Notice of intent to participate in 2023 NASA Tech Showcase

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Technology: High Performance Trapped Mercury Ion Atomic Clocks. A new type of atomic clock that uses trapped ions in a quadrupole or a higher order trap to achieve record atomic clock stability in space. The performance of the clock is comparable with masers while SWaP is an order of magnitude less. In a NASA TDM supported by the offices of STMD and SCaN over a 2-year period from 2019 to 2021 in low Earth orbit, the mercury ion clock, Deep Space Atomic Clock (DSAC), achieved a performance level of 7e-13/sqrt(tau), 3e-15 at a day, 3e-16/day long-term drift, and maintained a time stability of 200 ps at a day and less than 4 ns over 23 days [1]. This operation allowed the technology to reach TRL 7. DSAC had a SWaP of 19 liters, 19 kg and 56 W. A follow-on version, DSAC-2, has been proposed with a performance of 1.5e-13 at one second, 2e-13/sqrt(tau), and < 1e-15 at a day. The primary change in DSAC-2 is to improve manufacturability and reduce SWaP to 10 liters, 10 kg, and 34 W. The estimated instrument life of DSAC was 7 years. The DSAC-2 proposal has an instrument life goal of >10 years. This clock is also a promising replacement for Hydrogen masers in the DSN.

Primary Applications:

- Autonomous deep space navigation [2]. As demonstrated in DSAC [1] and in other versions of this technology [3], trapped ion clock inherent long-term stability and low drift enable in-situ one-way real-time navigation.
- Science requiring high-performance precise local timing such as Radio Occultation (RO) and gravitational field mapping.
    - RO measurements of planetary atmospheres can be done with a higher precision than is possible with a USO because the DSAC noise floor and drift are two orders and 6 orders of magnitude lower respectively. In addition, RO can be accomplished with more complete coverage than is possible with a two-way link because of reduced re-synching times, particularly true for the outer planets.
    - Trapped ion clocks can use the relativistic gravitational red shift to measure variations in gravitational fields. Sensitivity to Earth's J2 gravitational field harmonic was demonstrated during the TDM [1].
- As a DSN frequency standard. Many missions depend on a high-performance two-way link that provides near hydrogen maser frequency stability. The quality of these links is dependent on the DSN hydrogen maser used to reference them. There is currently only a single US source for these instruments and there is no guarantee that they will be available indefinitely. Trapped ion atomic clock technology has maser-like performance and would work well as a maser replacement should these become unavailable.

Potentially Relevant Mission Abstracts:

- Lunar Geophysical Network
    - *Precise timing of laser pulses:* Precise one-way In-situ timing of laser pulses for laser-ranging resulting in higher SNR range measurements
- Jupiter System Observatory at Sun-Jupiter Lagrangian point one

The work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

- *RO:* DSAC could enable a possible RO measurement of Jupiter and/or Jovian moon atmospheres
    - Such RO would have the benefit of very long occultation times due to relative Earth-Jupiter motion rather than orbital motion
- New Frontiers Titan Orbiter
  - *Gravity Mapping:* Mercury ion clocks can enable high precision measurement of higher order harmonics in Titan gravitational field [1].
  - *RO:* Mercury ion clocks could also enable radio occultation measurements of Titan's atmosphere with higher precision than is possible with a USO and with more complete coverage than is possible with a two-way link.
- Small Next-Generation Atmospheric Probe for Ice Giant Missions
  - *Atmospheric Dynamics:* For atmospheric dynamics measurements on time scales of 30 seconds or longer, DSAC frequency stability is better than that of the best USO's
- Uranus Orbiter and Probe
  - *RO:* Mercury ion clocks can enable more precise RO measurements of Uranus' atmosphere than are possible with a USO and with more complete coverage than is possible with a two-way link.
- Enceladus Orbilander
  - *RO and gravity mapping:* Mercury ion clocks can enable more precise radio/gravity science measurements of Enceladus' atmosphere and gravity field than are possible with a USO and with more complete coverage than is possible with a two-way link.
- Titan Orbiter and Probe
  - *Gravity mapping:* In support of the Titan Orbiter Probe's goal of performing gravity science, mercury ion clocks combine the relativistic gravitational red shift and in-situ real-time one-way navigation [2] for improved (over a two-way link) mapping of gravitational field variations.
- Triton Ocean Worlds Surveyer
  - *RO and gravity mapping:* Mercury ion clocks can enable more precise radio/gravity science measurements of Triton's atmosphere and gravity field than are possible with a USO and with more complete coverage than is possible with a two-way link.

References:

[1] E.A. Burt, J. Prestage, R.L. Tjoelker, D. Enzer, D. Kuang, D.W. Murphy, D.E. Robison, J.M. Seubert, R.T. Wang, and T.A. Ely, "Demonstration of a trapped ion atomic clock in space," Nature **595**, pp. 43-47 (2021).

[2] T.A. Ely, E.A. Burt, J.D. Prestage, J.M. Seubert, and R.L. Tjoelker, "Using the Deep Space Atomic Clock for Navigation and Science," IEEE Trans. On Ultrasonics, Ferroelectrics, and Frequency Control **65**, pp. 950-961 (2018).

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[3] E.A. Burt, W.A. Diener and R.L. Tjoelker, “A Compensated Multi-pole Linear Ion Trap Mercury Frequency Standard for Ultra-Stable Timekeeping,” IEEE Trans. On Ultrasonics, Ferroelectrics, and Frequency Control **55,** pp. 2586-2595 (2008).

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