# A COHERENT MATTER WAVE QUANTUM GRAVITY GRADIOMETER FOR SUBSURFACE REMOTE SENSING

Final Report

JPL Task 1021

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## A. OBJECTIVES

This task is for the development of a coherent matter wave atom interferometer suitable for use in a gravity gradiometer. The quantum interferometer gravity gradiometer (QUIGG) is an enabling technology which will allow remote three-dimensional mapping and the determination of density variations below the surface of a solid or fluid body.

## B. PROGRESS AND RESULTS

### 1. Development of all-optical source of Bose-condensed atoms

We have designed and built an apparatus that will allow us to Bose condense large samples of Rubidium atoms using entirely optical techniques. Bose-Einstein condensation (BEC) is a quantum-phase transition that occurs at low temperatures and high densities for samples of atoms which obey what is known as Bose statistics (most atoms fit this description). A Bose condensed sample of atoms has a large fraction of atoms in a single, macroscopic, quantum state. The atoms are coherent, meaning their De Broglie wavelengths (according to quantum mechanics all objects have both a wave and a particle nature), are in phase with one another. This property is important for a number of sensor applications, in particular those based on atom interferometry, potentially allowing an increase in the sensitivity of the instrument by a factor proportional to the square root of the total number of condensed atoms, a three orders of magnitude improvement for typical BEC experiments [5].

Our apparatus consists of two vacuum chambers, one of which contains a cold atomic beam source which delivers on order of 1 ► $10^9$ atoms per second to the second chamber, which is held at ultra-high vacuum (UHV) (5 ► $10^{-11}$ torr). Atoms are collected into a standard magneto-optical trap (MOT), consisting of six laser beams which confine the atoms in all directions and cool them to about 20 millionths of a degree above absolute zero. This low temperature is still several orders of magnitude too hot to achieve BEC, so the atoms are moved into a different type of trap called a quasi-electrostatic trap (QUEST), which is formed by a tightly focused crossed pair of $CO_2$ laser beams. This trap is purely conservative, so there is no lower limit to the achievable temperature. Once atoms are stored in the QUEST, the intensity of the trap is slowly ramped down, allowing the hottest atoms to escape, while the remaining atoms equilibrate at lower temperatures. This process, called evaporative cooling, is very efficient in a QUEST trap, allowing BEC conditions to be readily achieved.

The current status of this apparatus is that we have observed a cold atomic beam and are currently optimizing the loading into the UHV MOT. Once this stage is completed, we expect that loading into the final QUEST trap will be straight forward, with the only difficulties coming from the need to precisely align the two $CO_2$ laser beams. Once a suitable initial density of atoms is found in the QUEST, Bose condensation will follow immediately (all that is required is to ramp down the laser intensity slowly, so that evaporation proceeds steadily). All components of the final apparatus have been assembled. The apparatus is shown in figure 1. An image of the cold atomic beam in action is shown in figure 2.

Once Bose condensation is achieved, the next stage of this task is a demonstration of an atomic interferometer. Our approach is to use Bragg scattering as a beamsplitter[4]. Here the coherent matter-wave diffracts off of an optical standing wave which acts as a grating. A standing wave pulse diffracts a fraction of the condensate into momentum states $\pm 2n$▶$\boldsymbol{k}$, where $\boldsymbol{k}$ is the wave vector of the standing wave. A second pulse applied a time $t_1$ later creates an overlapping copy. The amplitudes of the matter-waves interfere where they spatially overlap. Such a technique is particularly easy to implement for a proof-of-principle test of a coherent matter-wave accelerometer.

2. Characterization of a dual-beam atomic beam source and observation of cold collisions

In the initial stages of this investigation, we converted an existing cold atomic beam source from operation as a cold Cesium beam to a cold Rubidium source (Rubidium is a standard atom for BEC experiments, while BEC has not yet been achieved in Cs). This allowed us to develop a novel and simple two-species (Cs and Rb) atomic beam source, and utilize this beam source to perform a preliminary study of cold collisions in a separate mixed-species trap under UHV conditions [1].

Simple modeling of these observed differences allowed us to make measurements of the heteronuclear (two atomic species) cold collision rate, which we compared to results from recent experiments in vapor cell traps[3].

## C. SIGNIFICANCE OF RESULTS

The optical BEC apparatus developed under this task will have vastly superior performance over what has been achieved previously [2]. It features atomic beam loading which gives a hundred times faster loading rates than the vapor cell used in the original demonstration, a vacuum which is also a hundred times better, giving much longer condensate lifetimes, along with an optical trap which has more than a factor of two higher power, which will result in tighter confinement. At a minimum, these improvements will allow us to produce condensates at a much more rapid rate than in the original experiment (by a factor of ten to a hundred), and allow us to study these condensates for much longer times (by about a factor of ten). The latter capability is particularly important for a future space-based instrument, since microgravity allows one to take advantage of significantly longer interaction times to achieve much higher sensitivity than can be achieved on the ground. Other improvements in our apparatus include increasing the amount of optical access, which will allow us to incorporate the additional laser beams needed to demonstrate an atom interferometer. We also expect that we will be able to produce much larger condensates in our apparatus than were achieved in the original experiment, though this will require a significant effort in optimizing the trap and evaporative cooling parameters.

A gravity gradiometer employing a coherent BEC source such as we have developed will allow, for the first time, the production of three-dimensional mapping of the gravity field by remote sensing. This will enable below-the-surface studies of the solid Earth, oceans, and other solar system bodies. We expect that such a capability will revolutionize Earth and planetary science investigations, and find important commercial and defense applications. The coherent QUIGG has the potential to offer room-temperature operation of a gravity gradiometer with ultra-high sensitivity (up to $10^{-4}$ E/Hz$^{1/2}$, where E =1►$10^{-9}$ sec$^{-2}$), and will be capable of long-term reliability. Such a gravity gradiometer will be especially suitable for on-board spacecraft applications.

The measurements of cold collision rates [1] are complementary to what has been achieved previously [3], in that they measure the effect of cold rubidium atoms on a cesium trap decay rate as opposed to the reverse. Understanding each of these rates is important for a variety of experiments involving two co-located samples of cold atoms, including a proposed NASA flight project, the Quantum Interferometer Test of Equivalence (QUITE). Furthermore, these measurements introduce a new technique into the field of cold collision studies, namely the use of cold beams for studying two-species interactions. This technique allows an unprecedented amount of control over the experiments, yielding results that are much cleaner and simpler to analyze. For example, we are able to turn off the loading rates of the two atoms independently, and neglect effects of background atoms because of our superior vacuum.

## D. FINANCIAL STATUS

The total funding for this task was $250,000, of which $205,000 has been expended.

## E. PERSONNEL

In addition to the co-investigators named above, Nathan Lundblad, a graduate student at Caltech, played a key role in putting together the BEC apparatus described above, and in gathering and analyzing data for the two-species beam/cold collision studies.

## F. PUBLICATIONS AND PRESENTATIONS

[1] Nathan Lundblad, David Aveline, Robert J. Thompson, James Kohel, Jaime Ramirez-Serrano, William M. Klipstein, Daphna G. Enzer, Nan Yu, and Lute Maleki, "A two-species cold atomic beam," submitted to *Physical Review A,* Rapid Communications.

[2] Nathan Lundblad, talk: "Production and Characterization of a Dual-Species Cold Atomic Beam", presented at American Physical Society's Division of Atomic, Molecular and Optical Physics Meeting, (5/29/02) Williamsburg, VA.

[3] Nathan Lundblad, poster presentation: "Production and Characterization of a Dual-Species Cold Atomic Beam", presented at Optical Society of America

Conference on Quantum Electronics and Laser Science, (5/21/02) Long Beach, CA .

## G. REFERENCES


[1] Nathan Lundblad, David Aveline, Robert J. Thompson, James Kohel, Jaime Ramirez-Serrano, William M. Klipstein, Daphna G. Enzer, Nan Yu, and Lute Maleki, "A two-species cold atomic beam," submitted to *Physical Review A,* Rapid Communications.

[2] M.D. Barrett, J.A. Sauer, M.S. Chapman, "All-optical Formation of an Atomic Bose-Einstein Condensate," *Phys. Rev. Lett.,* 87**,** 010404 (2001).

[3] G. D. Telles, *et al,* "Trap Loss in a Two-Species Rb-Cs Magneto-Optical Trap," *Physical Review A,* 63 033406 (2001).

[4] E.W. Hagley *et al.,* "Measurement of the Coherence of a Bose-Einstein Condensate,**"** *Phys. Rev. Lett*., 83 3112, (1999).

[5] P. Bouyer, M.A. Kasevich, "Heisenberg-Limited Spectroscopy With Degenerate Bose-Einstein Gases," *Phys. Rev. A,* 56 (2): R1083 (1997).


## H. APPENDIX: *Figures*

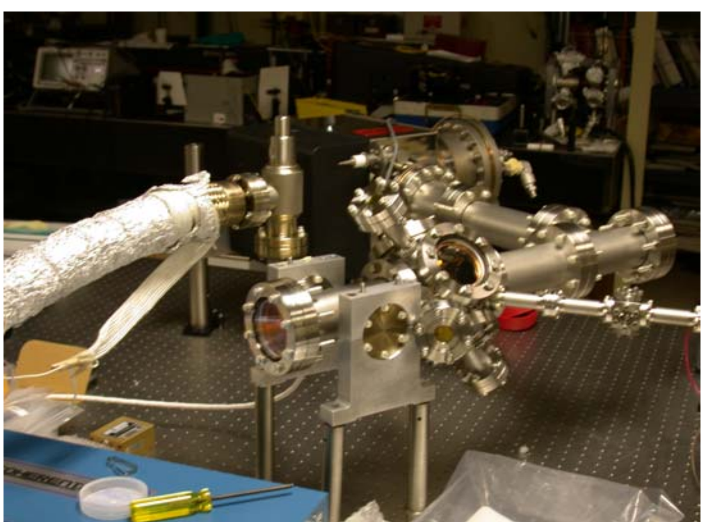

**Figure 1.Vacuum chamber for the JPL coherent matter-wave atom interferometer.**


**Figure 2. Cold atomic beam in operation.**