An Atomic Gravity Gradiometer for Earth Gravity Mapping and Monitoring Measurements

IIP-10-0009

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October 29, 2014

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Many others have been on the task and made significant contributions.
Gravity – Part of Whole Earth Science Measurements

Geodesy
Earth and Planetary Interiors
- Lithospheric thickness, composition
- Lateral mantle density heterogeneity
- Deep interior studies
- Translational oscillation between core/mantle

Earth and Planetary Climate Effects
- Oceanic circulation
- Tectonic and glacial movements
- Tidal variations
- Surface and ground water storage
- Polar ice sheets
- Earthquake monitoring

Why Atomic Sensors?

Freefall test mass + Displacement Detection + Atomic system stability

Laser-cooled Cs atom cloud at µK

Atomic beam

\( \pi/2 \) pulse \( \pi \) pulse

\( \pi/2 \) pulse

atom-wave interferometer (laser-based atom optics)

Fringes

Atoms are stable clocks

- Use totally freefall atomic particles as ideal test masses
  - identical atomic particles are collected, cooled, and set in free fall in vacuum with no external perturbation other than gravity/inertial forces; laser-cooling and trapping are used to produce the atomic test masses at µK and even pK; no cryogenics and little/no mechanical moving parts.

- Matter-wave interference for displacement measurements
  - displacement measurements through interaction of lasers and atoms, pm/Hz\(^{1/2}\) when in space; laser control and manipulation of atoms with opto-atomic optics.

- Intrinsic high stability of atomic system
  - use the very same atoms and measurement schemes as those for the most precise atomic clocks, allowing high measurement stabilities.

- Enable orders of magnitude sensitivity gain when in space
  - microgravity environment in space offers long interrogation times with atoms, resulting in orders of magnitude higher sensitivity compared to terrestrial operations.
Inertial Phase Shifts in Atom Interferometers

**Light-pulse atom interferometer accelerometer**

\[ \Delta \Phi = 2k a T^2 \]

- Independent of atom initial velocity.
- The laser wavenumber \( k \) is the only reference parameter.
- Sensitivity increases with \( T^2 \).

With over \( 10^6 \) atoms, the shot-noise limited SNR \( \sim 1000 \).

Per shot sensitivity = \( 2 \times 10^{-10} / T^2 \) m/s².
IIP Gravity Gradiometer: Instrument Overview

- A ground transportable gravity gradiometer with the system design comparable with microgravity operation in space
Fountain launch and detection.

The configuration for a space instrument will look like this without long fountain tubes.
Subsystem: Laser and Optics

Rack-mounted enclosures housing laser and optical system modules.

- Booster Laser Module, complete
- Repumper Laser module, complete
- High Frequency AOM module, x2 complete
- Slave module stack
- Laser module drawers
The optics and electronics rack contains all laser systems and electronics. Electronics has a combination of COTS, semi-custom parts, and in-house fabrications.
Example: Atom interferometer contrast loss limitation and optimization. The fringe contrast is limited by the atom cloud residual thermal expansion and size of the laser beam.

The plots show the expected and measured contrast of Raman fringes that impact the overall instrument performance.
**Instrument Analysis and Optimization**

- **Closed Loop Real-time Measurement**
  - Applicable for space-based missions
  - Addressed SNR-dominant sensitivity discrepancy
  - First-order insensitive to fluctuations in the atom interferometer contrast and offsets.

NEF: Normalized Excitation Fraction of atoms

Transportable gradiometer Instrument Sensor Rack
Instrument Sensitivity Evaluation

- 40E @ 1s (E: Eotvos, 10^{-9}/s)
- At the state-of-the-art reported in research lab experiments
Sensitivity Validation Measurements

- Five lead bricks (total 33kg) were placed near the apparatus.
- The instrument is sensitive to minute structural distortion due to additional mass.
- Disturbance to the instrument was minimized by supporting the mass from outside of the vibration isolation box.
Sensitivity Demonstration

- Observed clear modulated closed loop signal of 36.4 (1.0) E
- Agrees with the estimate of test mass gradient signal of 34.4 (4.0) E (Error due to 1 cm positioning precision.)

Modulation of 5 lead bricks (~30 kg)
Differential gravity gradient: 36.4 +/- 1.0 Eotvos
Microgravity Operation Evaluations

Generating stationary clouds

![Graph showing Signal (V) vs Time (ms) with peaks at different times for launched and released scenarios.]

- Releasing vs launching: Atoms released from the upper chamber rather than launched, detected in the lower chamber.
- No degradation in atom number by releasing.

Detecting stationary clouds

![Graph showing Allan Deviation (1/\text{SNR}) vs Averaging Time (s) with different return types.]

- Apex measurement: Atoms launched from the lower chamber, detected in the upper chamber when stationary at apex.
- No degradation in SNR with stationary clouds.
Current Status

• The JPL instrument is designed as a ground transportable gradiometer with an operation configuration compatible to space operation mode under microgravity condition.

• The instrument is capable of operating continuously with a sensitivity within a factor of four of the designed performance. Implementation to achieve the remaining factor is underway.

• The instrument sensitivity is current at the state of the art of atom-interferometer gravity gradiometers demonstrated in research labs.

• We are actively investigating and developing a technology infusion path to space missions for Earth Science gravity measurements.