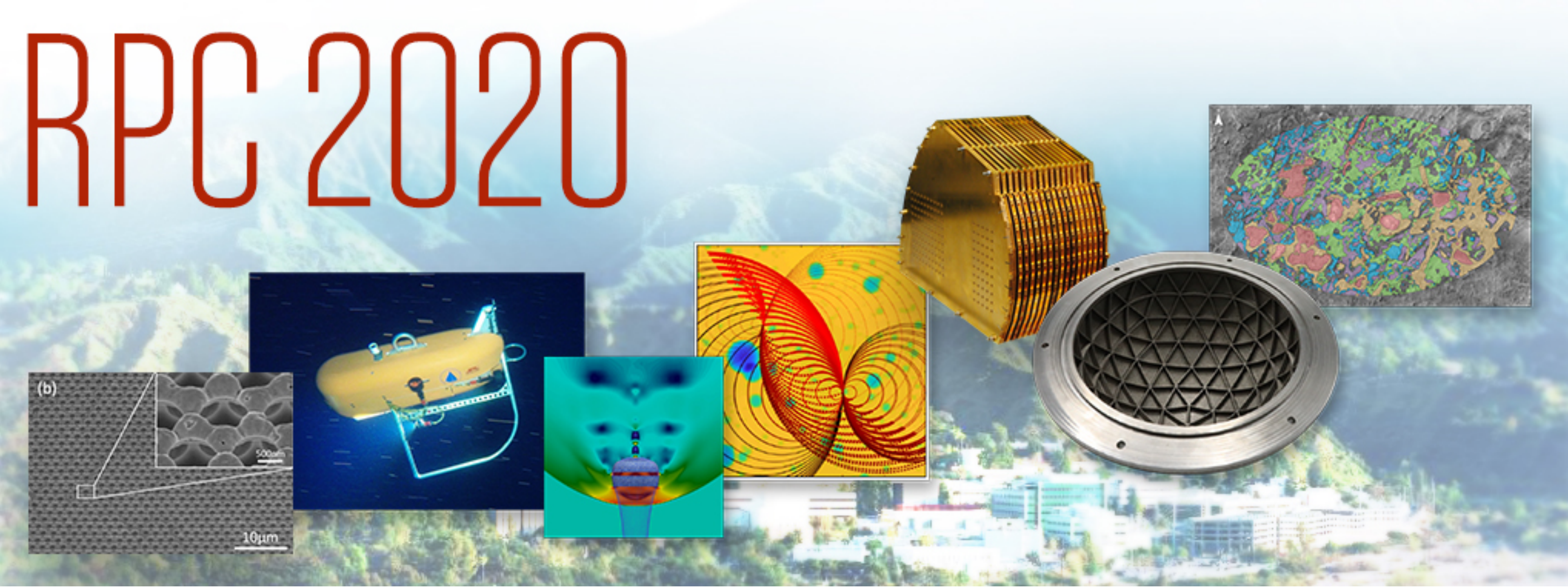
RPC 2020



Virtual Research Presentation Conference

Scattering of a particle with internal structure from a single slit in microgravity

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Program: SURP

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Tutorial Introduction

Abstract

The objective of this project was to study quantum scattering, tunneling, and confinement for a quantum system composed of a particle with internal structure and an optically engineered potential. Specifically, the possibility for this quantum system to be matured as a new type of ultra-precise sensor for rotations and accelerations and the implications of such a sensor for future NASA missions was a key aspect to this study. During the first year effort, we identified that a system of ultracold neutral atoms confined between two optical barriers can act as a Fabry-Perot cavity for matter waves, in analogy to Fabry-Perot optical cavities. The tunneling rates and momentum spectrum of the atoms leaving the trap can provide sensitive measurements of inertial forces on the atoms. The development of this technology would be relevant for NASA’s Fundamental Physics programs but also could provide enhanced performance for gravitational science and Position, Navigation, and Timing (PNT) capabilities.

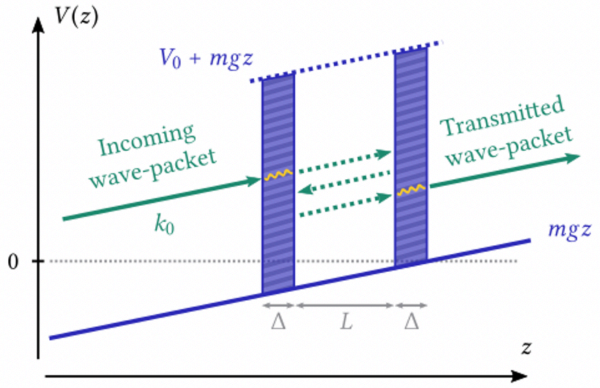
Problem Description

a) Technologies to leverage advanced capabilities for quantum sensors in space are being rapidly matured in academic and national research labs worldwide. Space missions to mature these technologies include:

- MAIUS (DLR) – Quantum gas and atom interferometer demonstrations on sounding rockets. [1]
- CAL (NASA) – Cold Atom Lab onboard the ISS. [2]
- ACES (ESA) – Atomic Clock Ensemble in space to be launched to the ISS in 2021. [3]
- BECCAL (DLR-NASA) – Second-generation cold atom lab to be launched to ISS in 2025. [4]

b) Here, we performed preliminary investigations of a matter-wave Fabry-Perot cavity [5] for use as a precise inertial force sensor (illustrated right). This is the first known effort to develop a new class of inertial force sensors based on scattering, tunneling, and confinement of ultracold atoms and molecules from optically engineered barriers and/or slits.

c) Based on the recent success of CAL and ongoing efforts to bring precision quantum sensors into space, results of this study can reveal new capabilities at the critical time when missions are under development to capitalize on the emerging promise of cold-atom-based technologies for novel space applications.



Matter-wave Fabry-Perot-interferometer

Schematic of a matter-wave Fabry-Perot cavity: A wave-packet with center-of-mass momentum $\hbar k_0$ impacting below the barrier height on the Fabry-Perot cavity formed by two light-generated potential barriers. The transmission resonances of the barrier act as a filter. The fraction of transmitted atoms after the barrier serves as an observable. Once a gravitational acceleration is present the transmission resonances of the cavity system are shifted and hence the number of transmitted atoms changes. The placement and form of the tunneling resonances and thus the sensitivity of the device can be engineered by tuning the barrier form, barrier separation L and thickness Δ.

Methodology

a) Our investigation included the following:

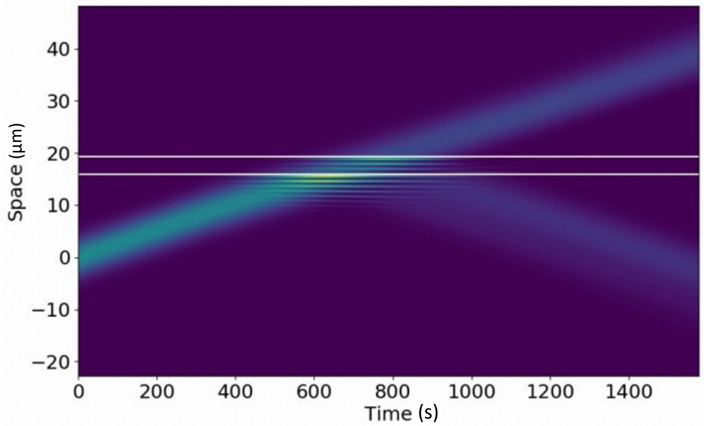
- ✓ **Milestone 1:** Formulation of the model system, including identification of the appropriate atoms, molecules, and barriers/slits.
- ✓ **Milestone 2:** Derivation of bound states and transmission characteristics by numerical and semi-analytical methods.
- ✓ **Milestone 3:** Develop acceleration sensitivity function for the model system.

In FY'21, these studies will be further expanded with experimental investigation of the model system at JPL.

b) Significant promise was identified for developing the matter-wave Fabry Perot cavity as a quantum sensor due to the strong analogues to optical cavities combined with novel aspects of quantum matter.

c) The combination of the numerical toolbox and semi-analytical models developed by Professor Schleich's group was used to:

1. Characterize the behavior of a Fabry-Perot matter-wave cavity (see the figure right as an example).
2. Calculate the relative sensitivity to gravitational acceleration (δg) from the transmitted fraction of atoms (T) as: $\delta g = \frac{\Delta g}{g} = \frac{1}{g}\frac{\sqrt{T(1-T)}}{\left|\frac{\partial T}{\partial g}\right|}$



Numerical simulation of the spatial time-evolution of a BEC wave-packet (with width 12 μm and initial center-of-mass velocity of 5 mm/s) transmitted through a Fabry-Perot cavity, indicated by white horizontal lines, and generated by two Gaussian barriers separated by 4 μm.

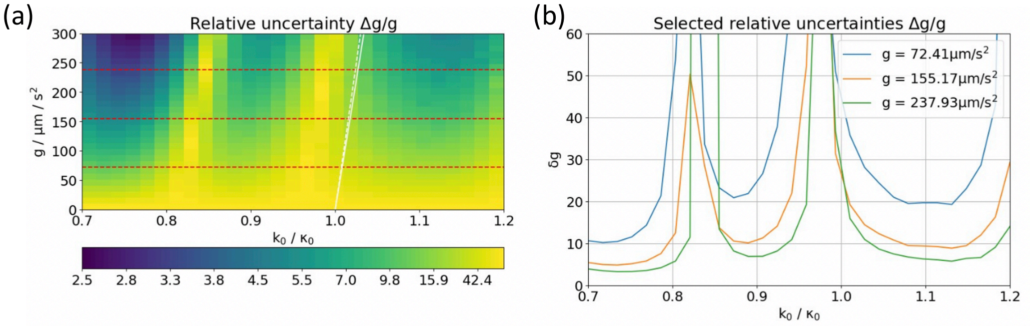
Results

a) Based on preliminary investigations and rescoping of the original 3-year project, we expanded from studying confinement of a molecule trapped in a slit by entanglement to modeling the sensitivity of ultracold atoms tunneling through a matter-wave Fabry Perot cavity to minute gravitational accelerations.

b) As shown in the figures below, acceleration sensitivities on the order of 100 microGal/rt(Hz) or below are reasonable with a continuous BEC source tunneling through the FP cavity, assuming a flux of a million atoms per second.

c) The development of this technology would be relevant for NASA's Fundamental Physics programs but also could provide enhanced performance for gravitational science and Position, Navigation, and Timing capabilities.

d) Future venues of investigation include efforts to further optimize the sensitivity of the matter-wave Fabry-Perot cavity to inertial and fundamental forces and to miniaturize a system as a uniquely compact and simple quantum sensor.



(a) Scaled relative uncertainty Δg/g (per atom) of the proposed Fabry-Perot matter-wave cavity as a function of initial center-of-mass energy $(\hbar k_0)^2$ in units of the effective barrier height $(\hbar \kappa_0)^2$ and gravitational acceleration. The cavity parameters are a width of 4 μm and an experimental duration on the order of ~100 ms. Optimal sensitivity for operation is obtained in the low-value (blue) regions of the density plot. **(b)** Relative uncertainty Δg/g (per atom) at selected gravitational accelerations (slices along the red dashed-lines in part **a** of the figure). Optimal sensitivity is obtained in the minima of the respective curves.

References

[1] Dennis Becker, *et al.,* “Space-borne Bose-Einstein condensation for precision interferometry”, *Nature* ***562*** (2018): pp. 391-395.

[2] David C. Aveline, *et al.*, “Observation of Bose–Einstein condensates in an Earth-orbiting research lab" ,*Nature* **582** (2020): pp. 193-197.

[3] Marc P. Hess, *et al.*, “The ACES mission: System development and test status”, *Acta Astronautica* ***69*** (2011): pp. 929-938.

[4] Kai Frye, *et al.*, “The Bose-Einstein Condensate and Cold Atom Laboratory," arXiv:1912.04849 [physics.atom-ph] (2019).

[5] Perumbil Manju, *et al.*, “An atomic Fabry–Perot interferometer using a pulsed interacting Bose–Einstein condensate," *Scientific Reports* **10** (2020): 15052.