National Aeronautics and Space Administration

Deep Space Atomic Clock (DSAC):
First Demonstration of a Trapped Ion Atomic Clock in Space

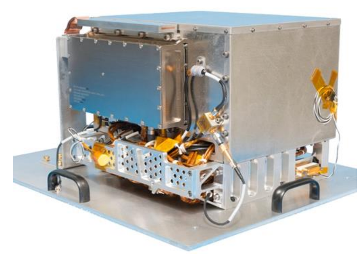
Jet Propulsion Laboratory
California Institute of Technology

Introduction

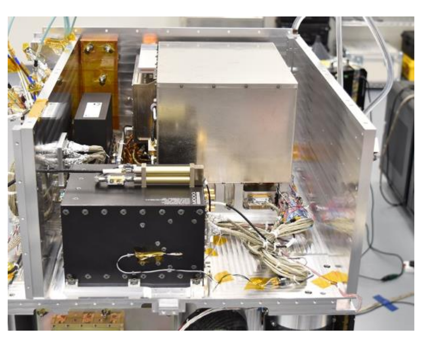
The 40.5 GHz transition in ^{199}Hg+, optically pumped with a ^{202}Hg+ discharge lamp, and buffer gas cooled has demonstrated state-of-the-art microwave clock performance while at the same time having potential for low SWaP. In 2011, NASA STMD and SCaN started the Deep Space Atomic Clock (DSAC) project to demonstrate a low SWaP version of this technology in space. The DSAC instrument was successfully launched in 2019 and operated for its entire 2-year mission.

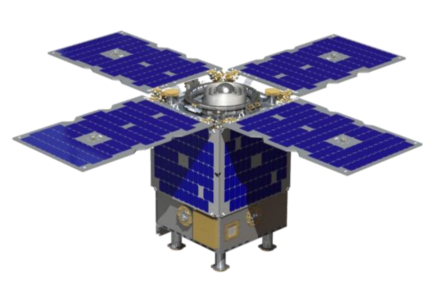

mercury ion trap


Ion trap in vacuum tube


Ion Clock Instrument

"***Mercury Ion Clock for a NASA Technology Demonstration Mission***"; IEEE TUFFC, Vol. 63, No. 7, July 2016.
R.L. Tjoelker, J.D. Prestage, E. A. Burt, P. Chen, Y. Chong, S. Chung, W. Diener, T. Ely, D. Enzer, H. Mojaradi, C. Okino, M. Pauken, D. Robison, B. Swenson, B. Tucker, R. Wang;


Integrated DSAC Payload


Host GA space craft

"***Using the Deep Space Atomic Clock for Navigation and Science***"; IEEE TUFFC, Vol. 65, No. 6, June 2018.
T.A. Ely, E.A. Burt, J.D. Prestage, J.S. Seubert, R.L. Tjoelker

DSAC measurement to UTC:

Calibrating GPS Receiver and Relativistic Effects

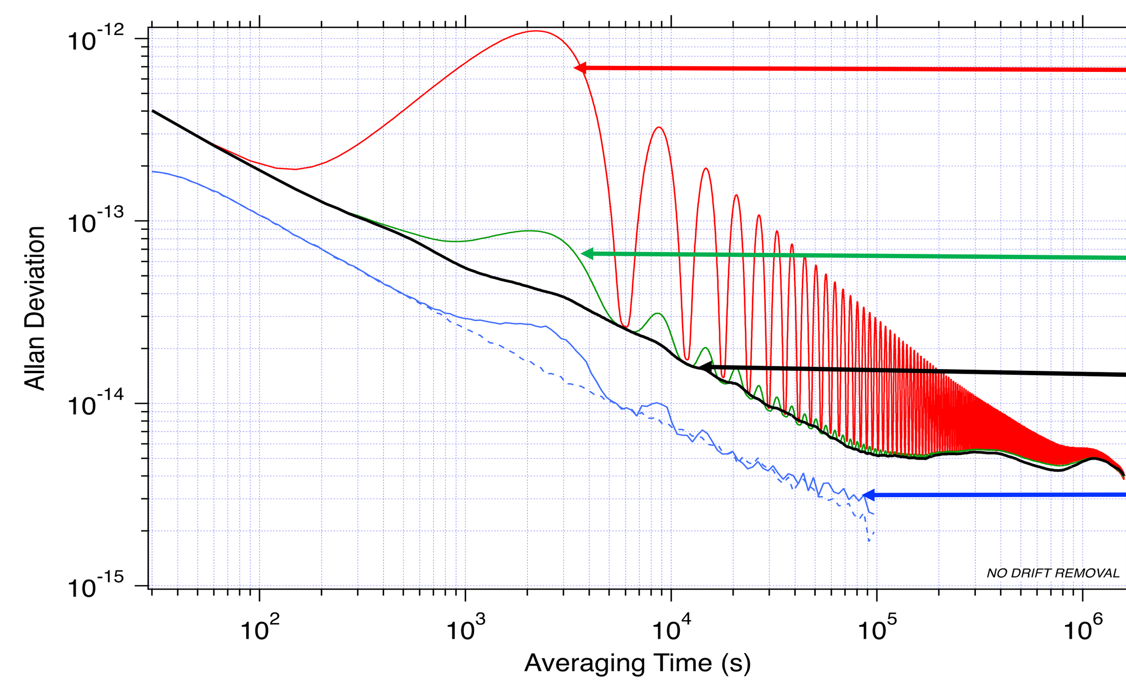
(Measurements: clock + OD + measurement system)

GPS phase dynamically corrected for gravitational effects (red shift)

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

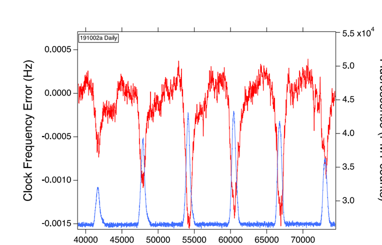
Must include higher order terms (J2) in the gravitational potential

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

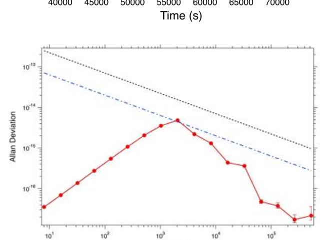


Environmental Sensitivities

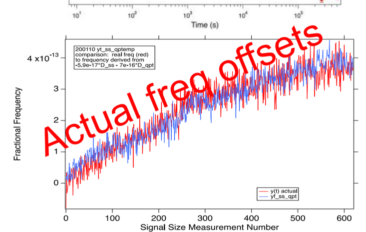
Radiation: SAA-induced USO drift variations taken out by clock control loop



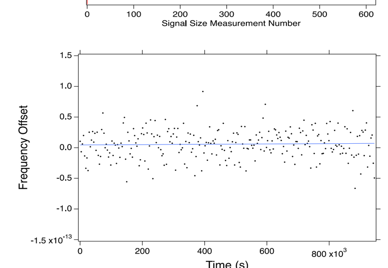
Magnetic Shifts: below measurement noise floor
- 250 mG/orbit variations (entire Earth's field) - 100x lab!
- Strength of Hg+ technology



Ion number variations:
- Actual = model: well understood



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



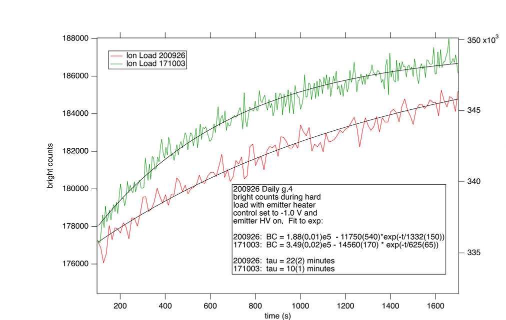
Light shifts: Not measured, but est. at <3e-15 measurement noise floor

Temperature sensitivity: 1e-14/C with NO thermal regulation
- Not fundamental, enters through each of the above effects
- **Path to unregulated 2e-15/C is known**

Clock Lifetime

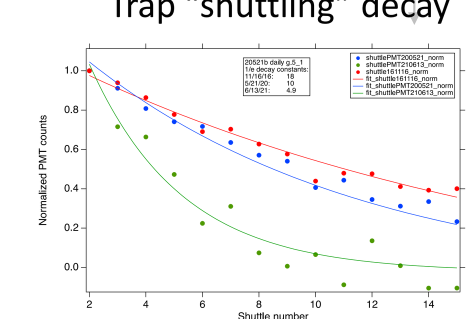
Mercury Vapor Evolution
- Extrapolate trap load time: **7-year life**
- Likely limit: Hg/Au amalgamation – gold to be removed in future versions

Trap load time variations



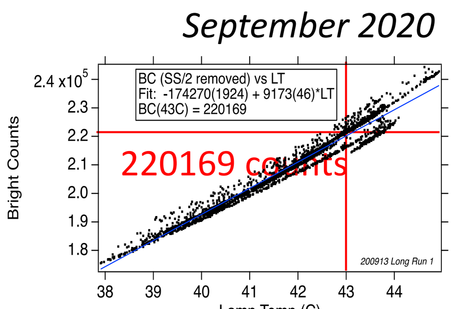
Neon evolution
- Shuttle decay measurements calibrated to neon pressure
- **Extrapolate to > 8-year life**
- Method to extend understood

Trap "shuttling" decay

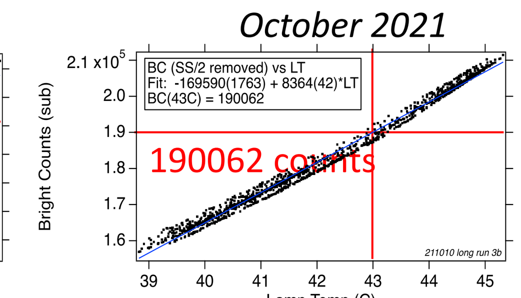


Optics aging
- 13.7% change in 13 months
- => > 7 years total life
- Most likely lamp

September 2020

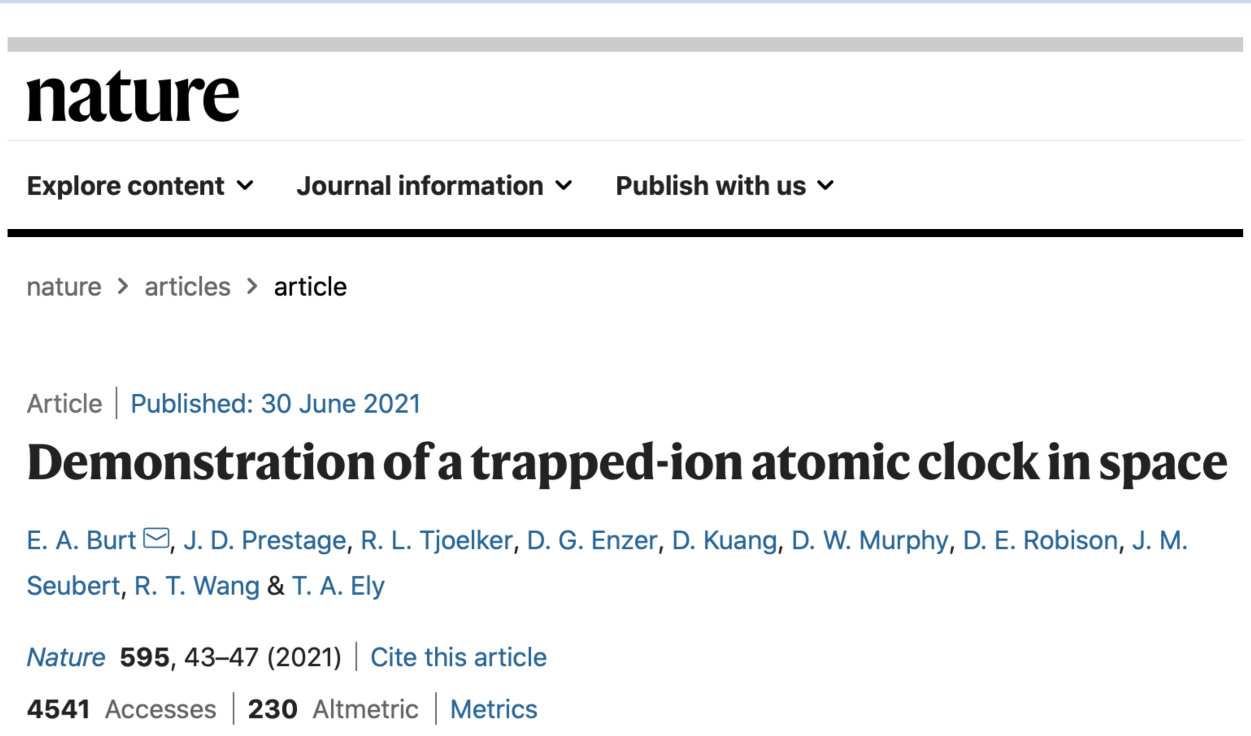


October 2021



Clock lifetime > 7 years with known methods to extend this

DSAC 2-Year Mission in LEO - Stability 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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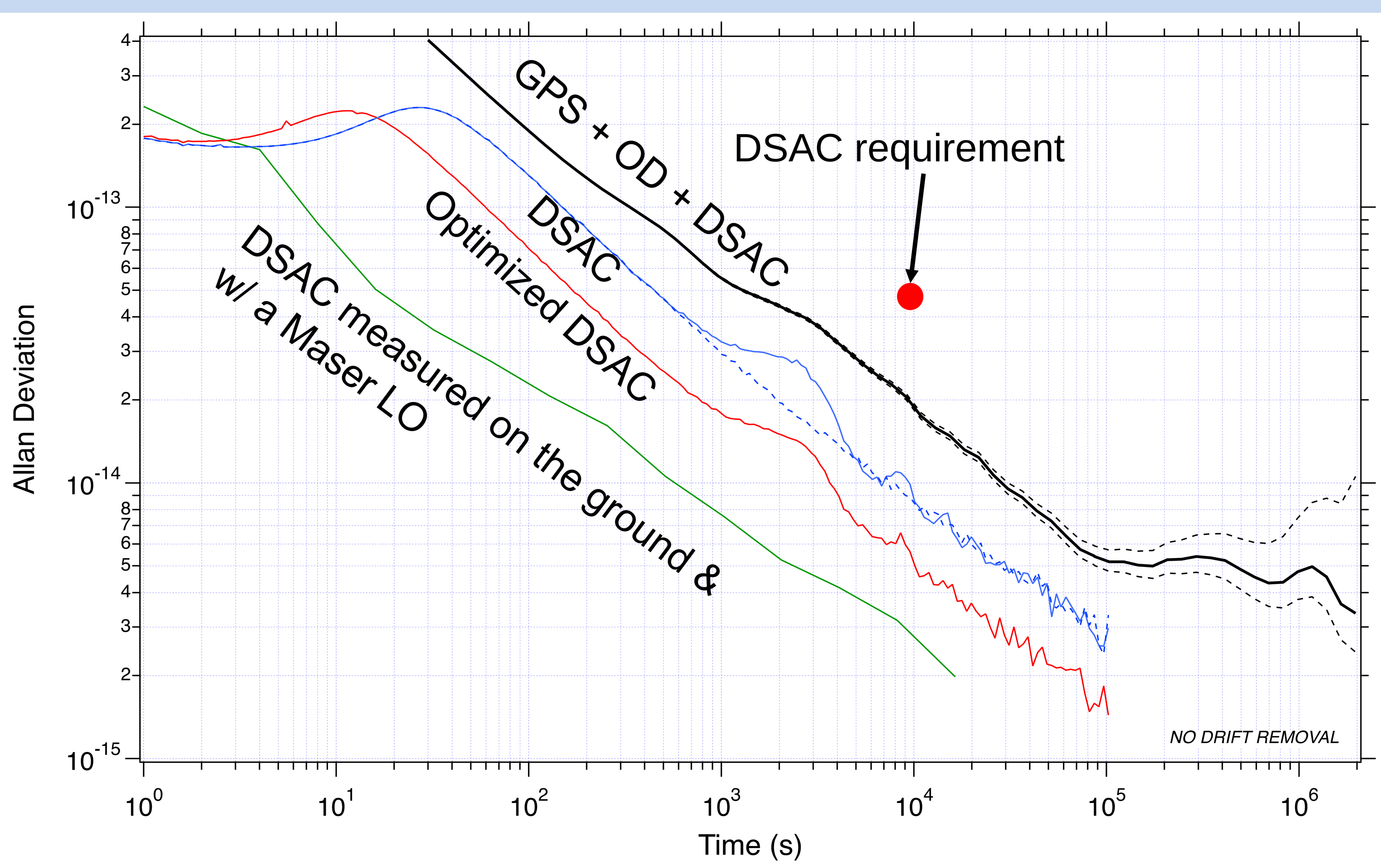
Stability at one-day of 3e-15

Drift of 3.0e-16/day

• ***establishes space clock record***



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