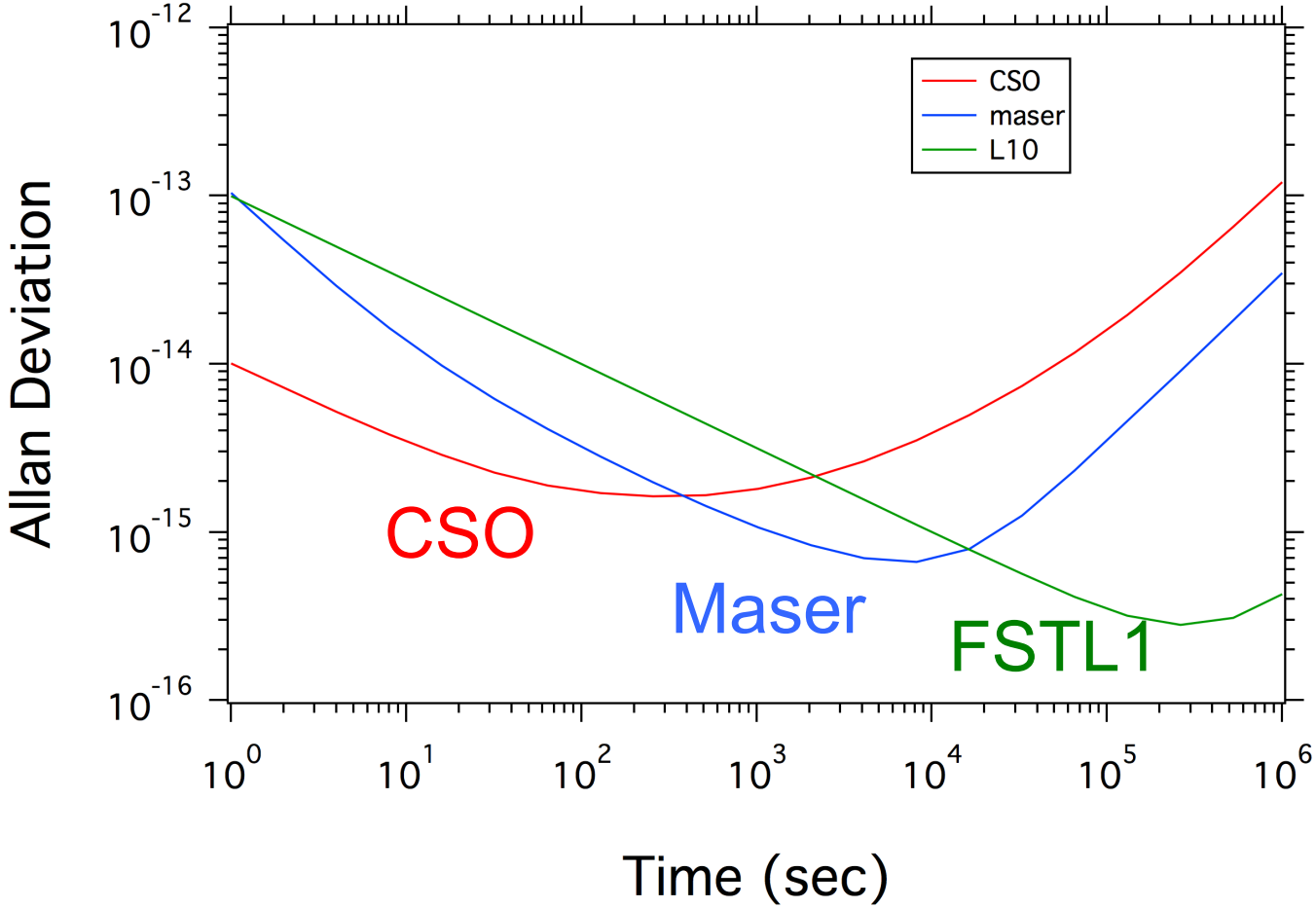
JPL link noise:
- 1e-14 at 1 s
- 3×10^{-18} noise floor at 1 yr



H-maser LO – Hg+ reference

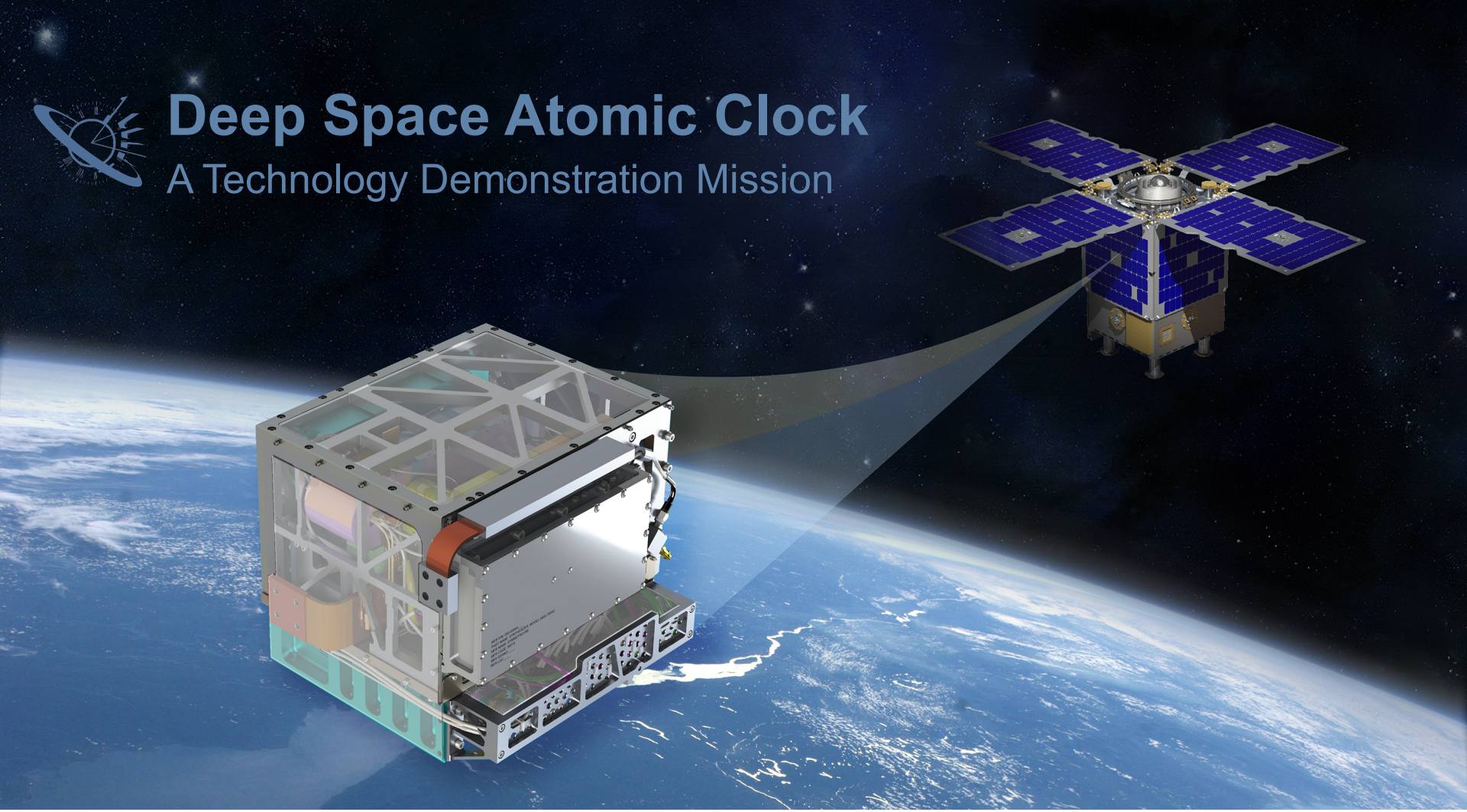


ACES Ground Terminal Reference: Clock Ensemble



Deep Space Atomic Clock

A Technology Demonstration Mission



NASA

TDM

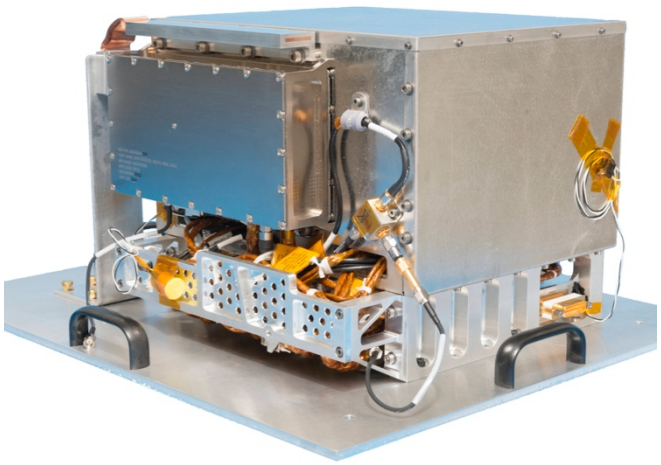
SPACE COMMUNICATIONS SCaN AND NAVIGATION

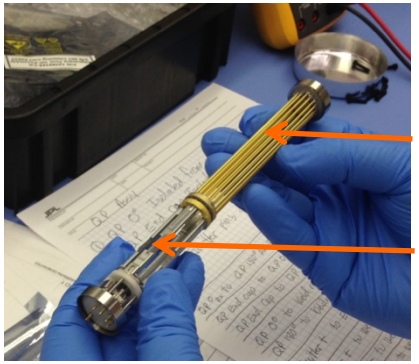
JPL
Jet Propulsion Laboratory
California Institute of Technology

SURREY
SATELLITE TECHNOLOGY US

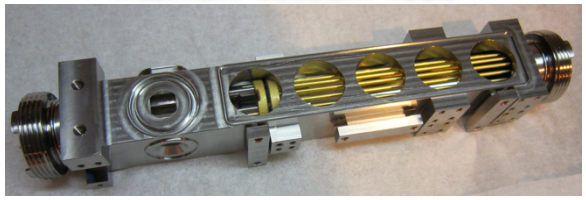
The DSAC Technology Demonstration Mission

DSAC Demonstration Unit

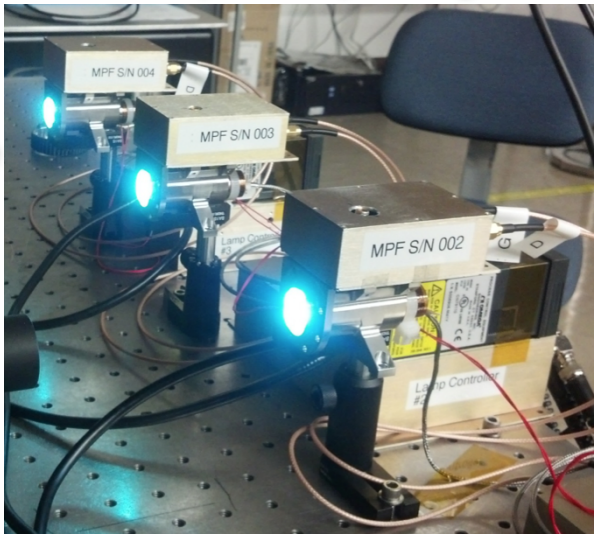




Titanium Vacuum Tube



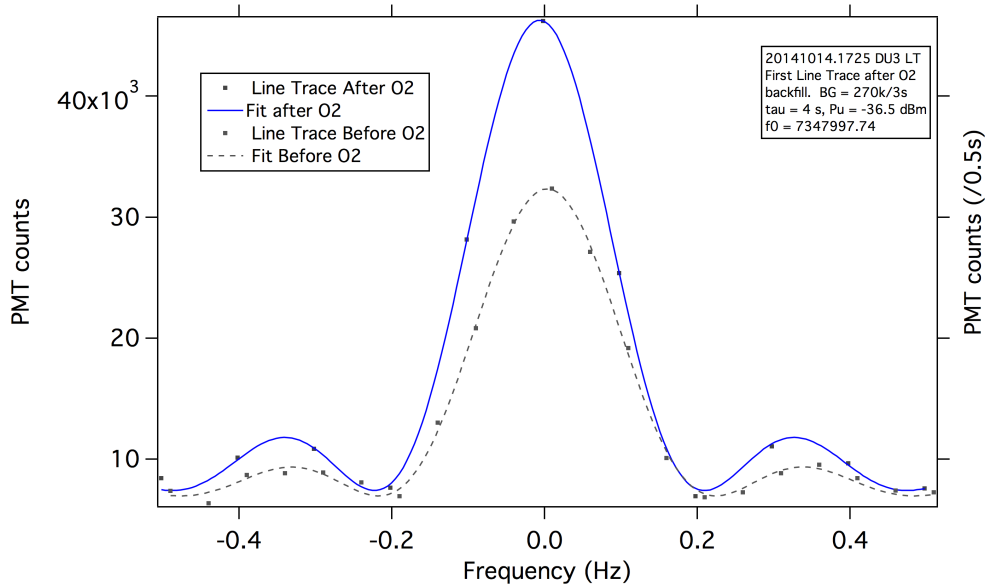
Mercury UV Lamp Testing

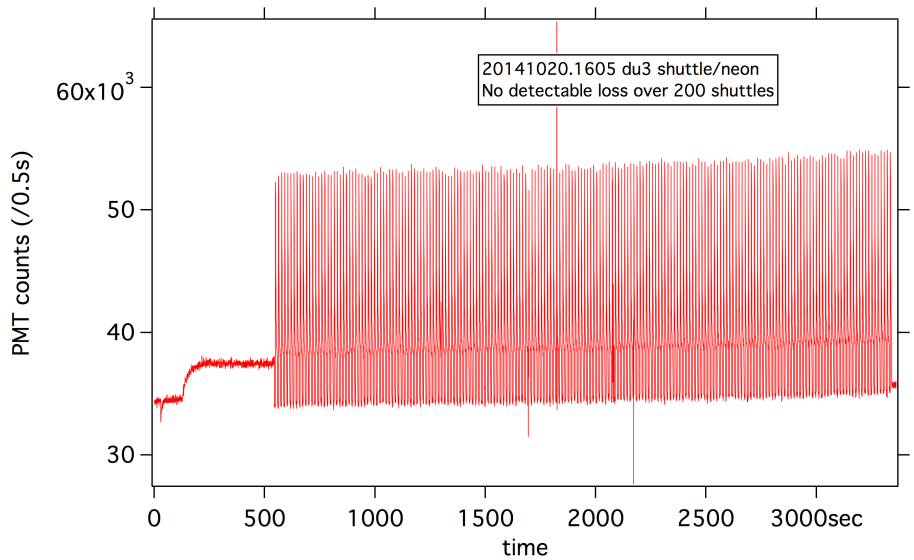


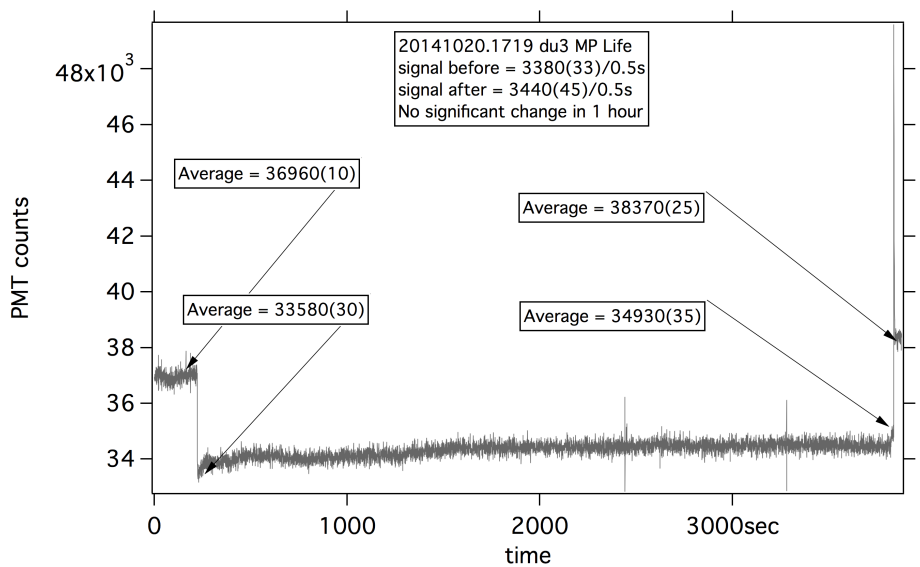
Develop advanced prototype mercury-ion atomic clock for operation in space

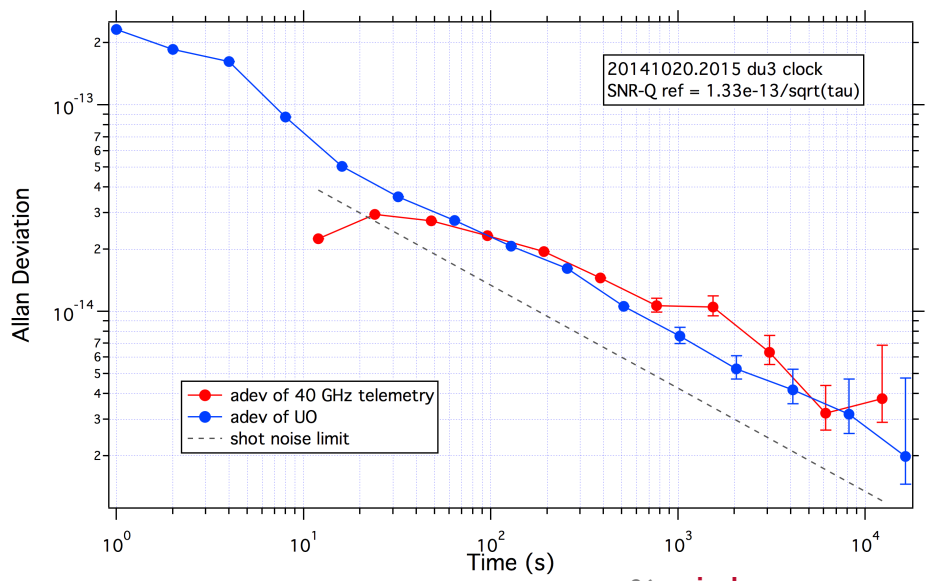
- Year-long demonstration in space beginning Dec 2017+ – advancing to TRL 7
- Mature the new technology
  - Ion trap and optical systems
  - SWaP
- Identify pathways for future operational units (TRL 7 → 9)

DSAC Performance





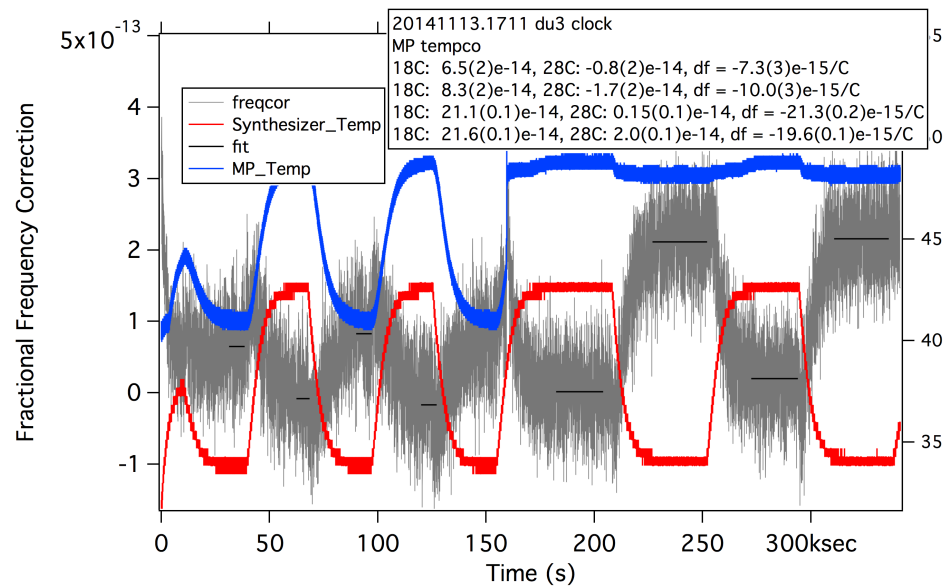




DSAC Environmental Sensitivity

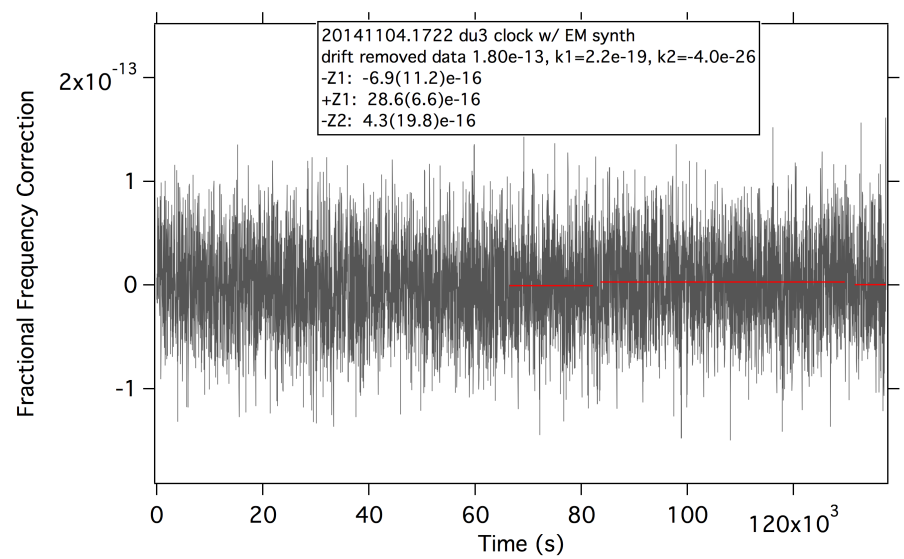
Temperature Sensitivity:

- $2x10^{-14}$/C
- Magnetic component
- Expect 1C variations at 80 minutes



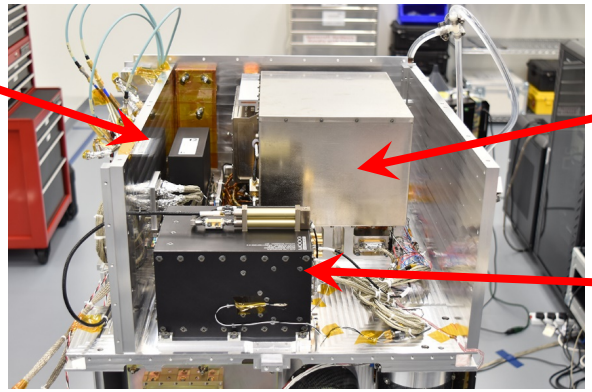
Magnetic Sensitivity:

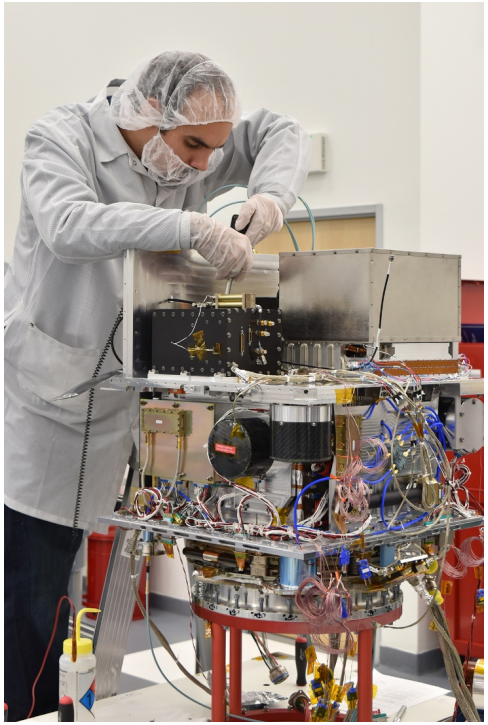
- < $1.5(1.3)x10^{-15}$/Gauss
- 3 layers of magnetic shielding
- expect 100 mGauss variations: < $1.5x10^{-16}$



DSAC integration onto OTB

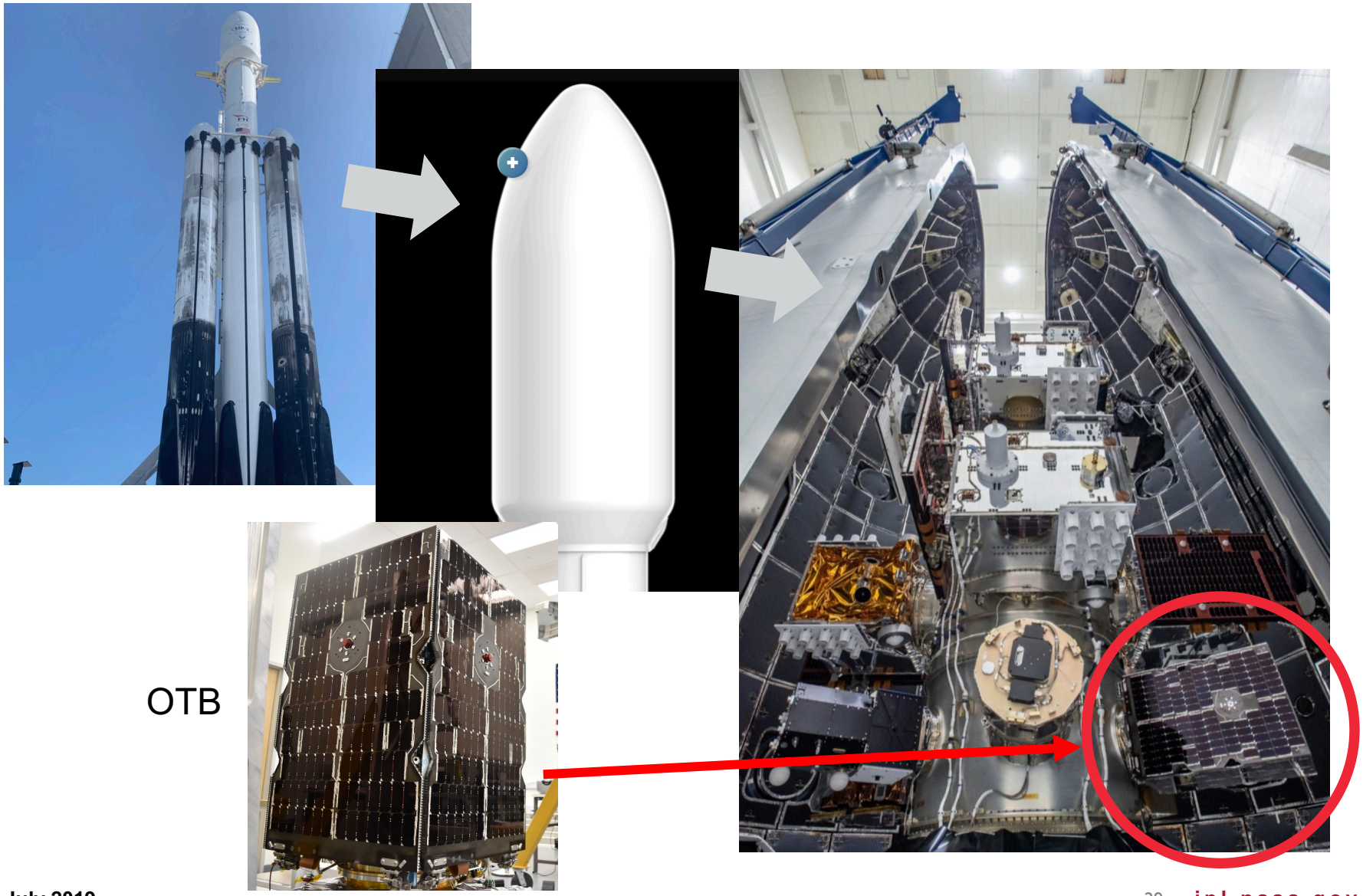
DSAC Payload





Orbital Test Bed (OTB) fully assembled

OTB integration into launch vehicle



Launch!

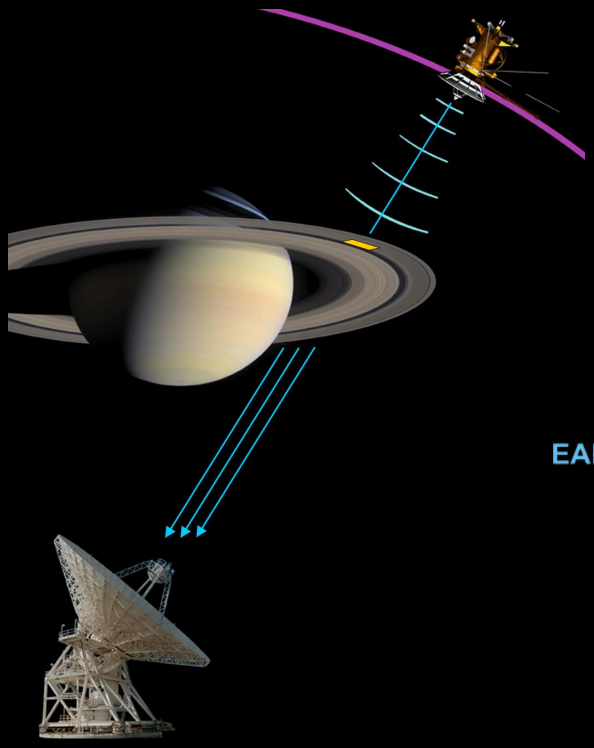
Photo credit: NASA/Joel Kowsky

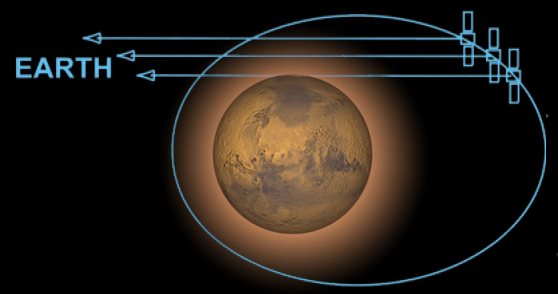
- Successful launch on June 24, 2019
- Space craft commissioning: July, 2019
- DSAC power on early August, 2019

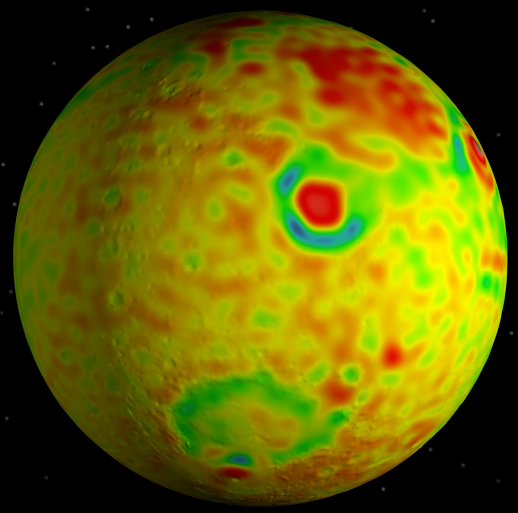
Advantages of a DSAC clock in space

Occultation and Gravity Science

DSAC + Ka-band crosslink/downlink = up to 100X precision & 2X tracking

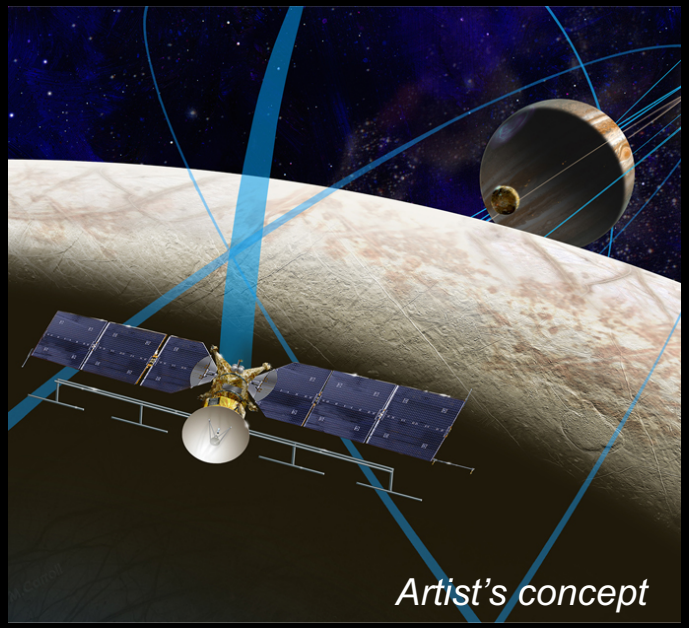


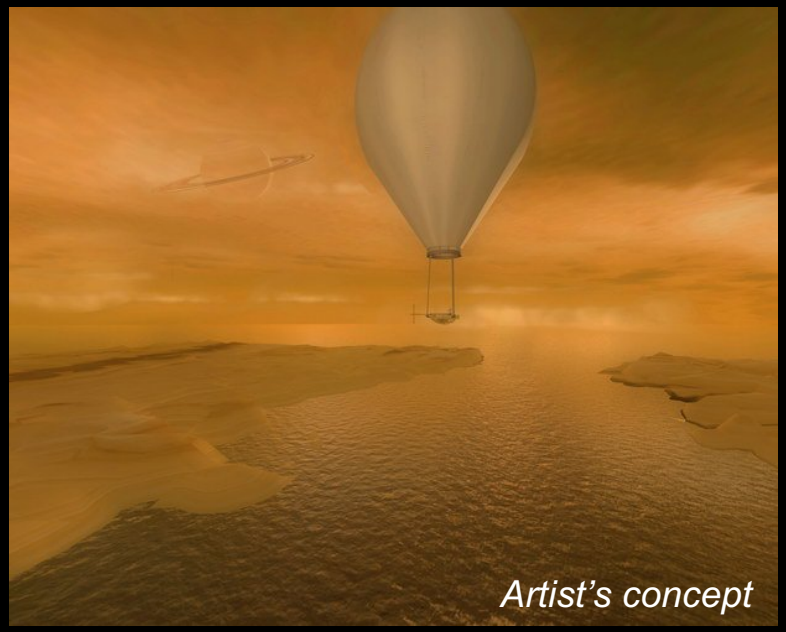




Increased Time for Science Observations…

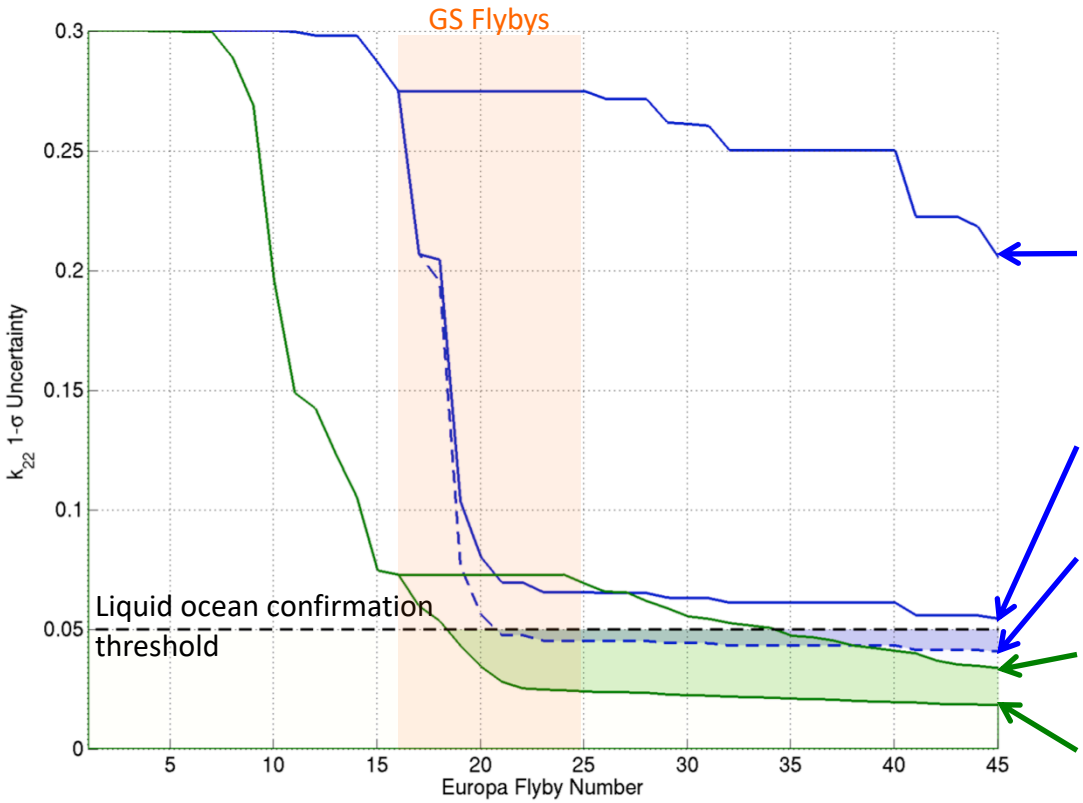
DSAC + Uplink/LGA + Radio =
Agile 'Attitude Free' Nav & Science





- DSAC enables 1-way uplink
- Receive only => low gain antenna (LGA) sufficient
- LGA's have wide aperture => work no matter what SC orientation
- Don't have to waste fly-by's on orientation to accommodate downlink

Example: Low-SNR, Attitude Free Tracking Enables Efficient Europa Gravitational Tide Recovery



Solutions obtained using solar powered spacecraft configuration with current trajectory (as of June 2015) with following results:

2-Way, DSN, No GS Flybys
✗ No confirmation

2-Way, DSN, All GS Flybys
✗ No confirmation

2-Way, DSN+ESA, All GS Flybys
✓ Confirmed, no flyby margin

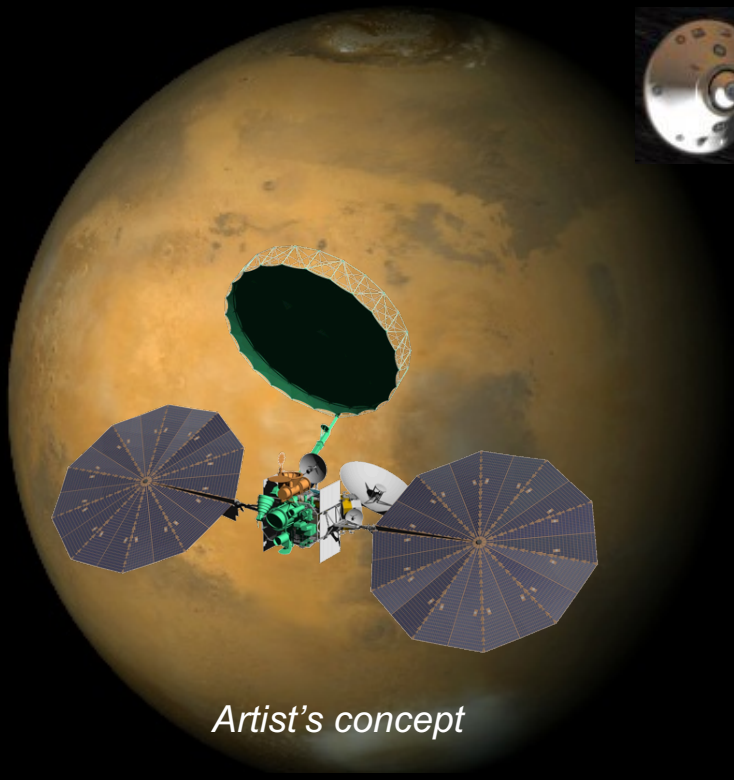
1-Way w/ DSAC, DSN, No GS Flybys
✓ Confirmed w/ flyby margin

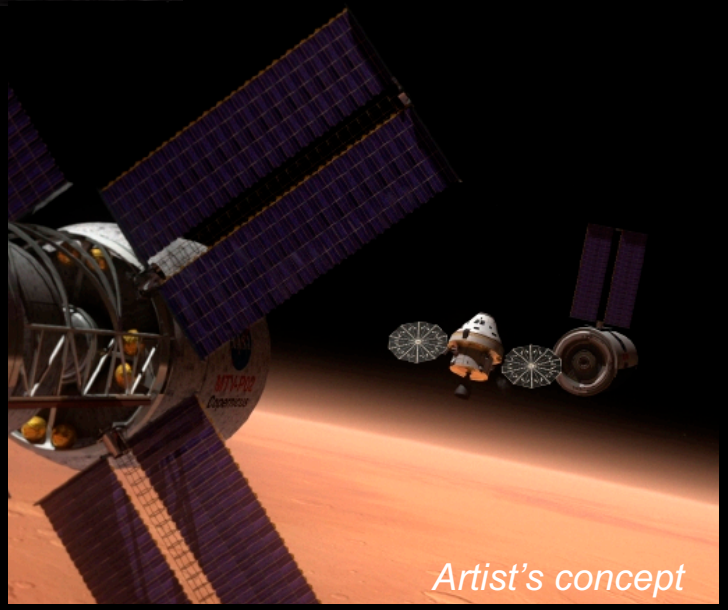
1-Way w/ DSAC, DSN, All GS Flybys
✓ Confirmed w/ flyby margin

1-Way with DSAC using low gain antennas yields solutions with margin with or without GS

Real-time navigation and precision landing

DSAC + uplink/LGA + radio + nav computer =
robust on-board nav





Conclusions

- Room temperature trapped ion clocks demonstrate < 3e-17/day
- New precision on hyperfine anomaly using 199Hg+/201Hg+
- Comparison to the ACES clock soon
- DSAC launched and inserted into orbit
- DSAC telemetry stream to start August, 2019
- Potential applications of DSAC:
  - Deep space navigation
  - Radio occultation
  - Gravity science