National Aeronautics and Space Administration

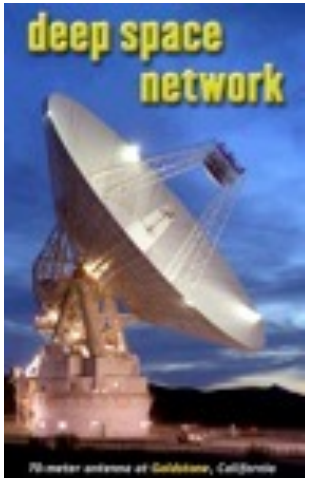
Miniature Space Optical Clock

Principal Investigator: Nan Yu (332); Co-Investigators: Thai Hoang (332), John Prestage (332), Dmitry Strekalov (332), Wei Zhang (335), Andrey Matsko (335), Thanh Le (332), Sean Muholland (National Physical Laboratory, UK)

Program: FY21 R&TD Strategic Initiative **Strategic Focus Area: Space Clocks Awareness**

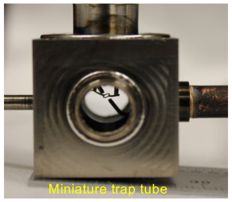
Objectives

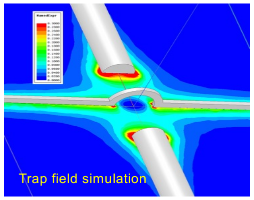
At 3x10-13/t1/2 and a stability floor at 10-15 level, JPL's Deep Space Atomic Clock (DSAC) is the state-of-the-art SOA microwave clock of its size. In order to have a clock capability beyond DSAC, one will have to take the new approach of the optical clock where the clock ticking rate is at hundreds of terahertz rather than tens of GHz. The high oscillation frequency enables the clock stability and accuracy performance beyond any of today's microwave clock can achieve, with fully transportable clocks demonstrating 1x10-16/t1/2 from 1 second down to 1x10-18 accuracy floors. This gives much margin of performance in reducing the size and power for a miniature space optical clock (mSOC) yet out-perform any microwave clocks of the similar size today. The overall objective of the RTD initiative effort is to develop and demonstrate the mSOC concept that will have 1x10-14/t1/2 clock stability with the accuracy floor of 1x10-16, which are 10x performance than the state of the art. With the approach of the single trapped ion as the atomic reference, it is possible to make the whole clock system small enough to deploy in Deep Space.



Background

Use of these space clocks will increase the efficiency of utilization of DSN apertures, enable radio science measurements from small spacecraft, and support autonomous operation of our spacecraft and ground systems. This effort aims at developing key components to advance the state of the art of Space Clocks—ultimately leading to full optical space clock systems. The target clock performance (stability and accuracy) and SWAP-C (size, weight, power and cost) have been chosen to maximize the utility of this instrument for future JPL/NASA missions. The new space clock capability will A) meet the Directorate Strategic Goals of efficient utilization of IND resources through reducing the aperture time for tracking and time synchronization/transfer, supporting spacecraft onboard automation, and providing network timing for planetary spacecraft networks and constellations; B) address NASA Technology Roadmaps of TA 5.4: Position, Navigation, and Timing, and TA 5.4.1: Timekeeping and Time Distribution – developing a new integrated space-qualified timekeeping system and providing nanosecond-level time transfer capability across the solar system; and C) answer JPL Strategic Implementation Plan and Strategic Technology Directions for Space clocks facilitating deep space navigation as well as autonomy. High performance clocks are also identified in the National Quantum Initiative as a national technology priority.


Miniature trap tube


Trap field simulation

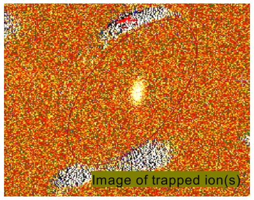


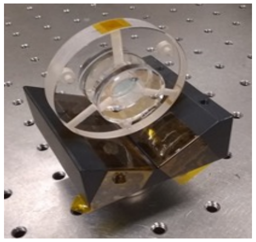
Image of trapped ion(s)

Trap Tube

In order to reduce the overall size and power, the trap tube will be completely sealed without an active pump. The tube is of titanium metal and sapphire glass window construction for non-magnetic property, DUV transmission and impermeable to helium. The trap consists of a small ring trap electrode with two endcaps, both mounted on a 4 pin feedthrough. A Yb appendage is attached and can be heated externally as the atom source. The vacuum is maintained by a small NEG. All parts are welded in place in a size of < 16 cc as shown in Figure 1a. The trap is driven by an rf voltage, creating a pseudo-trapping potential for ion confinement. The trapping field around the trap is simulated as shown in Figure 1b. Figure 1c shows an image of trapped ion(s). Even with multiple ions, ion storage lifetime is over 50 hrs. We expect a single ion will last a long time, only limited by a collisional loss/charge exchange with residual gas molecules.

Approach and Result:

mSOC consists of an atomic physics package containing trapped ions; a stabilized clock laser; a frequency comb divider; and necessary electronics. The focus of this task is to develop a miniature physics package, and to develop tabletop setups for the rest of the systems for the purposes evaluating the clock performance. The first year activity of this project was focused on design of the system as a whole as well as the construction of a testbed system using commercially available off the shelf parts. Both miniature trap tube package and testbed clock laser reference have been analyzed, designed and key components and parts procured. The second year activities focused on ion trapping in a miniature sealed trap vacuum tube and construction of the reference cavity and implementation of the clock laser.



Reference Cavity and Clock Laser

Following our design, the cavity is made of a 10 mm ULE spacer and two substrates with 1 inch diameter to form the Fabry-Perot cavity, as shown in Figure 2. To confirm the cavity finesse, we measured the cavity ringdown time which is 4 us, corresponding to a finesse of 200,000, meeting our design expectation. The cavity is installed in a two-layer thermal shield made by copper all housed in a vacuum chamber pumped a small ion pump. The vacuum housing is currently made of COTS parts without minimizing it size. in which all parts are over the shelf. The combination of the vacuum and the thermal shield will provide a 10 hour time constant, necessary for the slow frequency drift. We are also making efforts to miniaturize some of the electronic components and assemblies. One of electronics module is the trap driver.

Significance/Benefits to JPL and NASA

The successful fabrication of vacuum tight miniature trap confirmed our overall design and approach. We have demonstrated the ion trapping in the miniature trap tube and showed excellent lifetime for multiple ions with RF heating. The measured long lifetime is the indication of high vacuum level without an active pump. Based on the previous mercury ion systems, we expect the vacuum improves overtime after the seal off (pinch-off) completely from the large pump station. This is the very first laser-cooled ions in a small sealed tube. A good vacuum and lone lifetime is essential for reliable operation of the clock in real operating environment. The small ULE optical local oscillator will be one of the smallest ever developed with the specified performance. The small size increases the risk of high-finesse coating and optical contact bonding. This confirmed high finesse overcame the risk in cavity fabrication. The design of the small reference cavity and its corresponding stabilized laser oscillator will not only provide the needed clock system for mSOC, but will be useful for developing small photonic oscillators that better than quartz oscillators.

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
www.nasa.gov

PI/Task Mgr Contact
Email: Nan.Yu@jpl.nasa.gov

Clearance Number:
RPC/JPL Task Number: R20048