National Aeronautics and Space Administration

Spaceborne quantum sensors based on magnetically insensitive atomic gases

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Program: FY22 R&TD Topics
Strategic Focus Area: Origin, evolution, and structure of the universe

Objectives

The objective was to develop novel techniques to produce, trap and control ultracold neutral atoms to improve the capabilities of spaceborne quantum sensors. The primary goal is to develop a novel source of ultracold atoms with magnetic quantum number of zero, making them insensitive to weak magnetic fields. A second goal is to produce extremely cold trapped atoms and utilize these magnetic techniques for advanced atom interferometer designs. Novel trap shapes can be tailored to achieve 3D geometries ideally suited for inertial and force gradient sensing, while remaining immune to stray magnetic fields and residual fields.

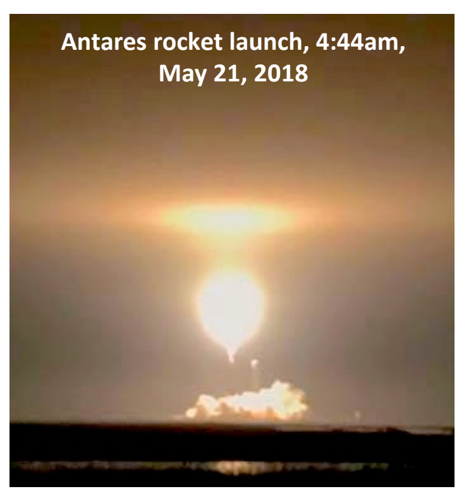
Background

The Cold Atom Lab (CAL), in operation aboard the ISS for over 4 years, has demonstrated routine production of Bose-Einstein condensates at nanoKelvin temperatures. The next generations of quantum systems promise to further revolutionize fundamental physics experiments, position, timing, and navigation technologies. All such quantum sensors applications could benefit from large atom numbers prepared at ultracold temperatures specifically in the *magnetically insensitive state.*

Approach and Results

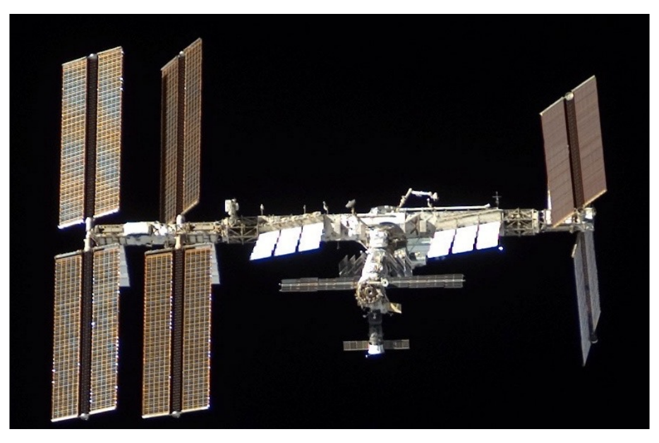
In microgravity, one of the primary goals is to reach low densities and extremely low temperatures by use of weak traps (extremely low trap frequencies <10 Hz), but these tend to be overpowered and imbalanced by residual magnetic fields and gradients. The quadratic Zeeman (spin-zero) traps, however, can achieve <10 Hz trap frequency with substantial fields and at modest ranges of the atom chip surface. This makes the spin-zero traps less susceptible to uncontrolled external field perturbations. The plots to the right show advantages of the quadratic Zeeman trap over the standard (linear) trap in transitioning to extremely weak traps in the presence of stray field gradients.

NASA's Cold Atom Lab Facility (CAL)

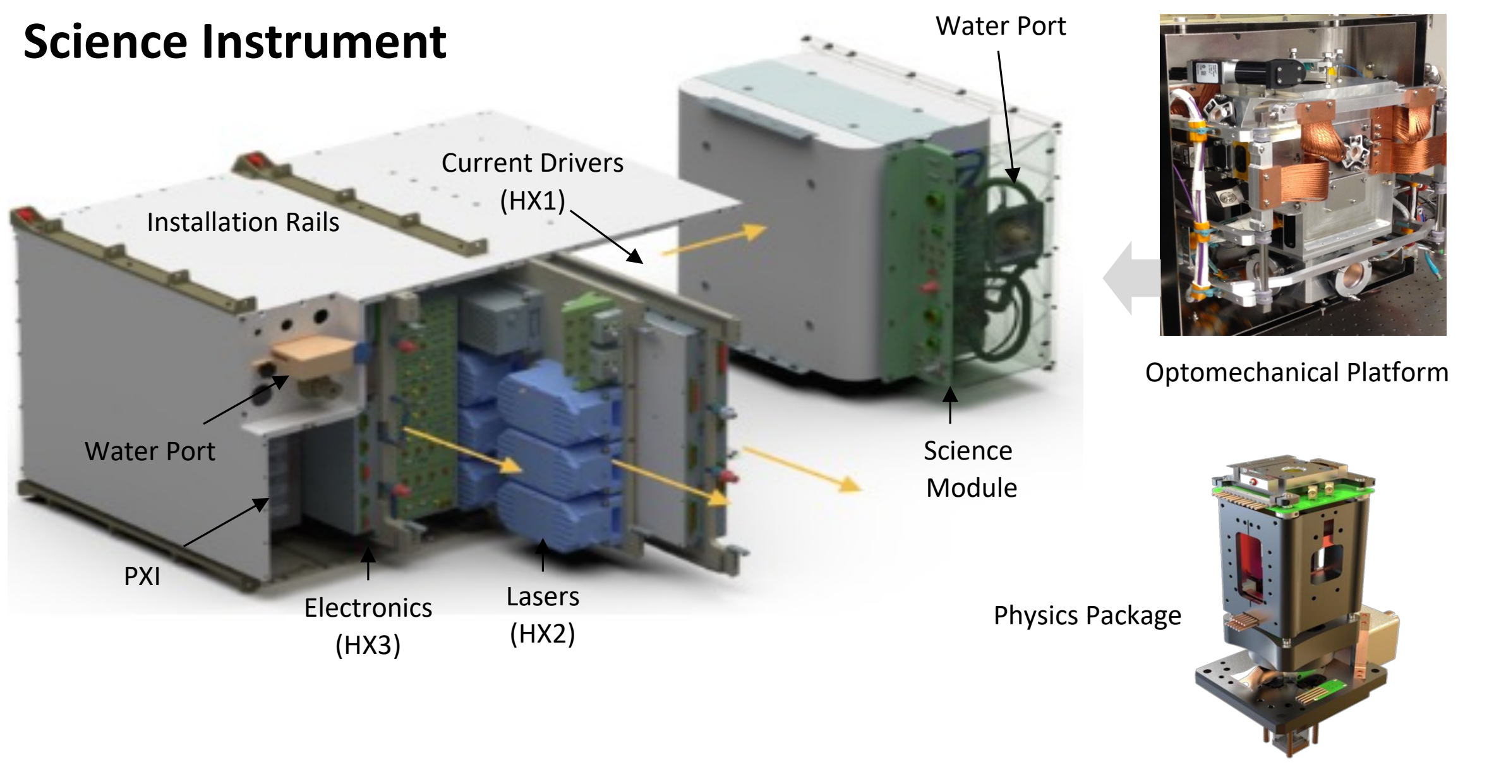

Antares rocket launch, 4:44am, May 21, 2018


OA-9 minutes before launch, Wallops Island, VA


CAL Install by Astronaut Ricky Arnold



Science Instrument



Aveline, Williams, Elliott, *et al.*
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- Multi-user facility on the International Space Station for atomic physics research
- A microgravity environment circumvents the gravitational limits of terrestrial quantum experiments
- The instrument produces and holds a cold quantum gas using laser light, RF radiation, and magnetic fields

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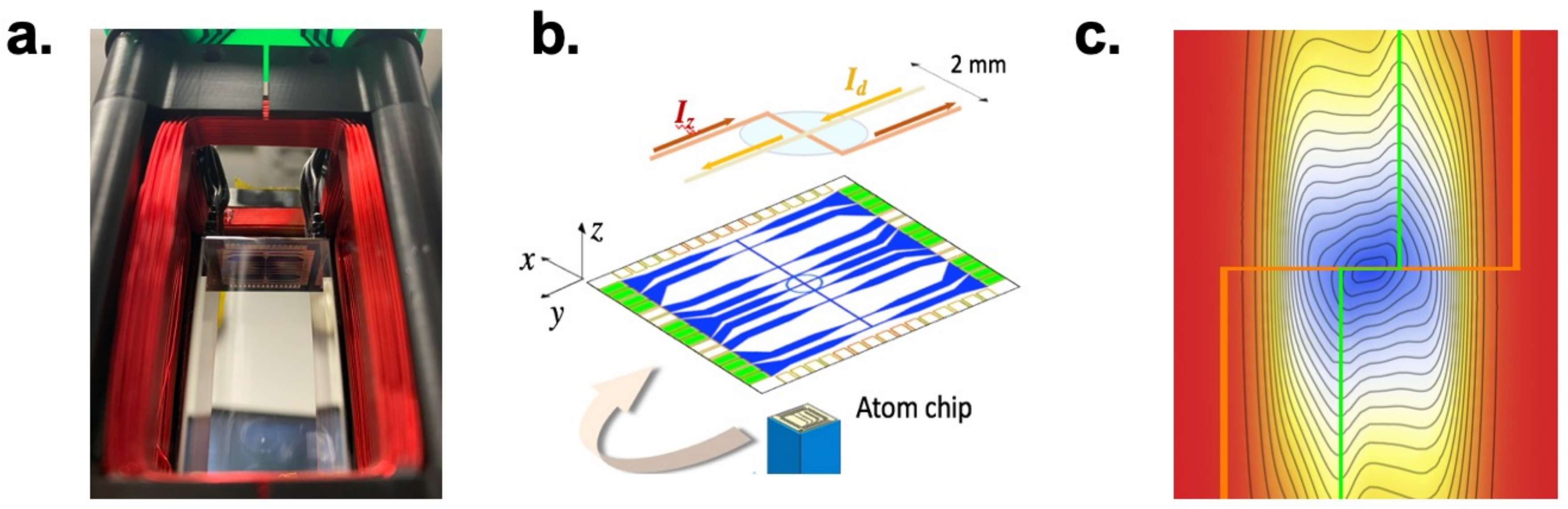
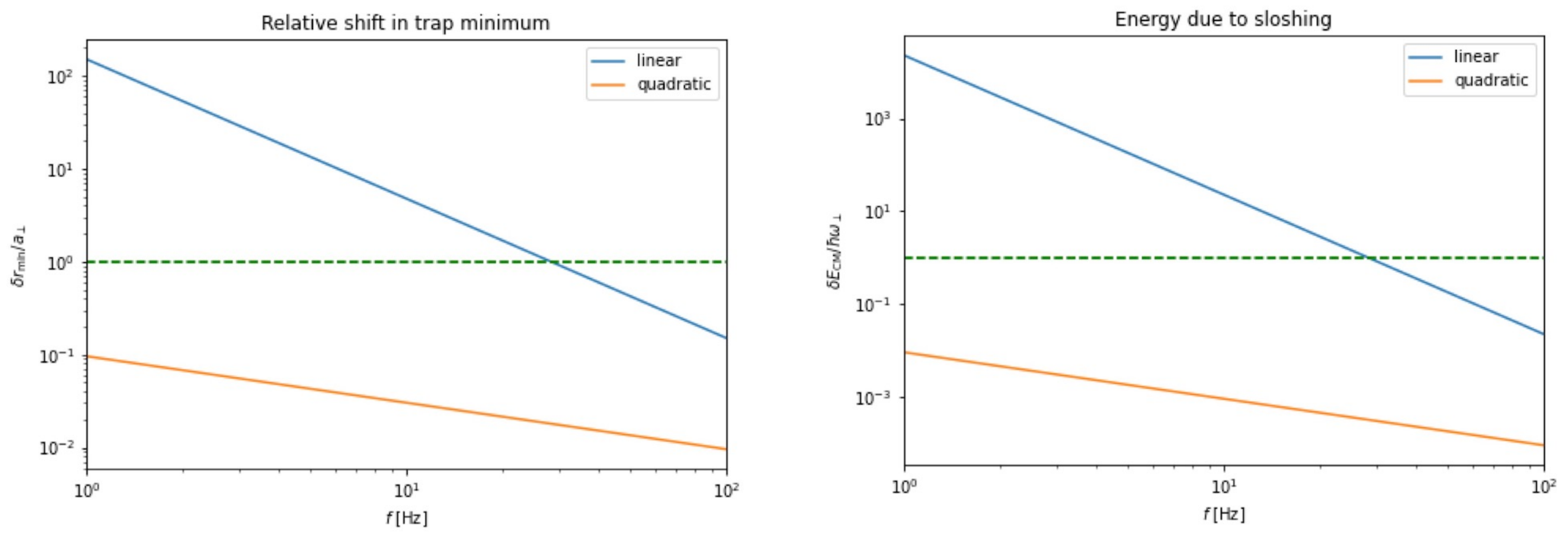
California Institute of Technology
Pasadena, California
www.nasa.gov

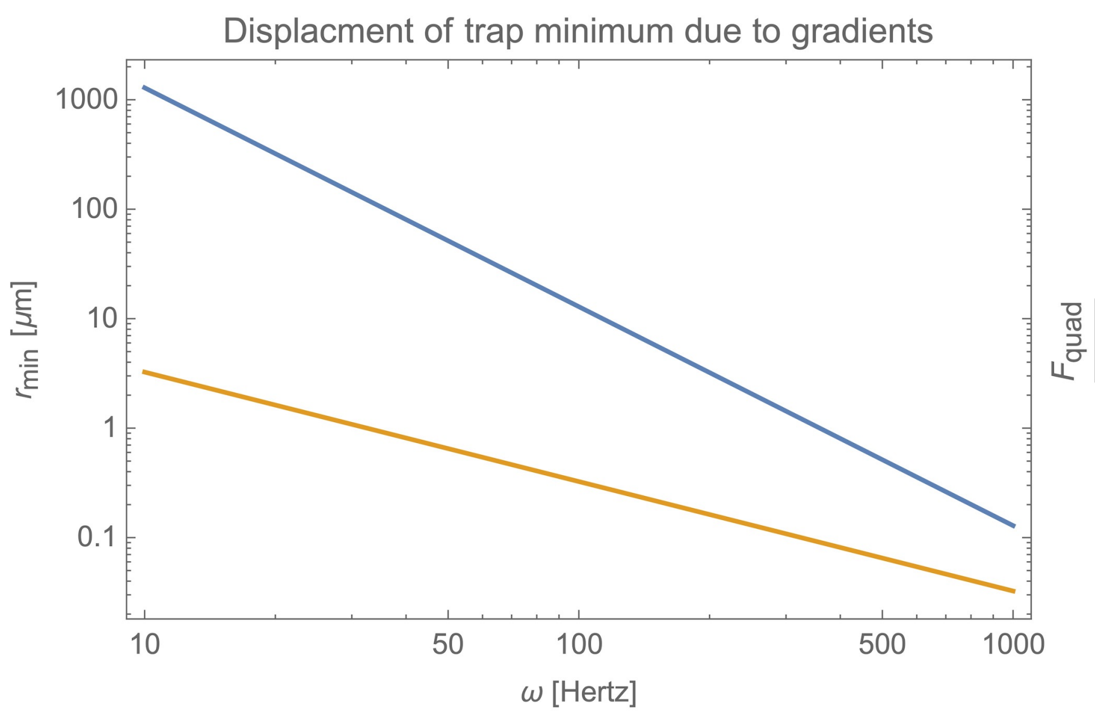
Clearance Number: CL#23-6314
Poster Number: RPC#



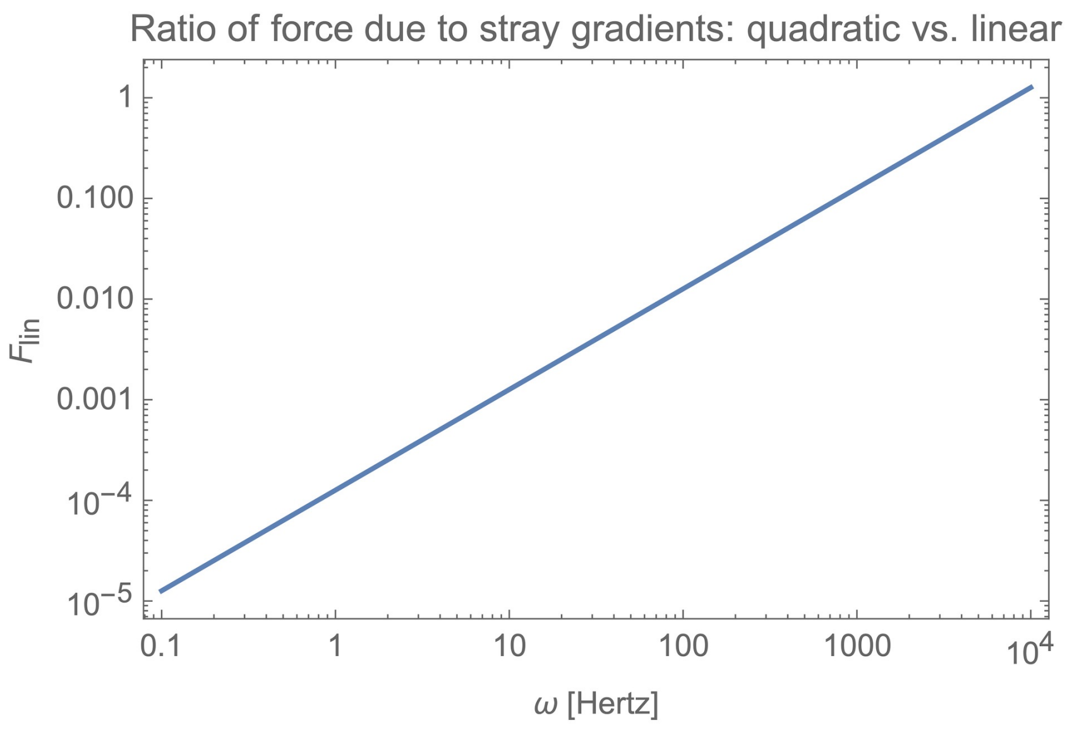
An atom chip located at the top of a dual-celled vacuum chamber (a.) is capable of forming a trap for neutral atoms by running currents through micro-wires on the semiconductor chip. The "z-d" planar geometry (b.) produces a [1.0 , 1.0 , 0.2] kHz trap for Rb atoms in the mf=2 state. A simulated atom chip trap shown here (c.) uses a BECCAL-like chip design.



For a spin-zero trap (quadratic) in the presence of a 0.1 G/cm gradient, the left plots show the trap's relative displacement is smaller (and therefore more stable than) a standard (linear) trap. The right plots show the heating or equivalent energy that would be imparted to a sloshing mode due to this physical shift of the trap bottom during a trap decompression. This advantage of the quadratic-Zeeman trap over the linear case is further magnified at lower trap frequencies.



Due to a 0.1 G/cm stray gradient along the direct normal to the chip surface, as the chip trap gets decompressed, its position moves away from the chip. This displacement grows particularly large (~1 mm) for a standard trap (blue) by the time it reaches 10 Hz. However, for a spin-zero trap, it would be less than 0.004 mm. The more the trap shifts around, the more difficult it is to stabilize it and prevent heating or loss of atoms.



The attenuation of the forces due to stray magnetic gradients for a spin-zero trap relative to a standard magnetic trap, F_quad/F_lin, plotted above illustrates the major advantage of spin-zero traps as one decompresses to low trap frequencies. The force from a stray gradient would be 10,000 times lower for a 1 Hz trap, and this technique could enable much colder atom temperatures (i.e. < 100 pK).

Significance

NASA continues to show a strong interest to perform microgravity experiments with ultracold atoms aboard the International Space Station (ISS), as well as the Lunar Gateway. JPL-built Cold Atom Lab (CAL) has now been routinely operating in space for over 4 years. Independent from on-going CAL activities, this research project will allow us to prepare for future funding opportunities for space-based quantum sensors with NASA SMD, while at the same time demonstrate the suitability of this technology for a number of scientific investigations. It will directly benefit microgravity-based science studies such as follow-on missions to CAL, including the potential investigations with the Bose-Einstein Condensate Cold Atom Lab (BECCAL), a joint NASA-DLR mission currently planned for 2026-2027 deployment on ISS. Additionally, there is a fourth Science Module ("SM-3B") installed as a CAL upgrade in October, 2023. This work could develop techniques that benefit future planetary missions for gravity mapping and inertial sensing.

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