# An Atomic Gravity Gradiometer for Earth Gravity Mapping and Monitoring Measurements

**IIP-10-0009**

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Many others have been on the task and made significant contributions.

# Gravity – Part of Whole Earth Science Measurements

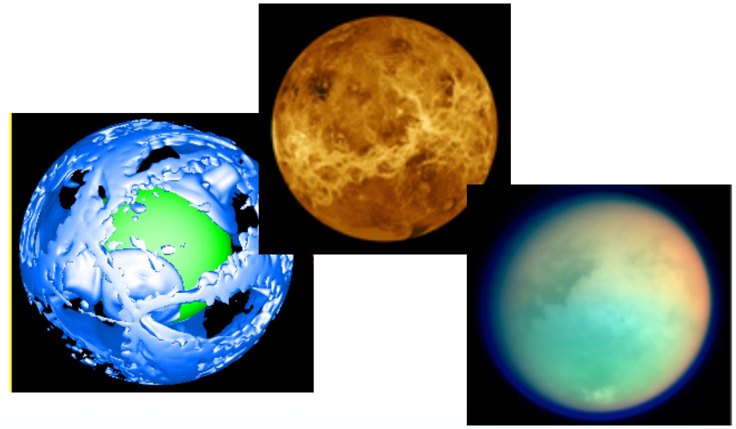
Geodesy

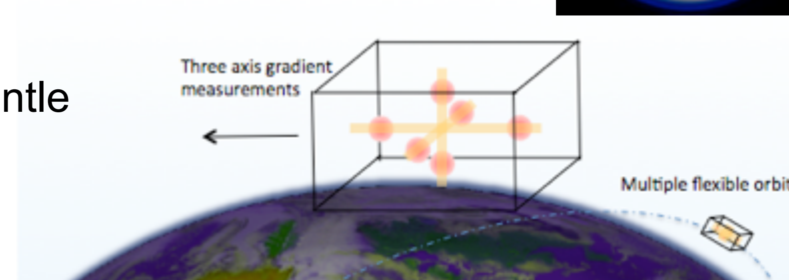
Earth and Planetary Interiors

- Lithospheric thickness, composition
- Lateral mantle density heterogeneity
- Deep interior studies
- Translational oscillation between core/mantle

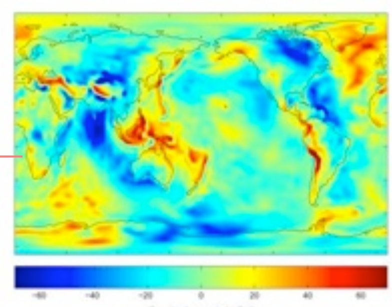
Earth and Planetary Climate Effects

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






N. Yu, J. M. Kohel, L. Romans, and L. Maleki, "Quantum Gravity Gradiometer Sensor for Earth Science Applications," *NASA Earth Science and Technology Conference* 2002. Paper B3P5. Pasadena, California (June 2002).





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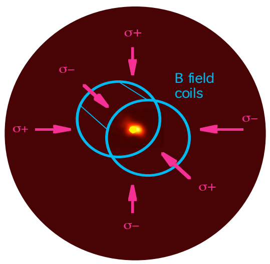
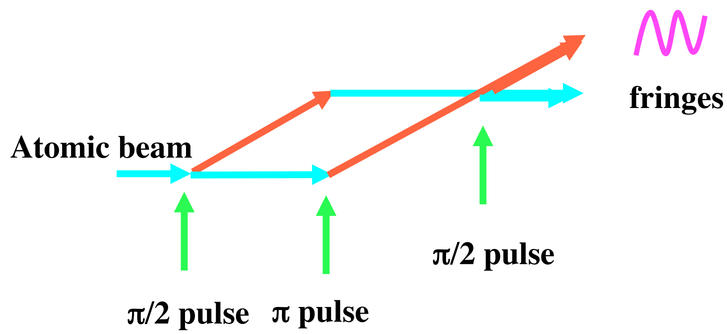
# Why Atomic Sensors?

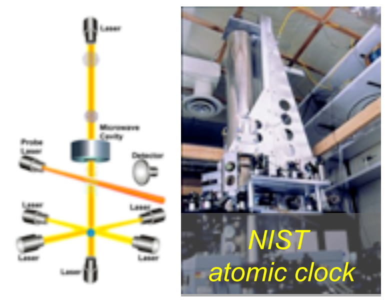
**Freefall test mass** **+** **Displacement Detection** **+** **Atomic system stability**




*Laser-cooled Cs atom cloud at μK*




*atom-wave interferometer (laser-based atom optics)*




*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 trough 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 orders of magnitude higher sensitivity compared terrestrial operations.*

# Inertial Phase Shifts in Atom Interferometers

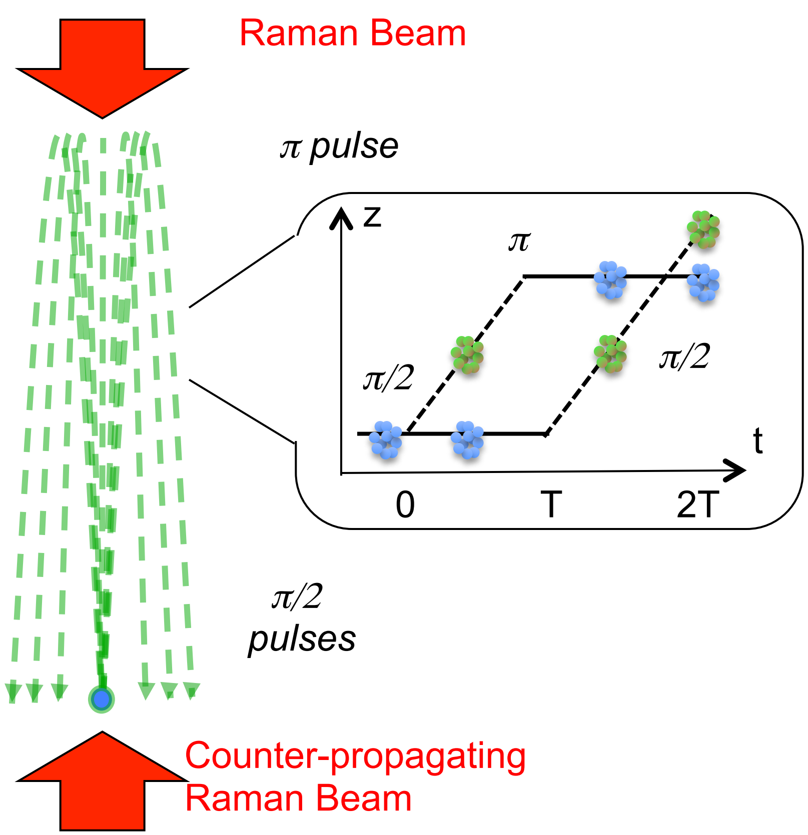
<u>Light-pulse atom interferometer accelerometer</u>

$$\Delta\Phi = 2\boldsymbol{k}\ \boldsymbol{a}\ \boldsymbol{T}^2$$

- Independent of atom initial velocity.
- The laser wavenumber $\boldsymbol{k}$ is the only reference parameter.
- Sensitivity increases with $T^2$.

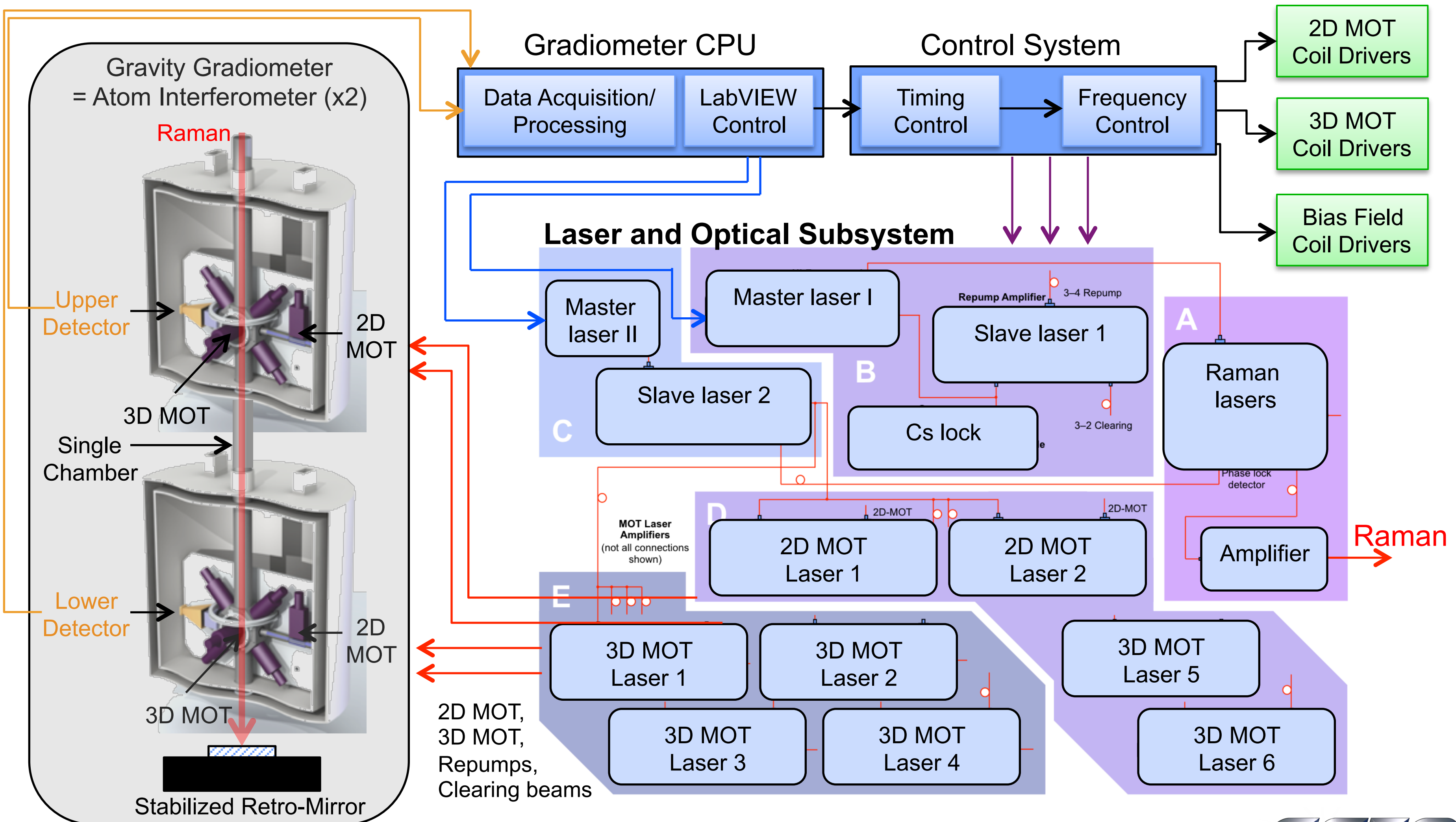
With over $10^6$ atoms, the shot-noise limited SNR ~ 1000.
Per shot sensitivity = $2 \times 10^{-10}/T^2$ m/s$^2$.

*<u>Atomic fountain on ground</u>*

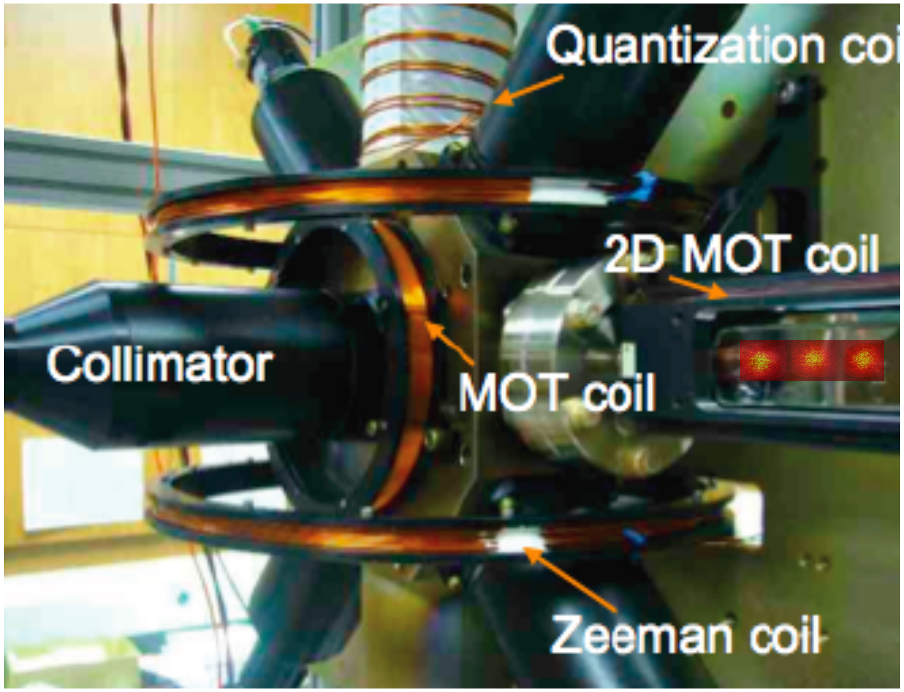


# IIP Gravity Gradiometer: Instrument Overview

- *A ground transportable gravity gradiometer with the system design comparable with microgravity operation in space*

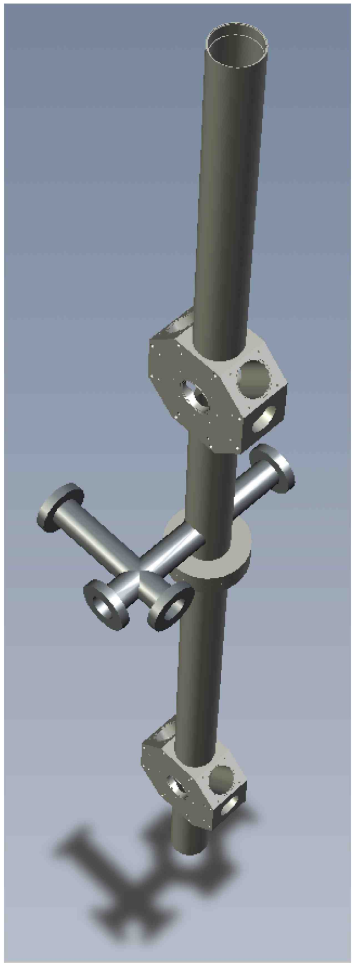


# Subsystem: Atomic Physics Package




Fountain launch and detection.

The configuration for a space instrument will look like this without long fountain tubes.

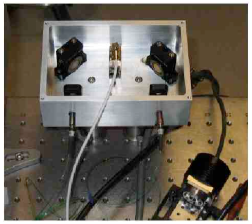


Single Vacuum Chamber

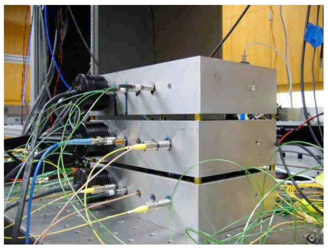
# Subsystem: Laser and Optics

Booster Laser Module, complete

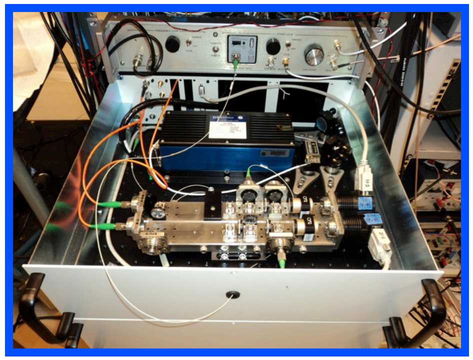
Repumper Laser module, complete

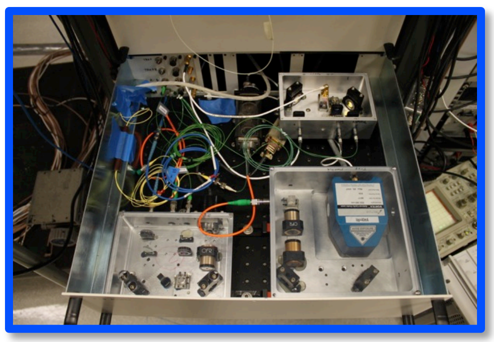


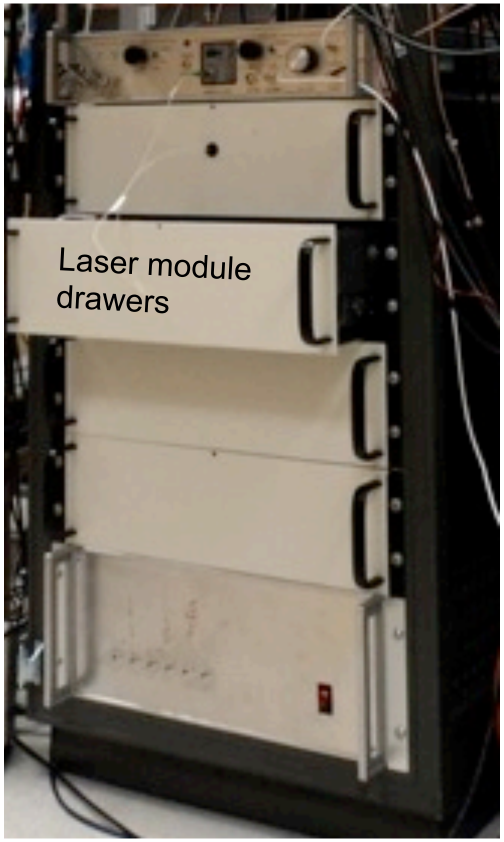
High Frequency AOM
module, x2 complete



Slave module stack

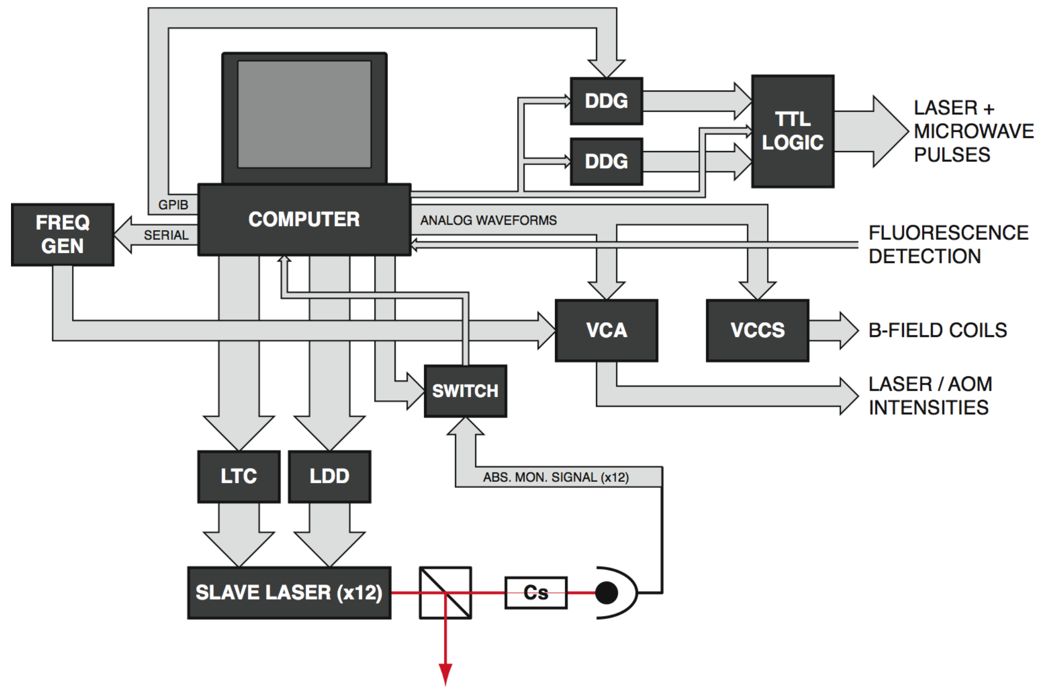







Rack-mounted enclosures housing laser and optical system modules.

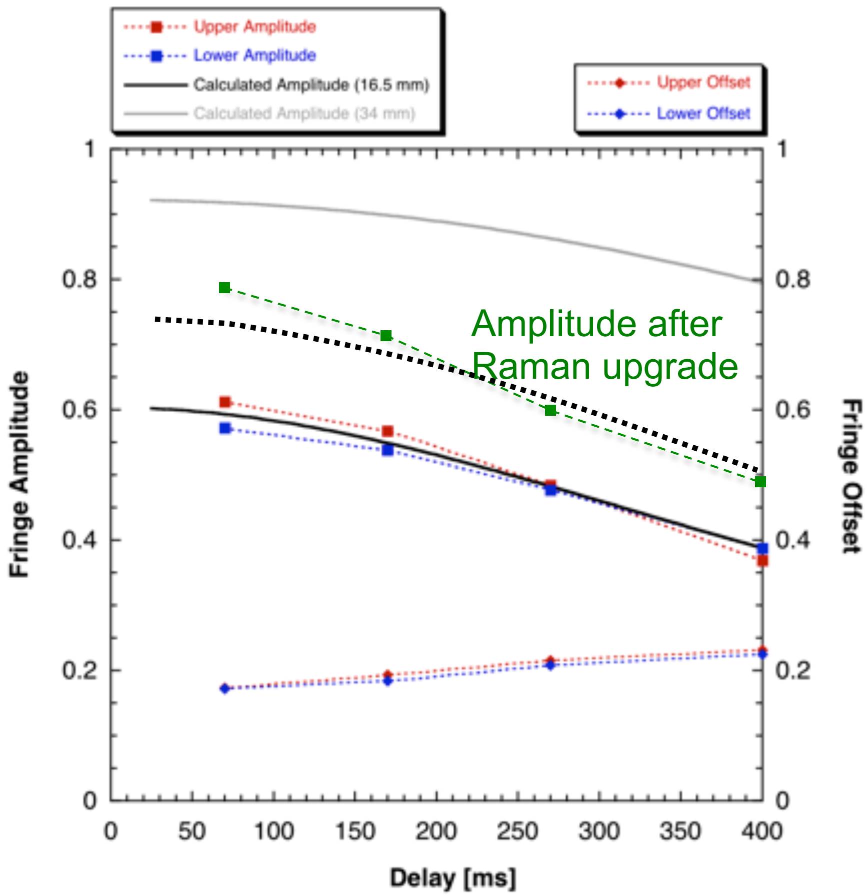
# Subsystem: Electronics and Control




The optics and electronics rack contains all laser systems and electronics. Electronics has a combination of COTS, semi-custom parts, and in-house fabrications.

# Instrument Analysis and Optimization

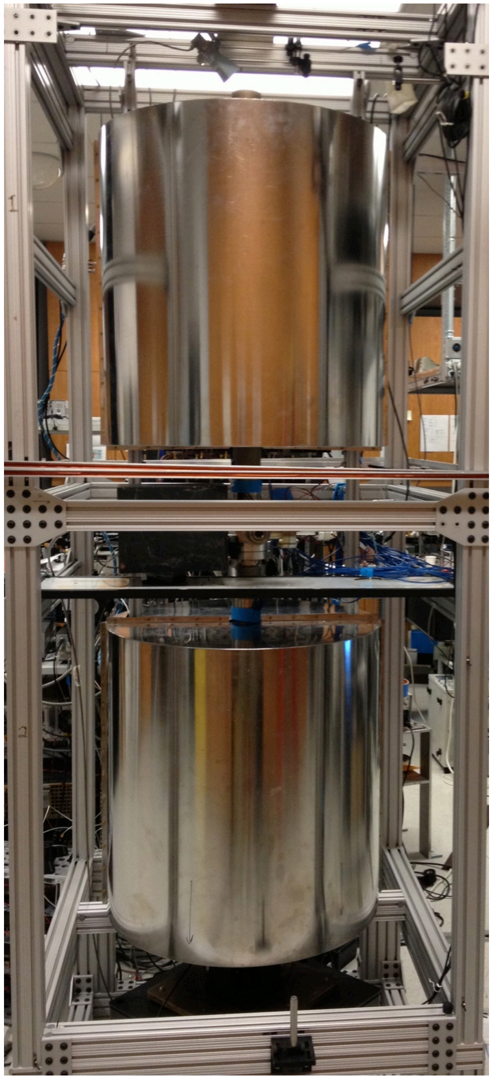
Example: Atom interferometer contrast loss limitation and optimization. The fringe contrast is limited by the atom cloud residual thermal expansion and size of the laser beam.



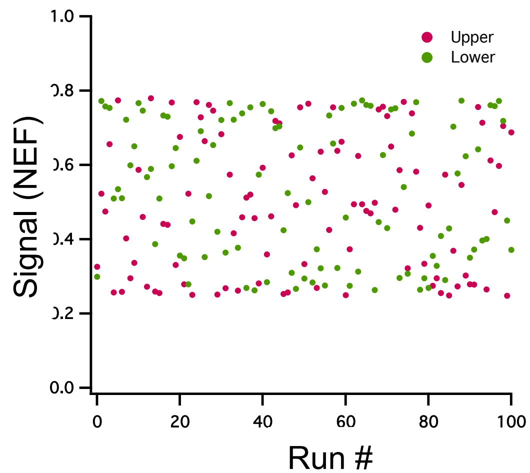

Added optical amplifier for a larger sized optical beam.

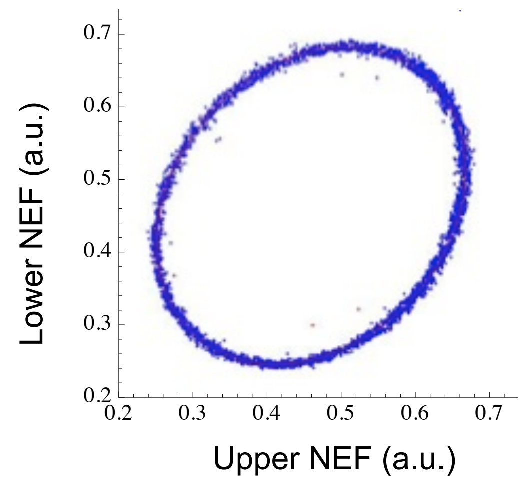
The plots show the expected and measured contrast of Raman fringes that impact the overall instrument performance.

# Instrument Analysis and Optimization

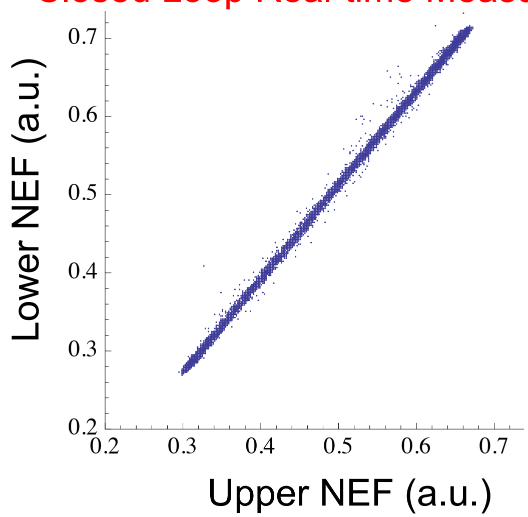


Transportable gradiometer
Instrument Sensor Rack



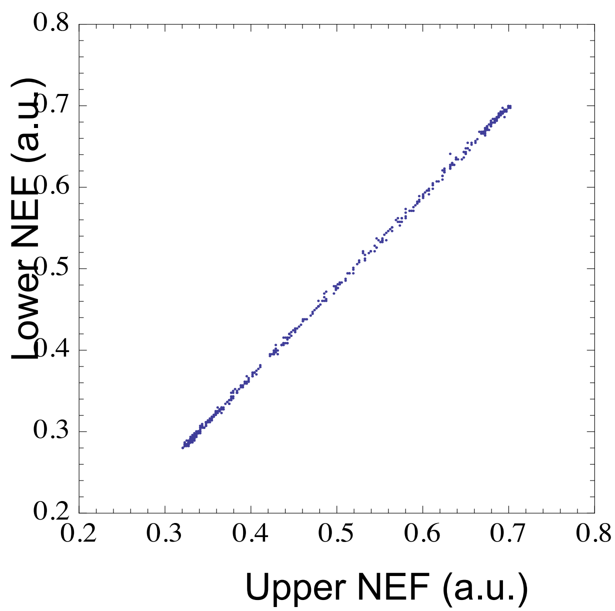

Closed Loop Real-time Measurement

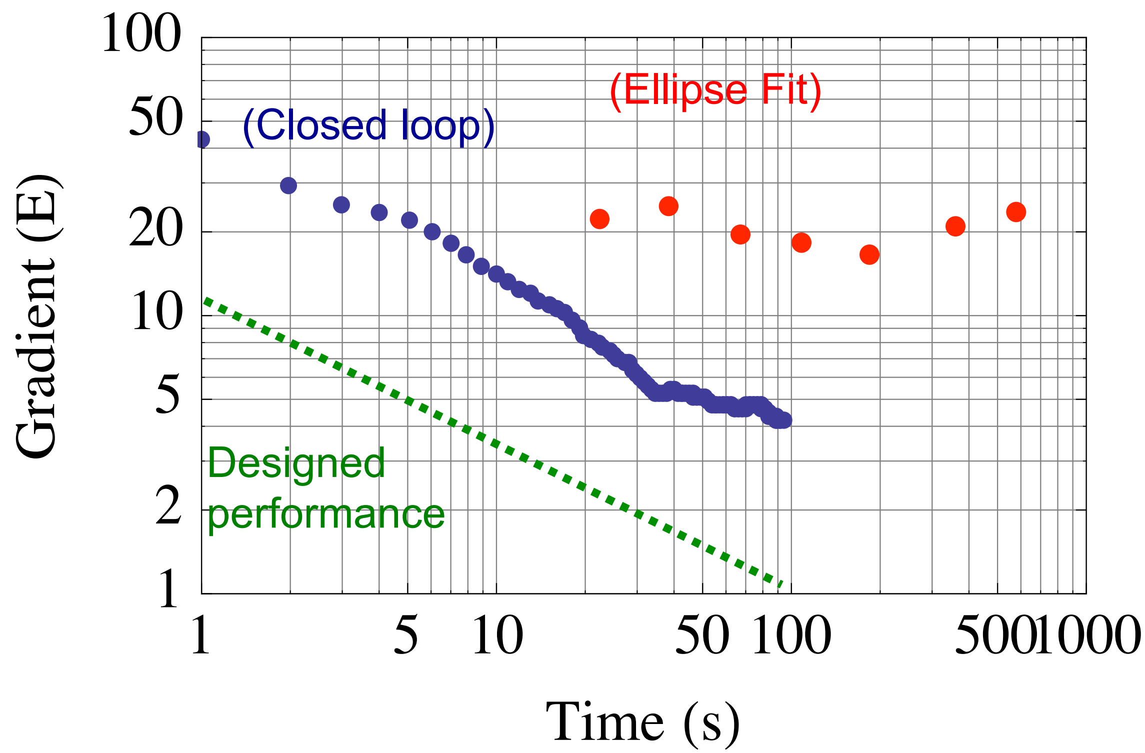



NEF: Normalized Excitation Fraction of atoms

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

# Instrument Sensitivity Evaluation

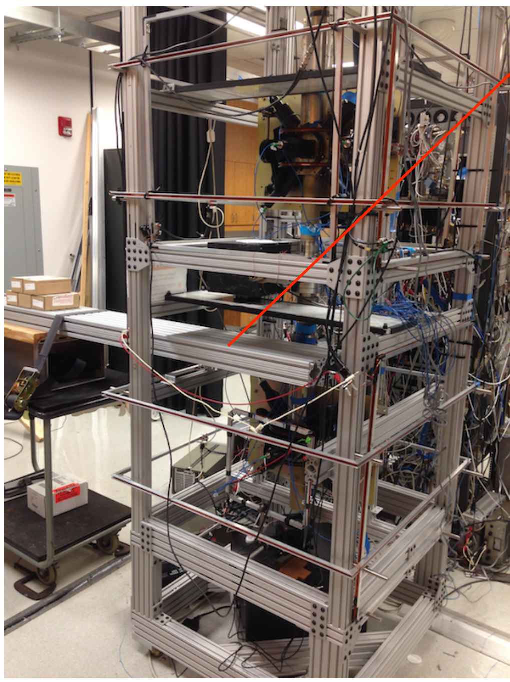


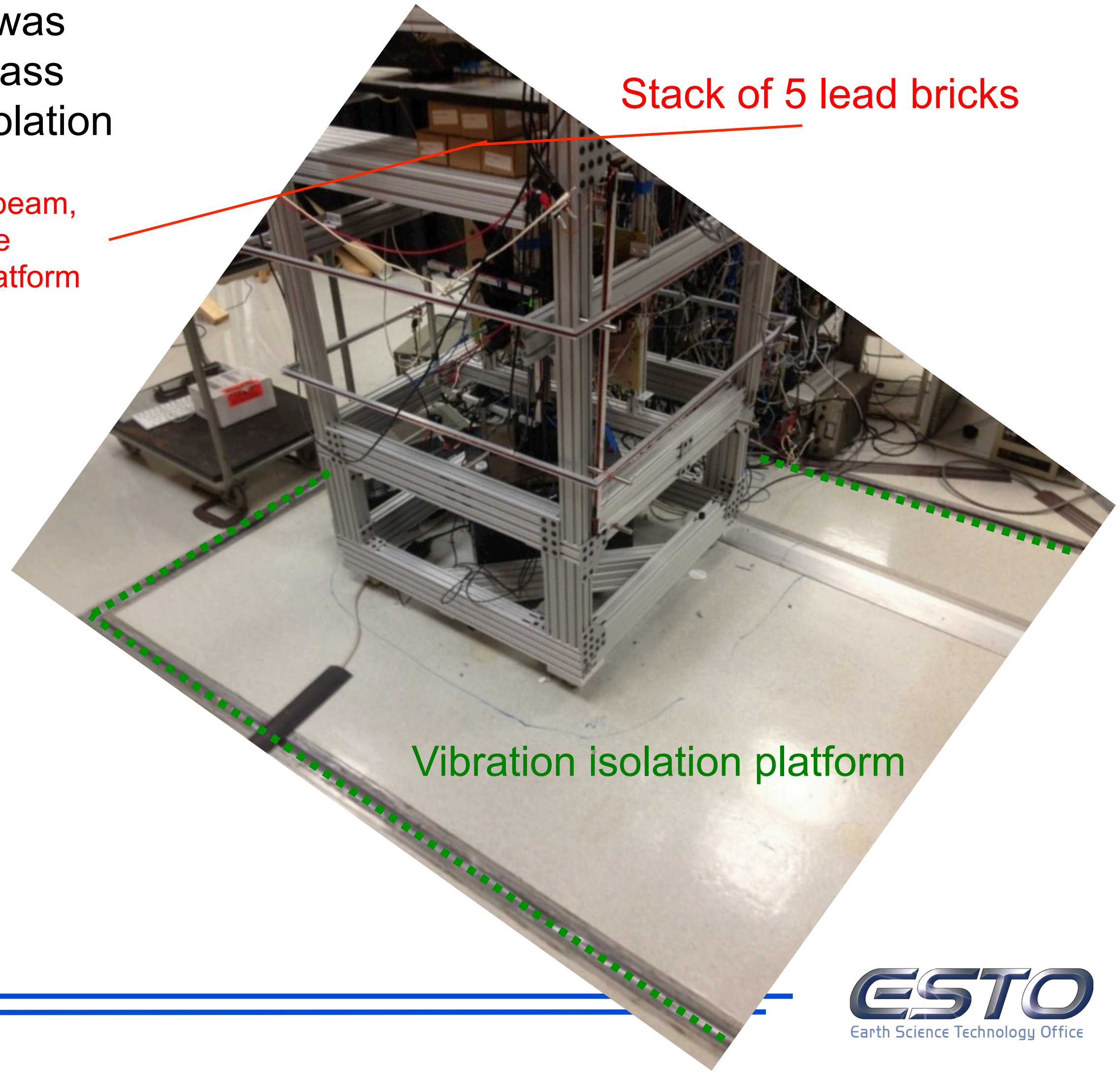




- 40E @ 1s (E: Eotvos, $10^{-9}/s$)
- At the state-of-the-art reported in research lab experiments

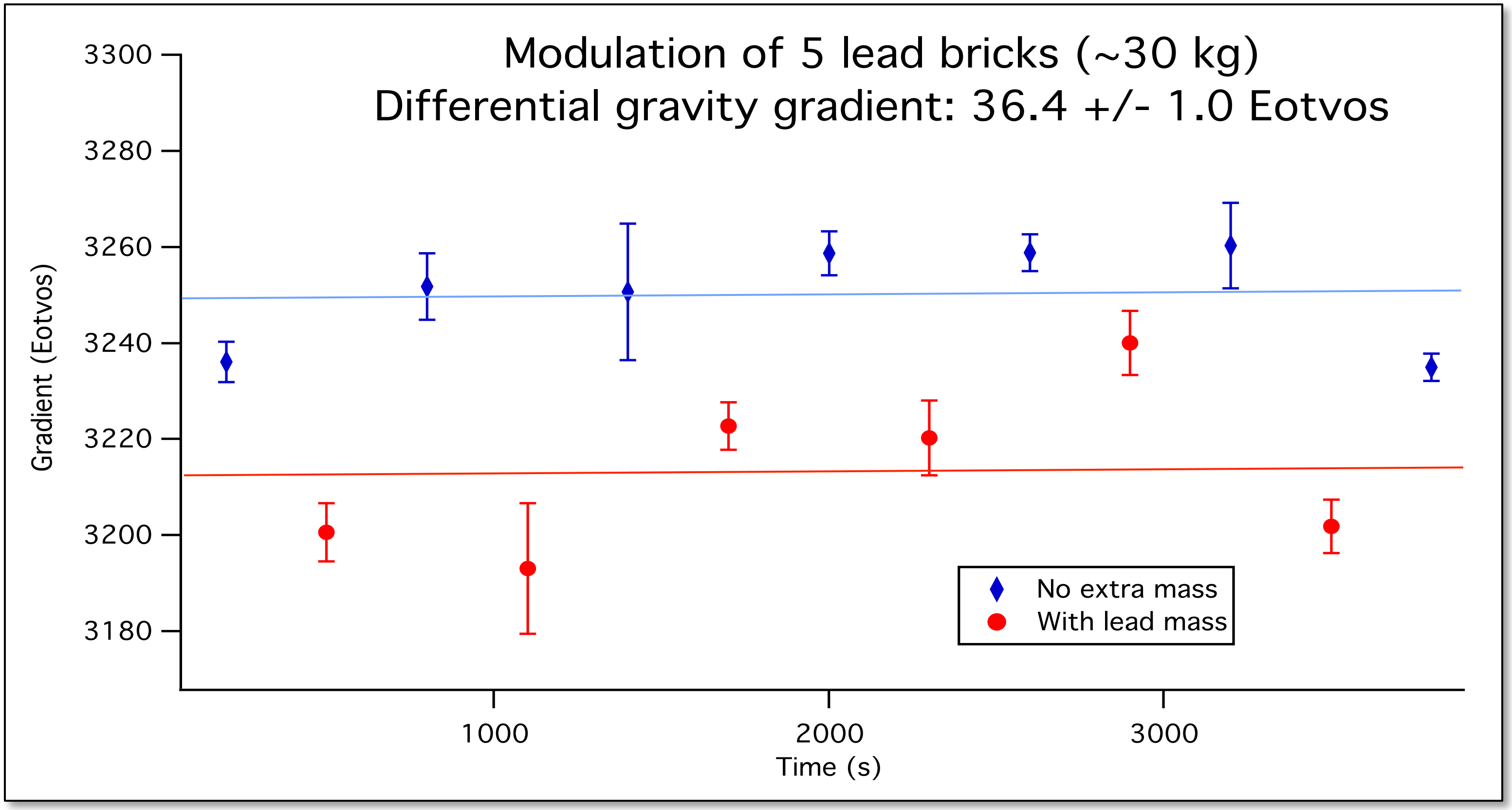
# Sensitivity Validation Measurements

- 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



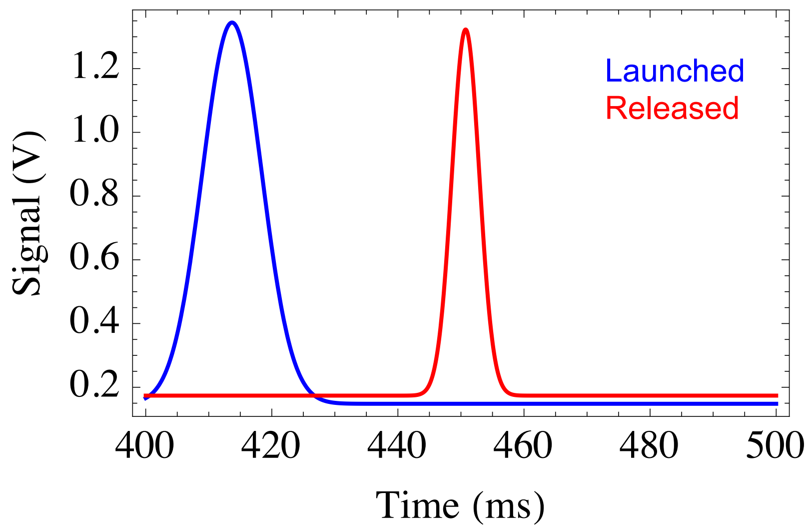
# Sensitivity Demonstration




- 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.)

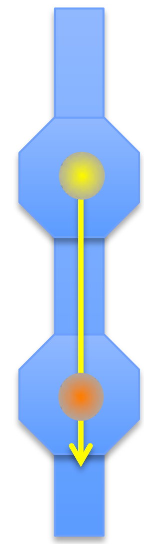
# Microgravity Operation Evaluations

Generating stationary clouds

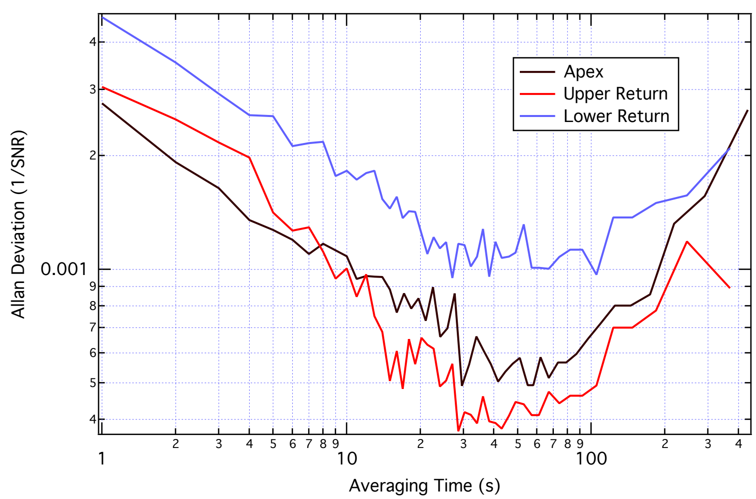



Releasing vs launching: Atoms released from the upper chamber rather than launched, detected in the lower chamber.

No degradation in atom number by releasing.

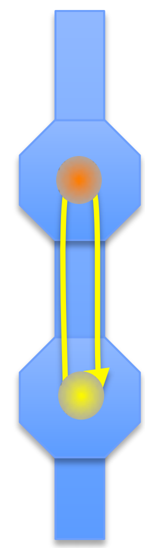


Detecting stationary clouds




Apex measurement: Atoms launched from the lower chamber, detected in the upper chamber when stationary at apex.

No degradation in SNR with stationary clouds.



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# 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.