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Miniature Space Optical Clock (mSOC)

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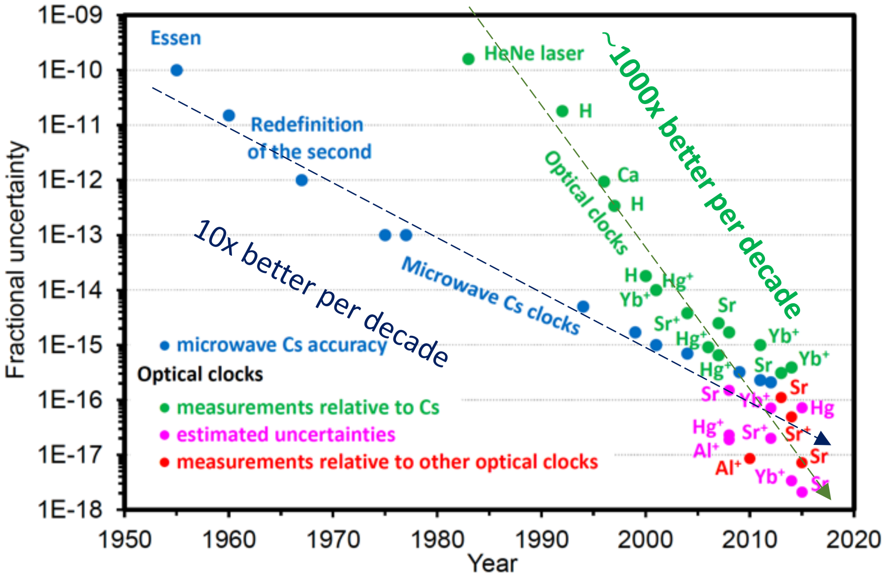
Tutorial Introduction

Abstract

- Precision atomic clocks are the critical system for modern position, navigation and timing such as GPS.
- New, more stable and accurate clocks will significantly improve the deep space navigation in precision, robustness and autonomy, as well as enabling new science measurements for tests of fundamental physics and detection of dark matter ultra-light fields.
- Recently, the clock research community has invented new type of atomic clocks that tick at optical frequencies (100s of THz) rather than a quartz oscillator based clocks at 10s of MHz. The optical clock technology has revolutionized the clock precision advancement exponentially (chart on right).



The chart show the revolutionary advancement of the optical clock approach to the precision of atomic clocks over the years. Microwave clocks have been improving at 10x per decade and leveled off at 1e-16 level, while the optical clocks have been improving one hundred times faster, and surpassed the microwave clocks down to 1e-18 level. (Courtesy of R. Godun, NPL)

Problem Description

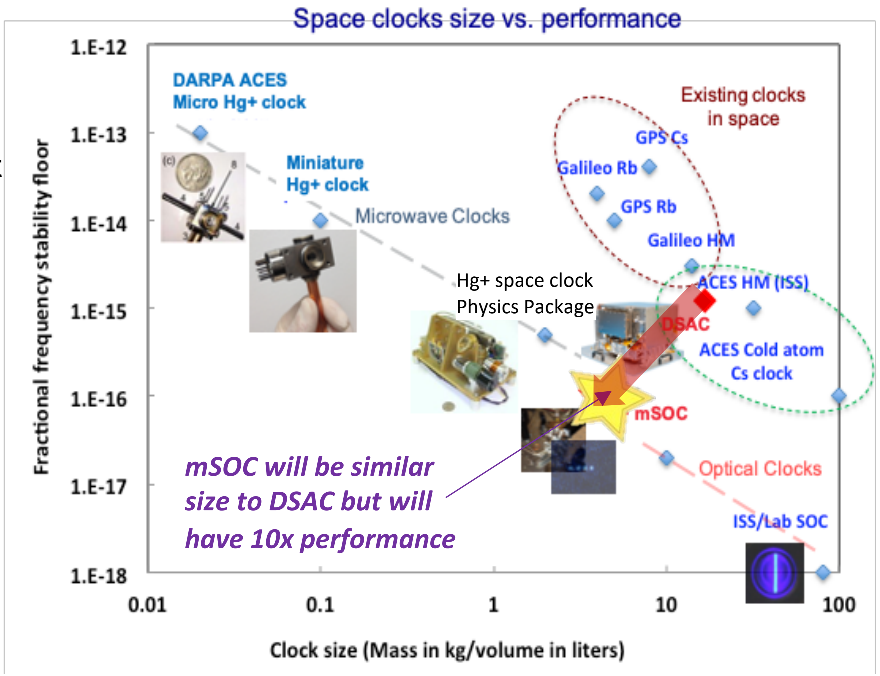
Context – The challenge is to reduce the reduce the size of optical clocks from room sized laboratory research setups to a compact and robust clock package to be deployed in space. Such reduction cannot be simply accomplished by engineering. New approaches and new technologies are called for.

The overall objective of this strategic initiative task is to develop towards a Miniature Space Optical Clock (mSOC) in a shoebox size with key components performance at with $1\times10^{-14}\tau^{-1/2}$ clock stability and accuracy floor of 1×10^{-16}, or 10x better than any microwave clocks in the similar size and deployable in space.

State-of-the-art – The state of the art in space microwave atomic clocks is the Deep Space Atomic clock (DSAC) developed by JPL and currently in orbit in a NASA technology demonstration mission. The existing space clocks and those being developed at JPL are illustrated in the chart, showing the clock performance stability floor as a function of the nominal mass/volume.

Relevance to NASA and JPL

1) Efficient use of the tracking antenna time
2) Increased spacecraft autonomy and improved navigation.
3) Timekeeping and Time Distribution to sub-nanosecond accuracy across solar system.
4) Enabling new science measurements

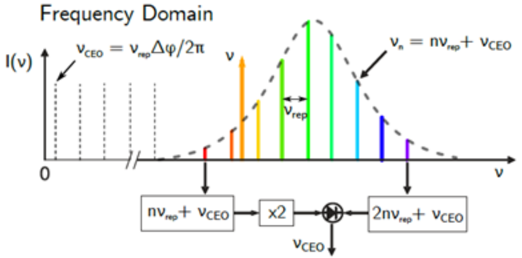


The chart shows the space atomic clock stability floors at various nominal size and mass. Dashed circled ones at upper right are the existing space clocks including the JPL newest DSAC in orbit. Others are clocks being developed at JPL. This RTD focuses on smallest optical clock indicated with the yellow star .

Methodology

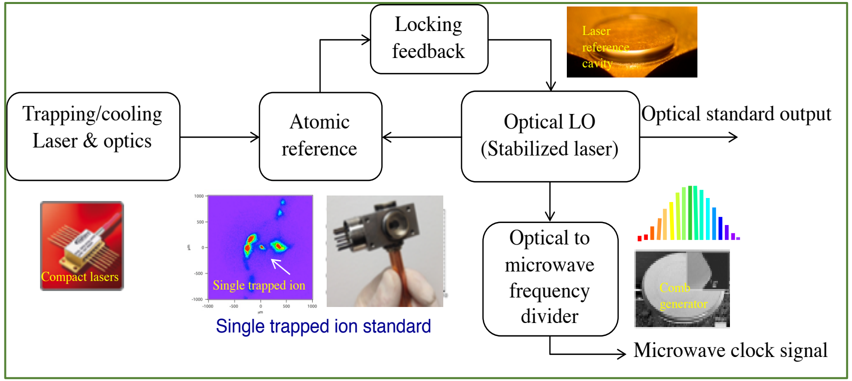
Approach

- Adopt the method of ***optical clock*** to surpass any microwave clocks capable to deliver today.
- Focus on the tradeoff of performance vs size, power and complexity with the goal of x10 improvement over the SOA.
- Intelligent choice of single trapped Yb+ as the atomic reference, requiring less power and size.
- Leverage JPL's expertise as well as external investments and research results for the final product



Innovation and advancement

- We are focusing on the breakthroughs in miniature trap vacuum systems at JPL stemmed from a DARPA micro clock program and extend it to laser-cooled single trapped Yb+ ions.
  - no active pumping with ion lifetime in 100s of days.
- Miniature clock laser performing at the fundamental thermal noise limit.
- Leverage the chip-based optical frequency comb being vigorously developed in DARPA programs
- Ultimately use Photonics-Integrated-Circuit (PIC) approach for laser and optical systems

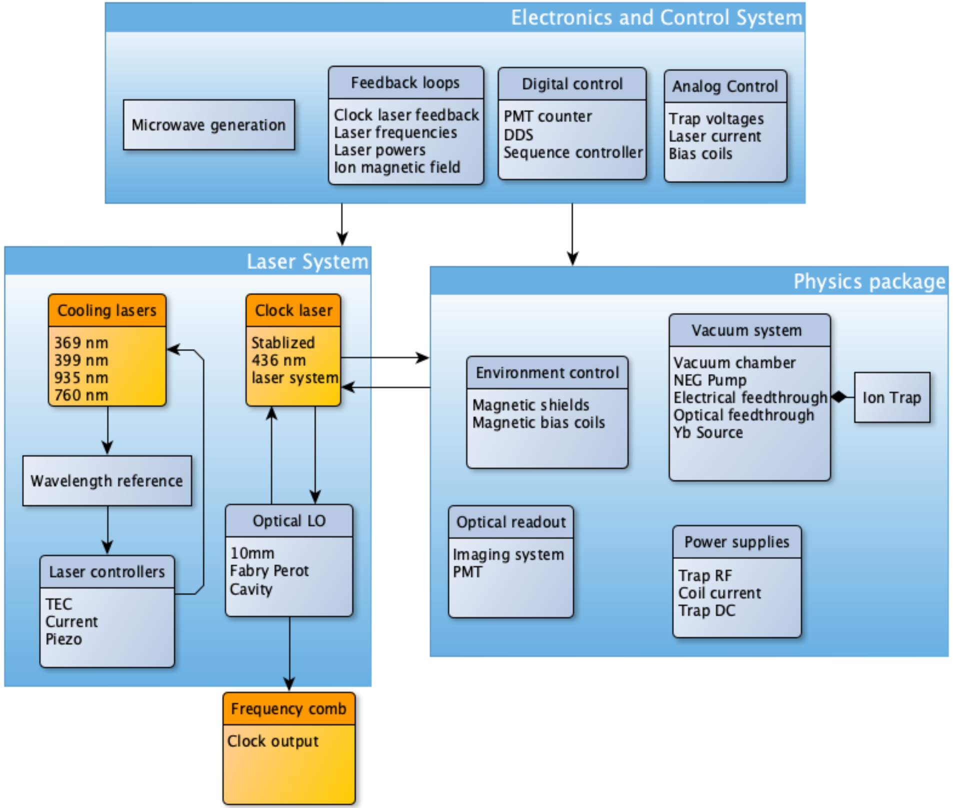


Envisioned single trapped Yb+ clock approach diagram: atomic reference with a cc-sized vacuum tube, clock laser stabilized to a micro resonator, lasers on photon-integrated-circuit, and optical frequency comb divider on chip.

Results 1/3

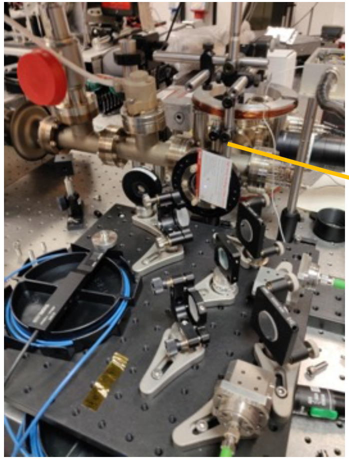
The Covid19 situation made it extremely difficult to implement the mSOC experimental tasks as planned. Nevertheless, we were able to take advantage of the remote work time and resources to advance the overall progresses and position ourselves for rapid progresses next year.

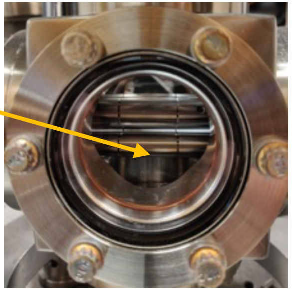
1. Prototype clock system investigated and high-level requirements defined.
2. Interactions with external partners resulted three directly relevant proposals and two SBIR tasks funded.



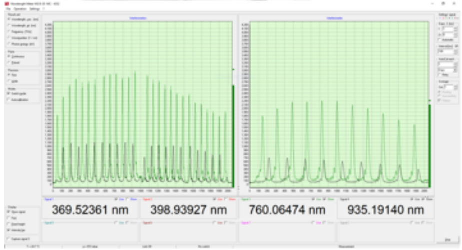
Results 2/3

3. Breadboard laser system has been configured and ready for ion trapping and cooling
4. The laser locking wavemeter acquired and installed in the breadboard setup
5. The testing ion trap system has been completed and ready to be used

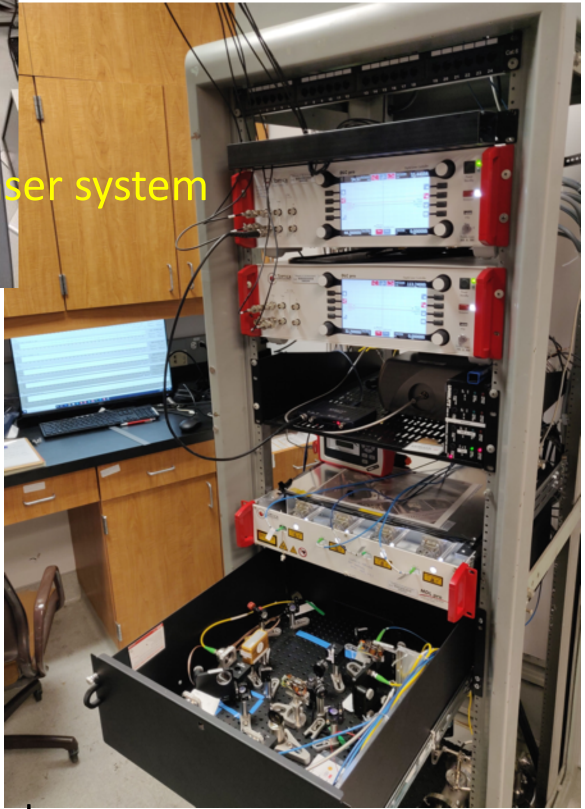




Test trap system



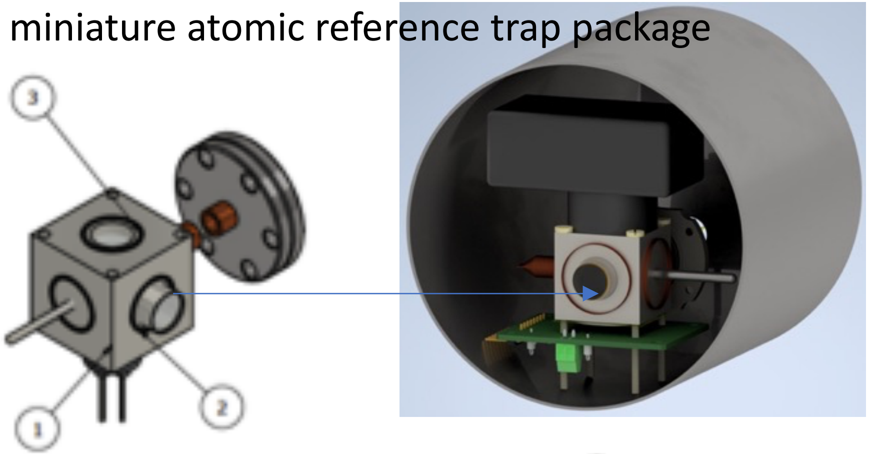
Reference wavemeter installed



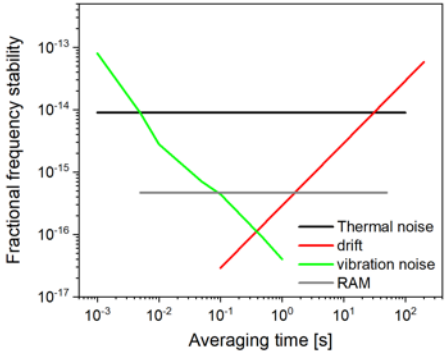
laser system

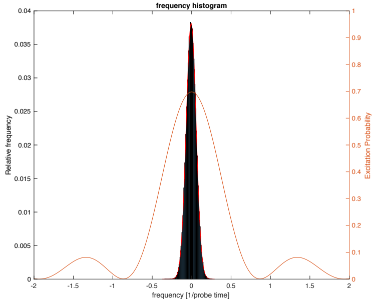
Results 3/3

miniature atomic reference trap package

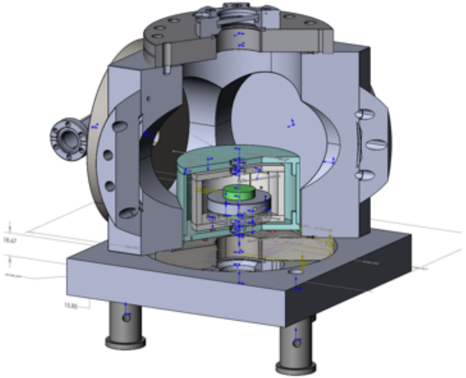


6. Atomic reference tube designed and parts procured.
7. Clock reference cavity requirements defined, design complete, and major parts partially procured.





Clock laser reference noise analysis



Clock laser cavity design