Development of a Transportable Quantum Gravity Gradiometer for Gravity Field Mapping

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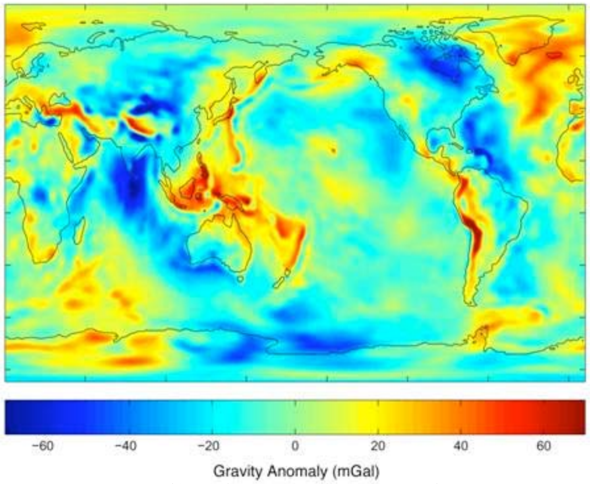
Global Gravity Field Measurements in Space

Earth Observatory for Climate Effects

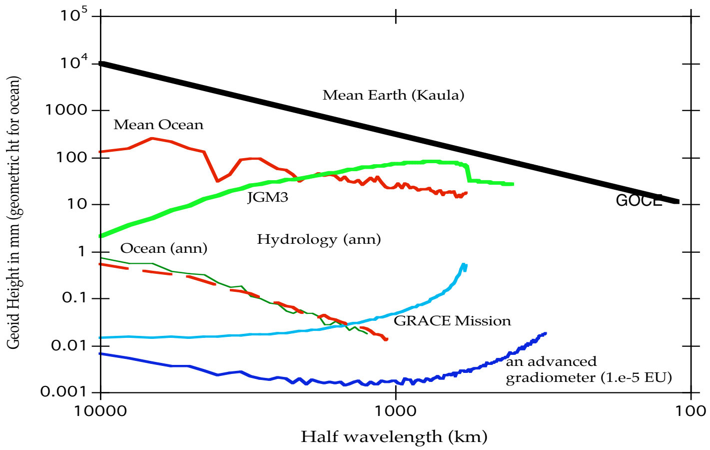
- Surface and ground water storage
- Oceanic circulation
- Tectonic and glacial movements
- Tidal variations
- Earthquake monitoring



Gravity anomalies from 111 days of GRACE data

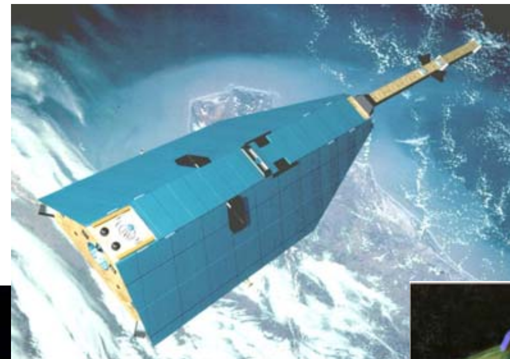
Solid Earth and planetary interior modeling

- Lithospheric thickness, composition
- Lateral mantle density heterogeneity
- Deep interior studies
- Oscillation between core and mantle

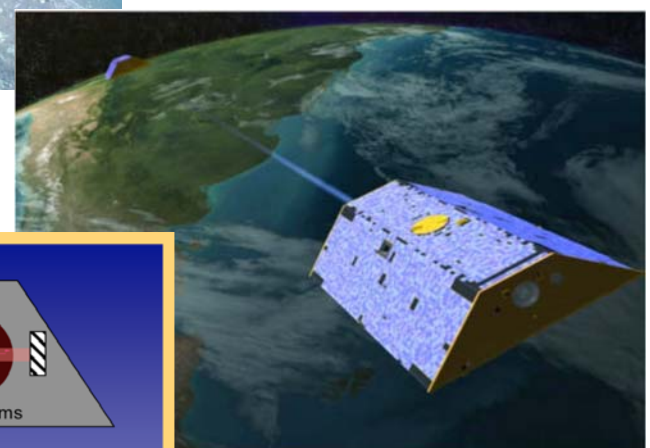


Advanced Gravity Missions

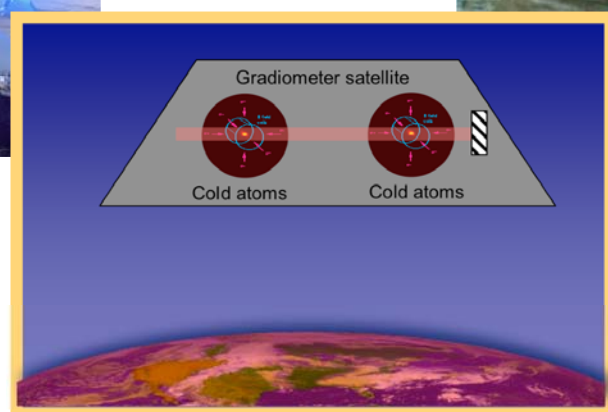
GPS-CHAMP high-low satellite-to-satellite and ground-based laser tracking



GRACE uses low-low satellite-to-satellite microwave tracking and ranging for long (~500 km) wavelength and time variation



GOCE uses 3-axis accelerometers for high resolution (100 km) gradiometry

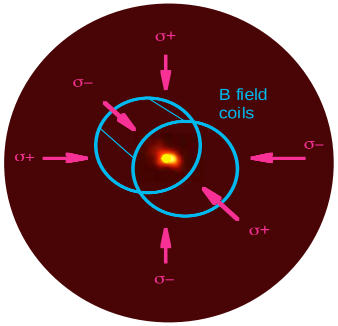


Quantum atom-wave gravity gradiometer uses atoms as drag-free test masses for high spatial resolution and high stability for monitoring temporal variations

Technology Overview

TECHNOLOGY

Laser-cooled atoms are used as freefall test masses. The gravitational acceleration on atoms is measured by atom-wave interferometry. The fundamental concept behind atom interferometry is the quantum mechanical particle-wave duality. One can exploit the wave-like nature of atoms to construct an atom interferometer based on matter waves analogous to laser interferometers.



A cloud of laser trapped and cooled Cs atoms in magneto-optical trap (MOT), with cloud fluorescence in false color.

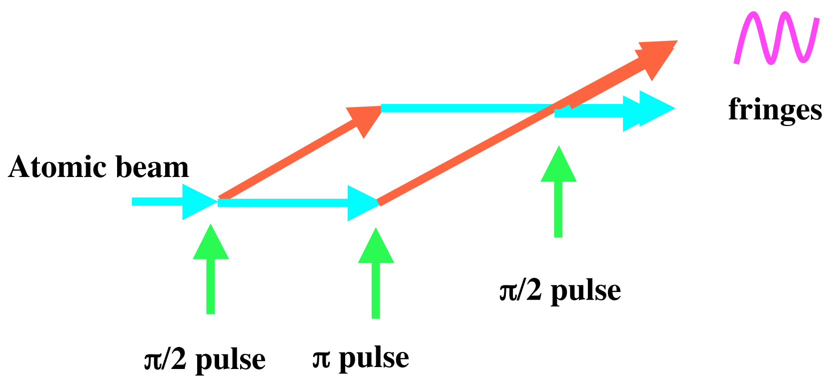


Illustration of Mach-Zehnder atom-wave interferometer, which is implemented by a sequence of laser pulses.

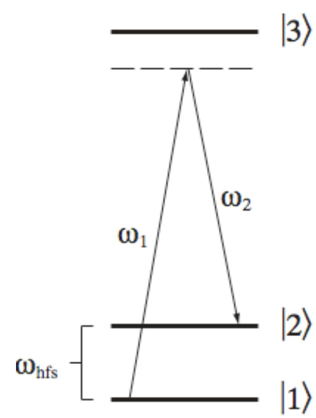
Laser Cooling and Atom Interferometer

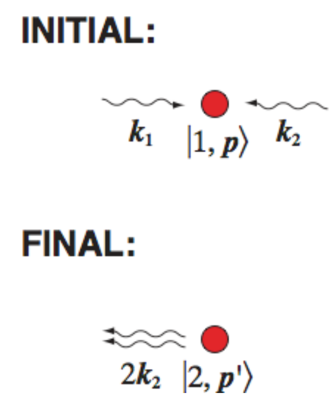
Light-Pulse Atom Interferometry

Stimulated Raman transitions modify an atom's momentum by

$$\Delta \mathbf{p} = h\mathbf{k}_{\mathbf{eff}}$$

where $\mathbf{k}_{\mathbf{eff}} \equiv \mathbf{k}_1 - \mathbf{k}_2 \approx 2\mathbf{k}_1$ for velocity-sensitive transitions.





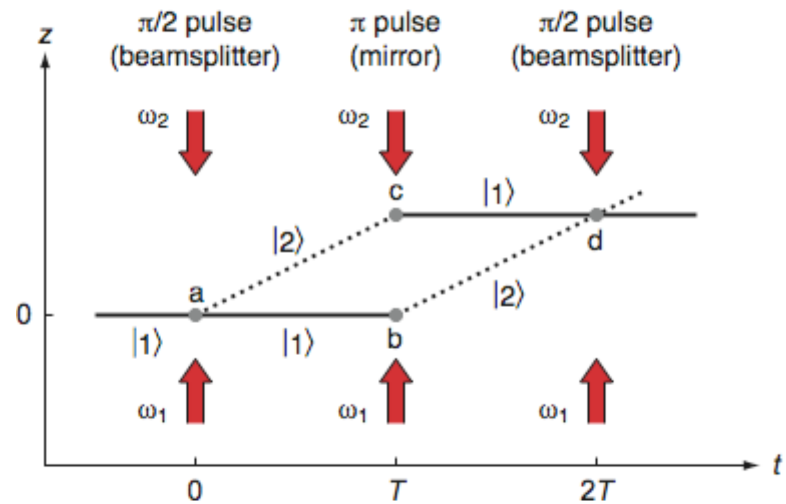
The atom interferometer is realized by a three-pulse ($\pi/2$–π–$\pi/2$) Raman sequence.

The transition probability resulting from this sequence is given by

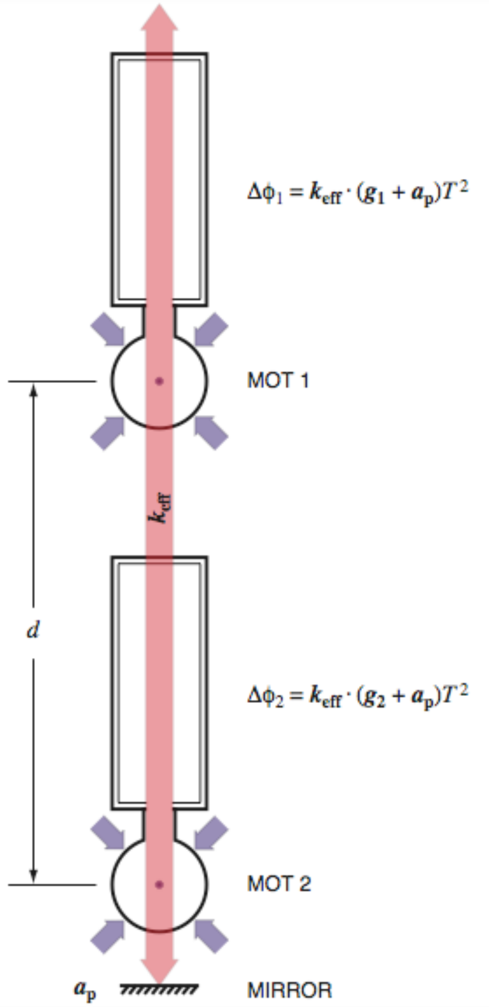
$$P = [1 - \cos(\Delta\phi)]/2$$

and the phase shift $\Delta\phi$ is related to the local acceleration $\mathbf{a}$ by $\Delta\phi = \mathbf{k}_{\mathbf{eff}} \cdot \mathbf{a}\, T^2$, where T is the time between pulses.

This phase shift is measured by monitoring the relative populations following this pulse sequence.



Gravity Gradiometry with Atom Interferometers



The phase shift is measured simultaneously in two atom interferometers using *common laser beams* to drive the Raman transitions.

The phase shift in each interferometer is given by

$$\Delta\phi_i = \mathbf{k_{eff}} \cdot (\mathbf{g}_i + \mathbf{a_p})T^2$$

where $\mathbf{a_p}$ is the acceleration of the mirror platform and $\mathbf{g}_i$ is the average gravitational acceleration at the position of the i^{th} atom interferometer.

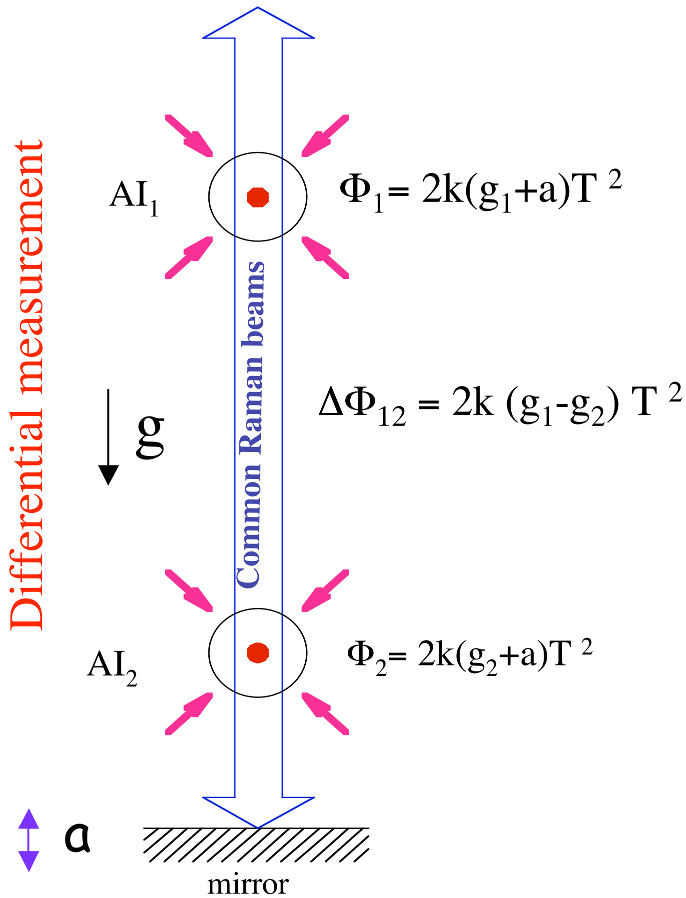
The linear gravity gradient is determined from the difference in the measured phase shifts in the two interferometers separated by a distance d:

$$\Delta g/\Delta z = (\Delta\phi_1 - \Delta\phi_2)/(k_{eff}\, T^2\, d)$$

and common-mode platform vibrations $\mathbf{a_p}$ are effectively cancelled.

$\Rightarrow$ *Measurement possible on moving platforms …*

Gradient Measurement Sensitivity



gravity gradient = $(g_1-g_2)/L = \Delta\Phi_{12}/2kLT^2$

Single satellite:
(L=10m) 5×10^{-4} EU/Hz$^{1/2}$

Long baseline:
(100 m) 5×10^{-5}EU/Hz$^{1/2}$

Satellite formation:
(200km): 3×10^{-8}EU/Hz$^{1/2}$

Gravity gradient unit, *EU=10^{-9} (m/s^2)/m.*
(One person, 10 meter away, about 1 EU gravity field gradient)

Operation in Microgravity Environments

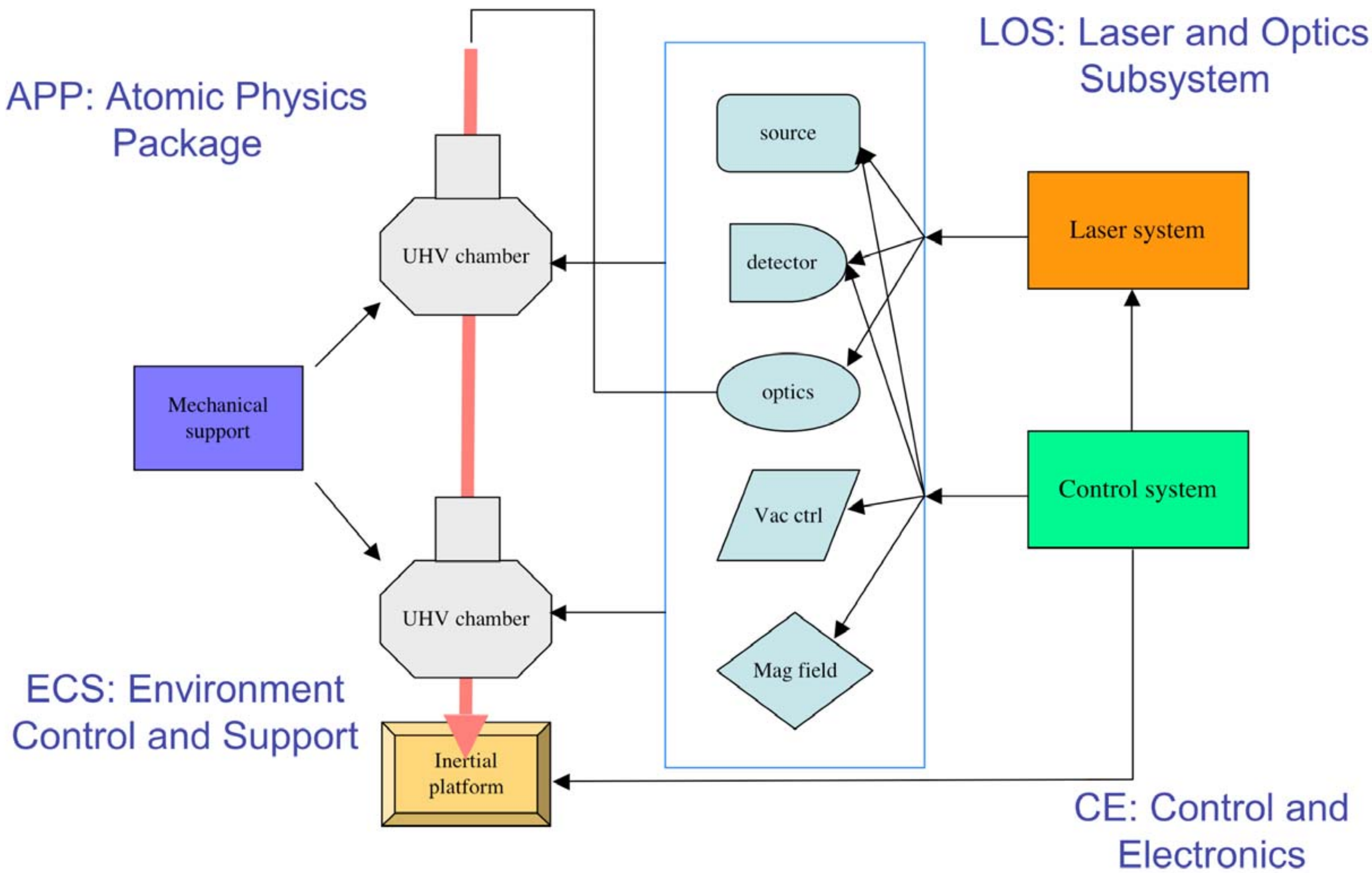
Advantages in microgravity

- Enhancement of measurement sensitivity due to longer interaction times
  - Sensitivity increases as T^2, in contrast to Fourier transform-limited measurements
  - Measurement of 3-D gravity fields feasible
- Atomic system stability facilitates temporal monitoring and time-averaged measurements

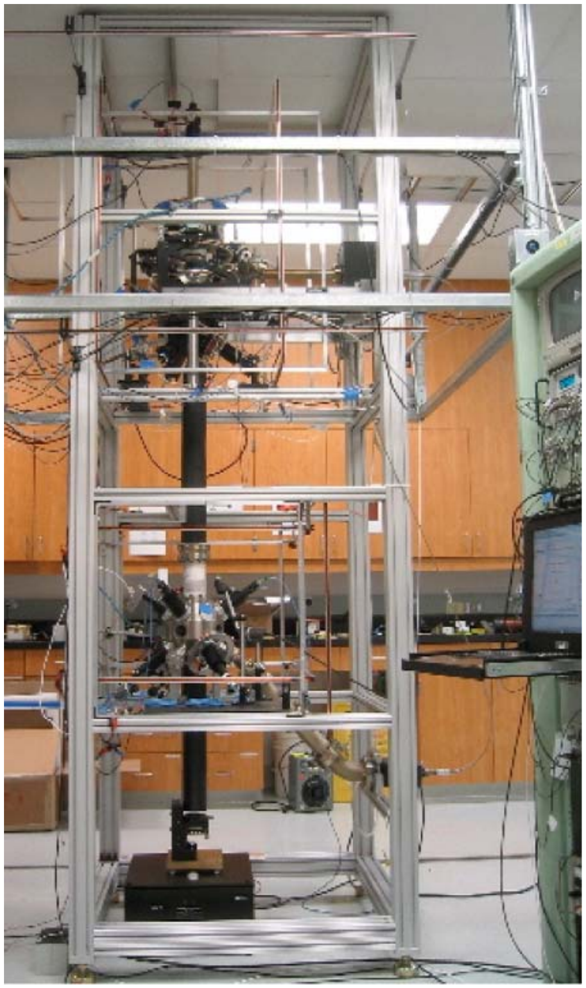
Operational Advantages

- All-optical manipulation of atoms, minimal mechanical moving parts
- Laser cooling, no cryogens
- Interferometric measurements are referenced to atomic transitions, long-term stability
- In situ self-calibration possible

System Overview Diagram

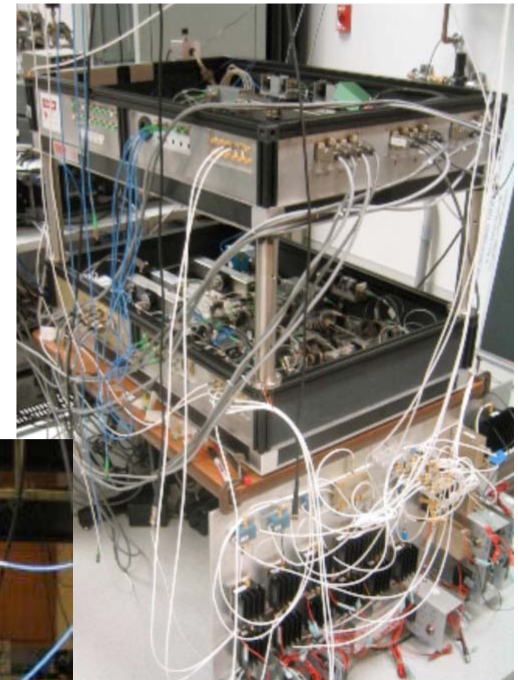


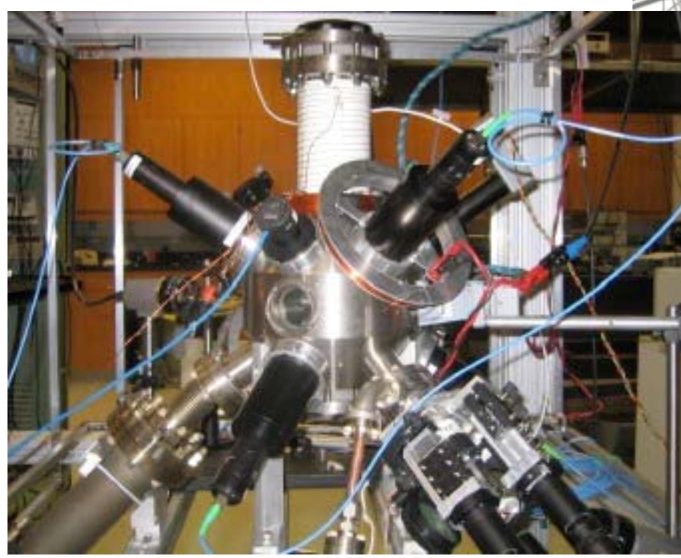
Laboratory Demonstration



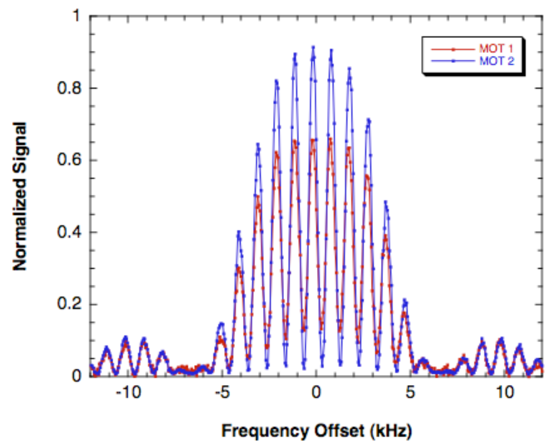
Dual atom interferometer-based **gravity gradiometer** in the laboratory (*left*), close-up of the **atomic physics package** APP-2 (*below*), and modular **laser and optics system** (*right*).

(2005)





Accelerometer and Gradiometer Sensitivities

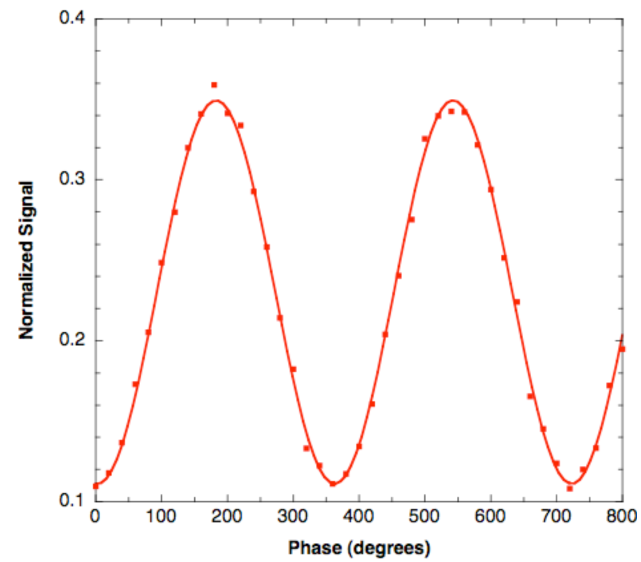


Ramsey interference spectra observed in the dual interferometers using two Doppler-insensitive Raman $\pi/2$ pulses separated by 1 ms.

Accelerometer performance

Demonstrated atom interferometer fringes for interaction times up to $2T = 200$ ms, limited by environmental noise on passively-isolated reference platform.

Demonstrated an acceleration measurement sensitivity of ~ $\mathbf{3 \times 10^{-9}}$ ***g*** $\mathbf{Hz^{-1/2}}$ in a single interferometer.

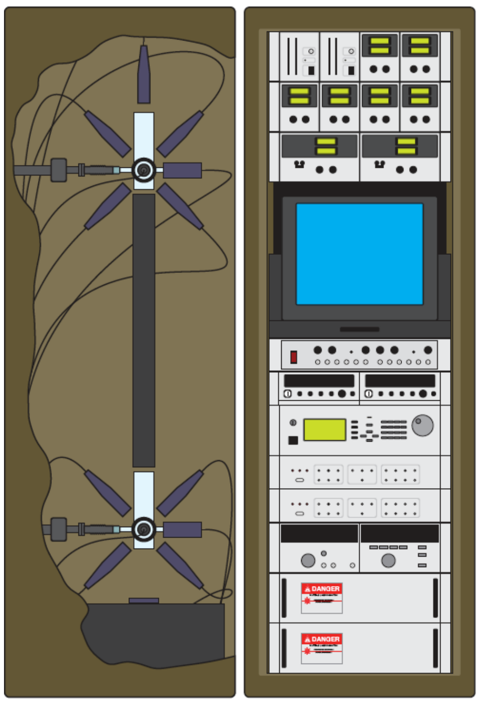


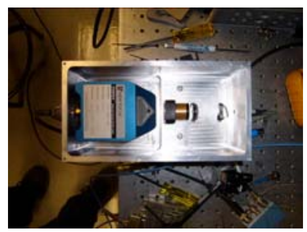
Gradiometer sensitivity

For the baseline separation of $d = 1.4$ m, we infer a gradiometer sensitivity of $\mathbf{34\ E\ Hz^{-1/2}}$ at $T = 100$ ms ($5\ \mathrm{E\ Hz^{-1/2}}$ with 10 m baseline) for our system.

Transportable Instrument Prototype

To advance the AI technology towards a space application by developing a portable gravity gradiometer prototype with improved sensitivity of 2 $E/(Hz)^{1/2}$.

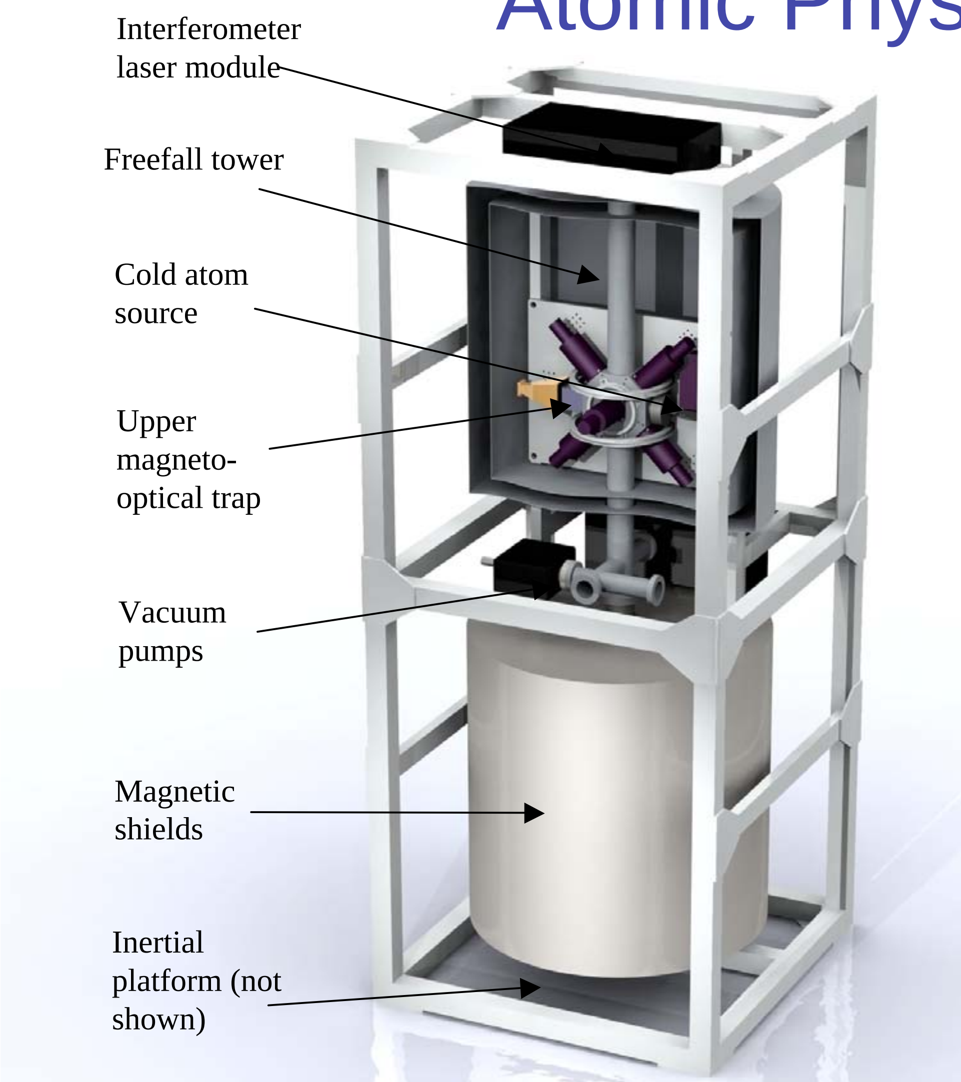


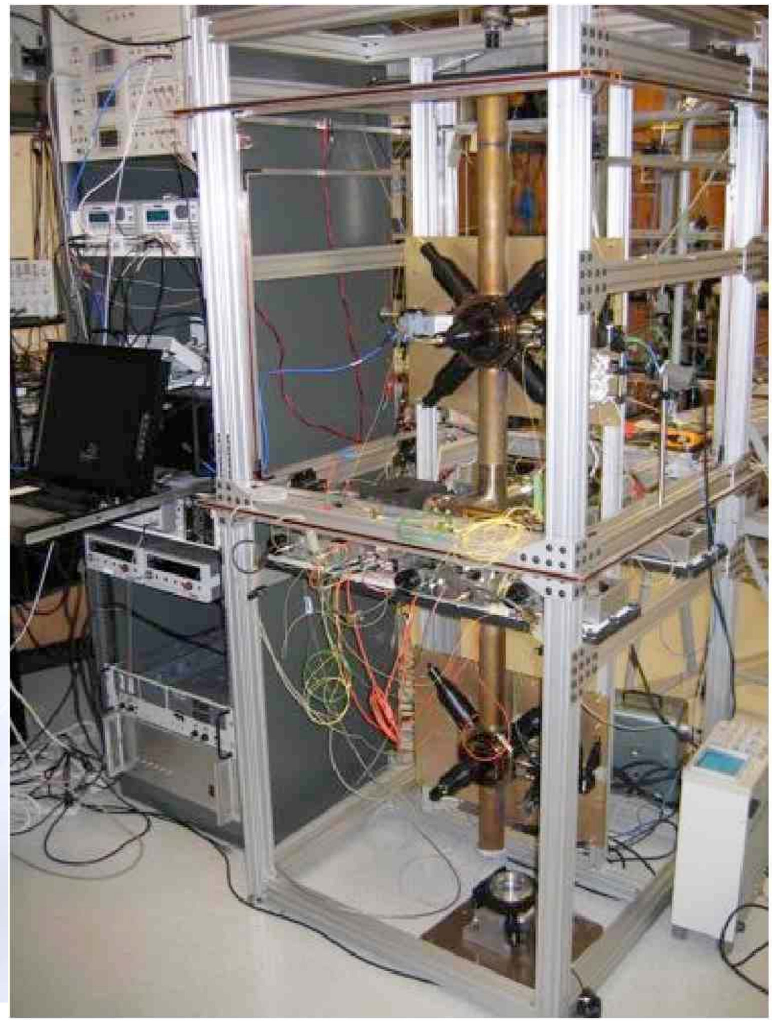


Left: Conceptual illustration of IIP instrument; Top: Laser and optics subsystem; Bottom: atomic physics package design concept drawing.

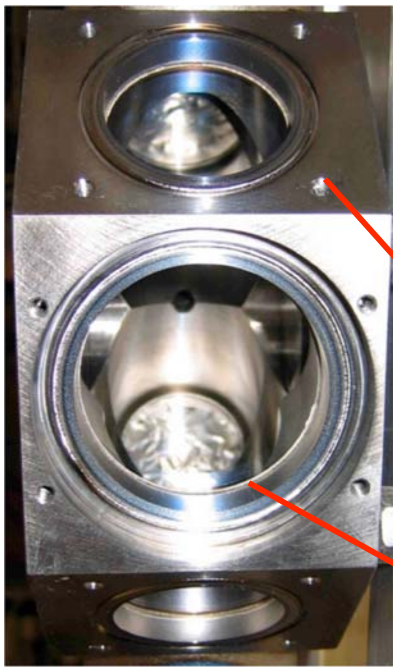
Possible mobile platforms

Atomic Physics Package





High Quality Sapphire Optical Windows



High quality MOT windows with flatness <λ/5 at 850 nm, to yield cold, 2uk, molasses and improved fringe contrast

Large Raman Beam windows: 2" diameter and <λ/10 flatness at 850nm, to minimize wavefront distortion of Raman Interference Beams, and yield improved fringe contrast

Large Solid Angle Detection window: inset for optimal solid angle, yielding 4x improvement in collection efficiency over previous system, and increased SNR

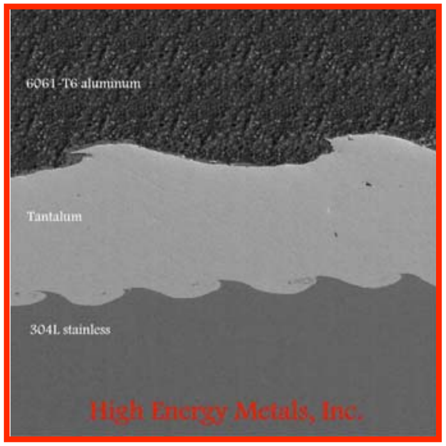
Titanium Chamber with 316 SS Flanges

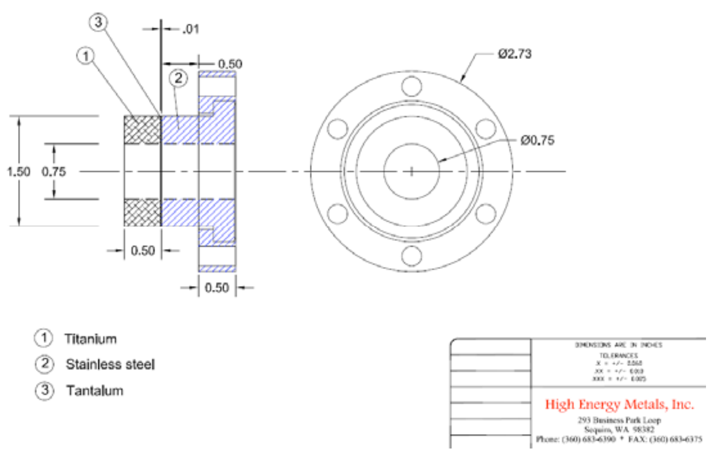
•Opted for Stainless Steel flanges to use with copper gasket seals, to allow for high bake-out temperatures, >400C, and minimize risks for leak failures

• Using Stainless Steel 316, non-magnetic, better than SS 304

•Bi-metallic joints for transition from Titanium chamber to SS 316

•Explosion bonds from High Energy Metals, Inc. with Tantalum interlayer to minimize diffusion between dissimilar metals (UHV application)

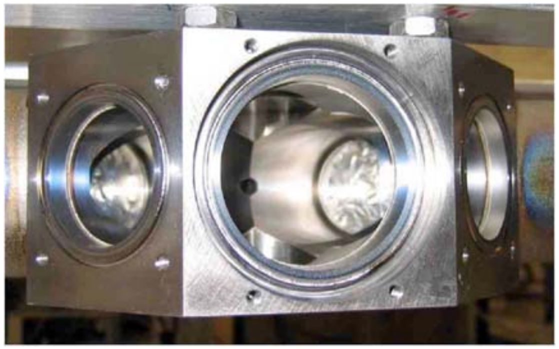




Close-up Views of Completed Chamber

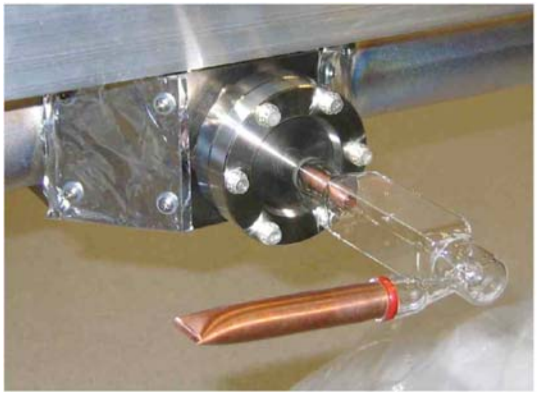
Getter pump

Explosion bonded Ti to Stainless



Loading chamber

2D MOT cell

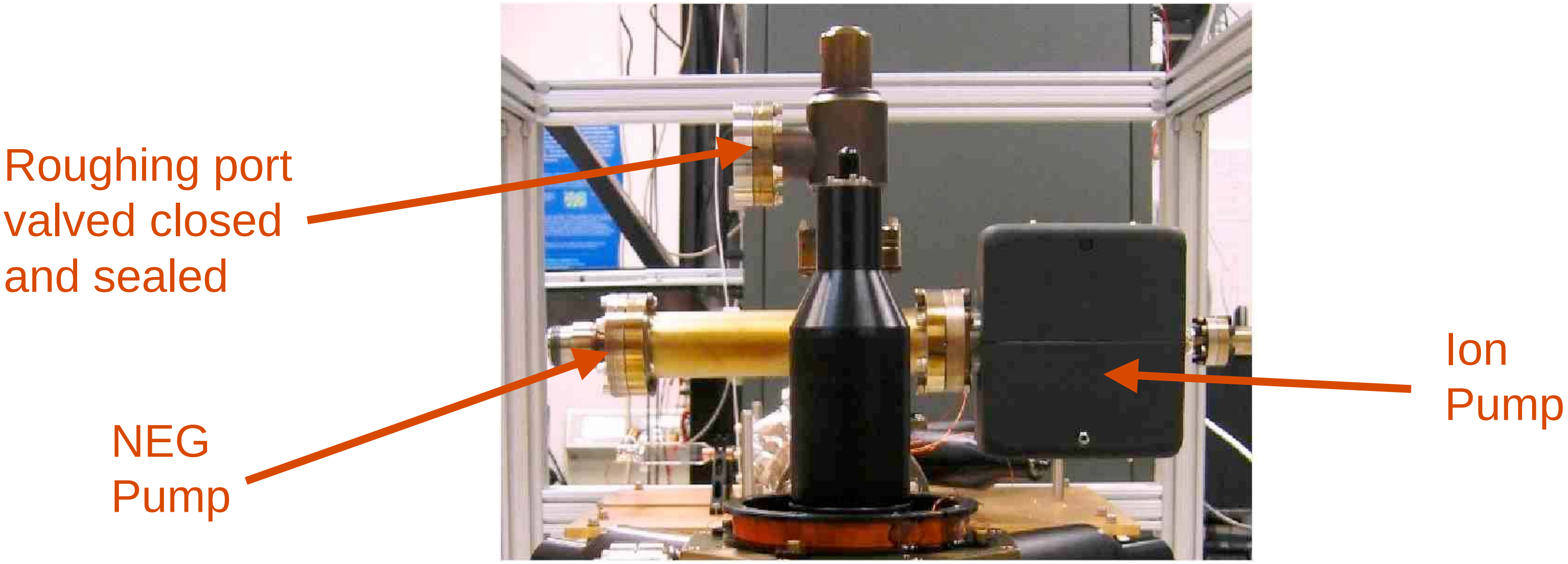


Raman window

Background Pressure in Vacuum Chamber

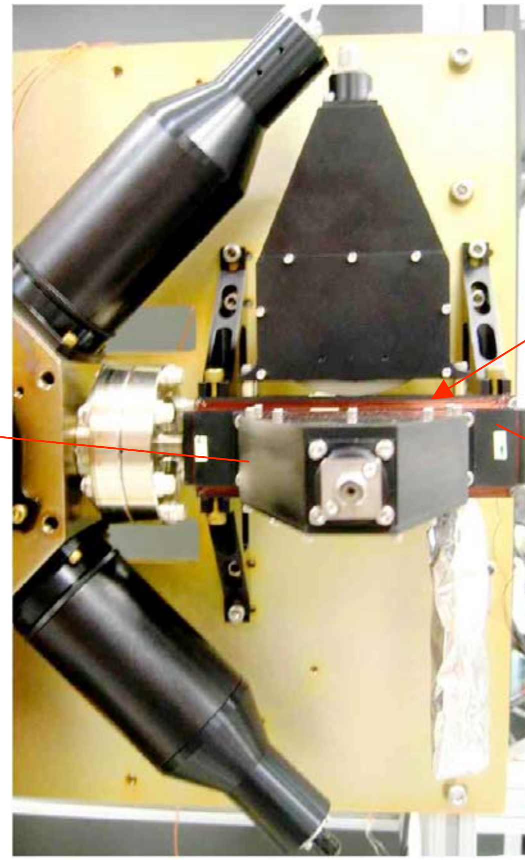
- Ultra high vacuum <10^{-10} torr achieved with ion pump operating
- Argon outgas rate <7×10^{-11} torr-l/sec, requiring continuous ion Pump operation

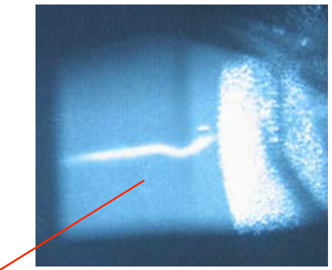
(Argon is likely due to the titanium TIG welds that were flooded using inert Argon gas, not noticeable in previous known systems.)



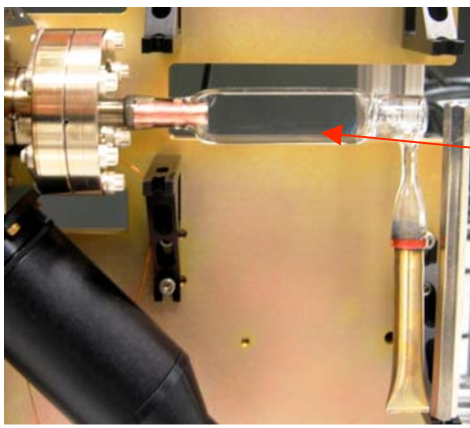
2D MOT Cs Source

2D MOT with magnetic coil form and collimators





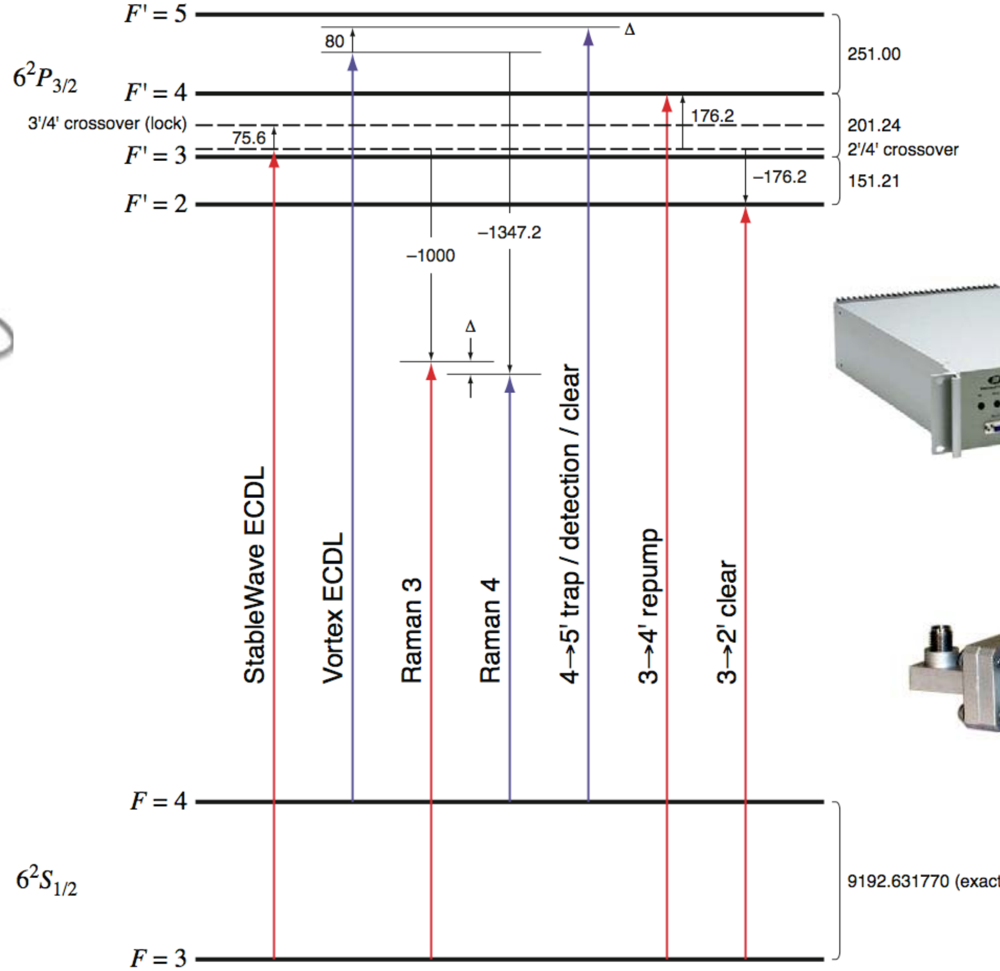
Cold atom beam of 2D MOT

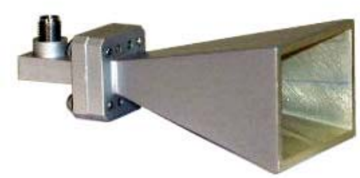


2D MOT Cs Source Glass Cell

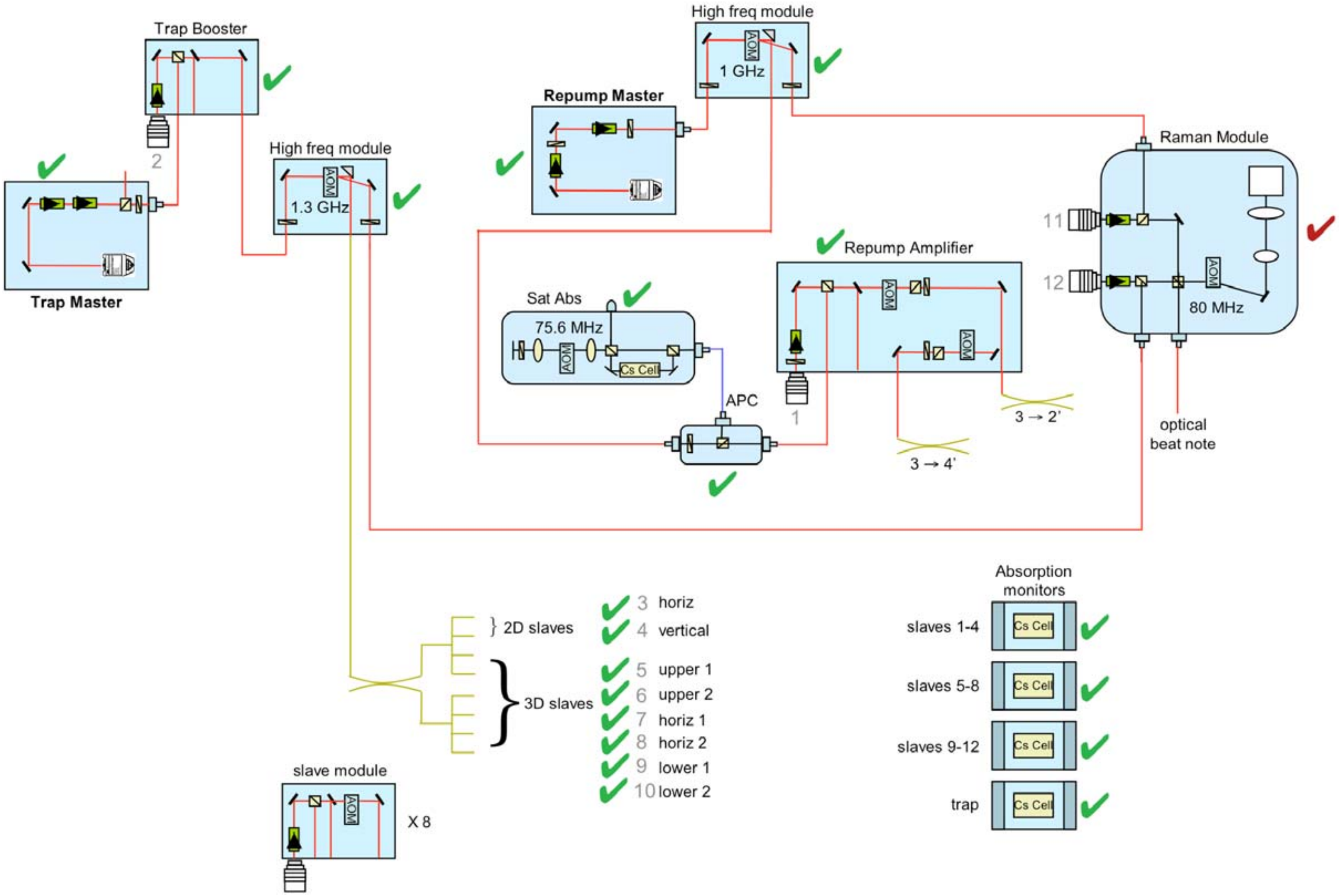
Magnetic coil form

Generation of Laser Frequencies

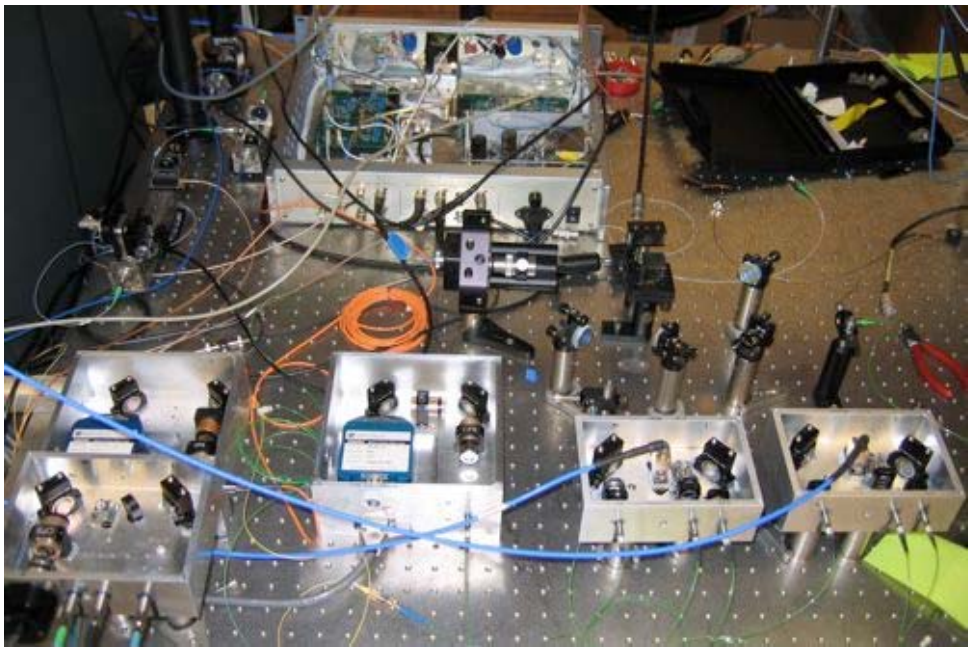




Simplified Laser and Optics System



Laser and Optical Module Approach

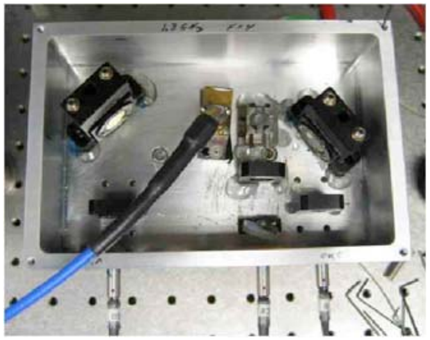


Master, slave, and frequency shifter modules on an optical table.

- Each type of module is functionally distinct and interchangeable.
- COTS free-space components used within modules.
- Modules are engineered for thermal and mechanical stability.
- Modules are inter-connected using SM optical fibers and integrated fiber splitters.
- Final amplified outputs coupled to APP via SM fibers and integrated fiber splitters.

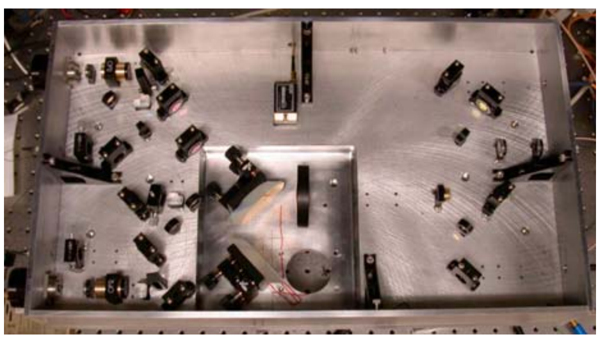
⇒ *Robust, high-power (~ 1 W total), narrow-linewidth (<300 kHz), frequency- and phase-stabilized laser system*

Sample Laser and Optics Modules



Frequency shifter module

Laser laser module



Raman laser module

Master laser module

LOS system consists of:

Master lasers x2

Booster lasers x1

Repump laser x1

Slave lasers x8

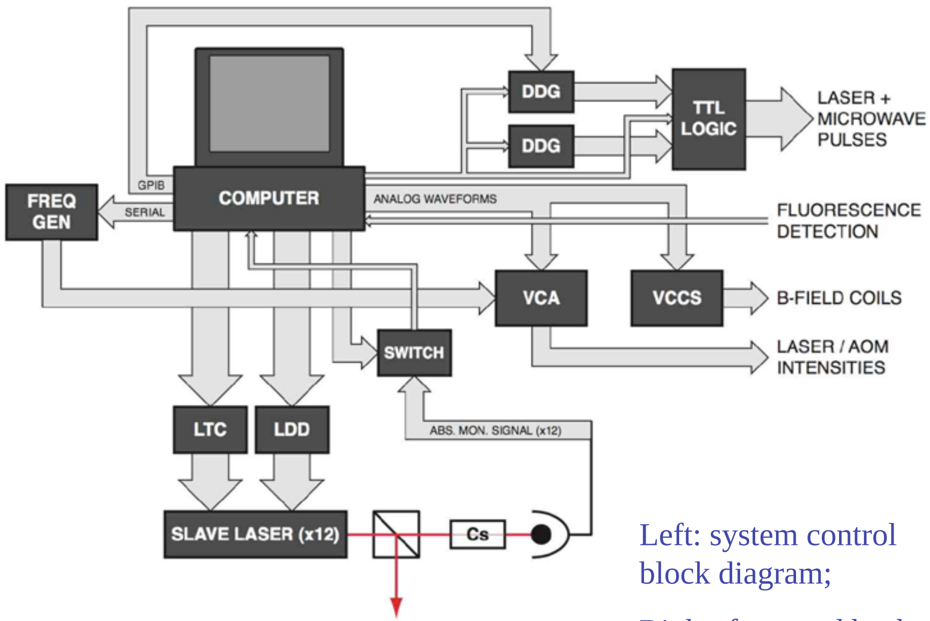
Frequency shifter x2

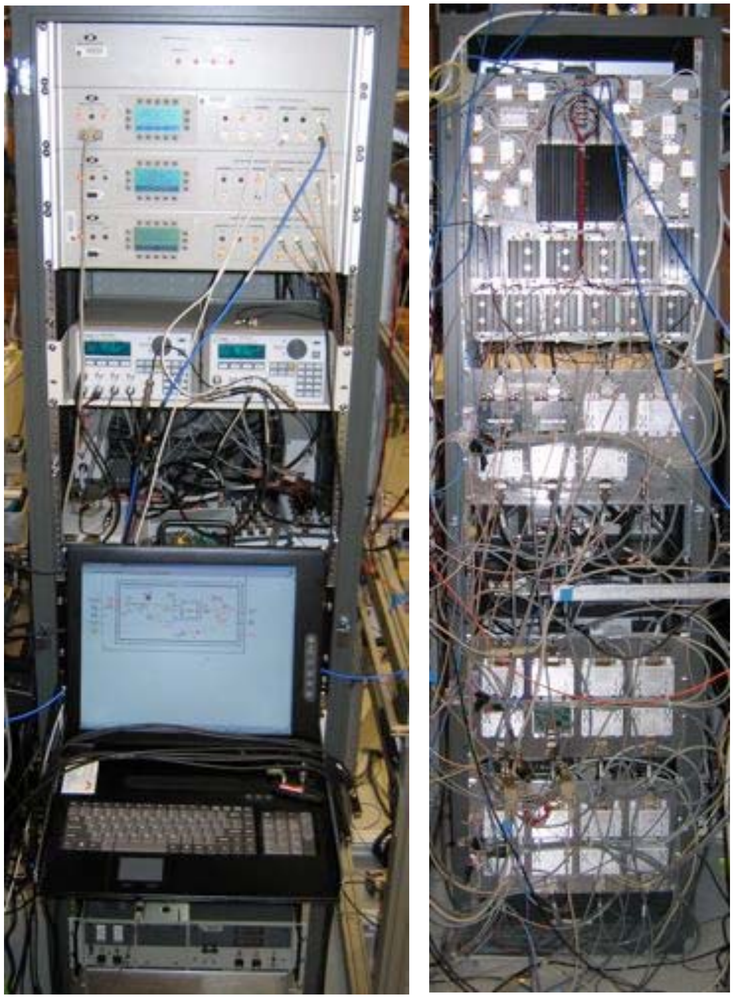
Absorption cell modules x3

Raman module x1

Laser Drivers and Controllers

- Temperature and current controllers mounted for all 12 slave lasers.
- I/O connections made for remote frequency and temperature agility necessary for injection locking.
- All slaves now computer enabled and controllable.



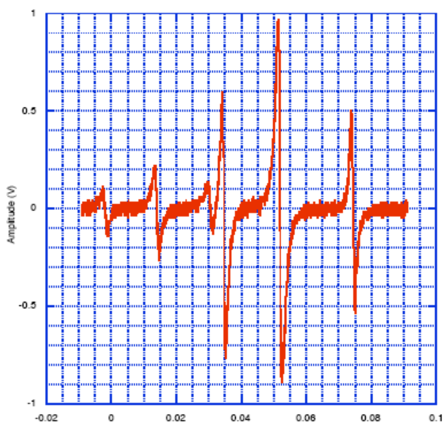


Left: system control block diagram;

Right: front and back of the electronics rack.

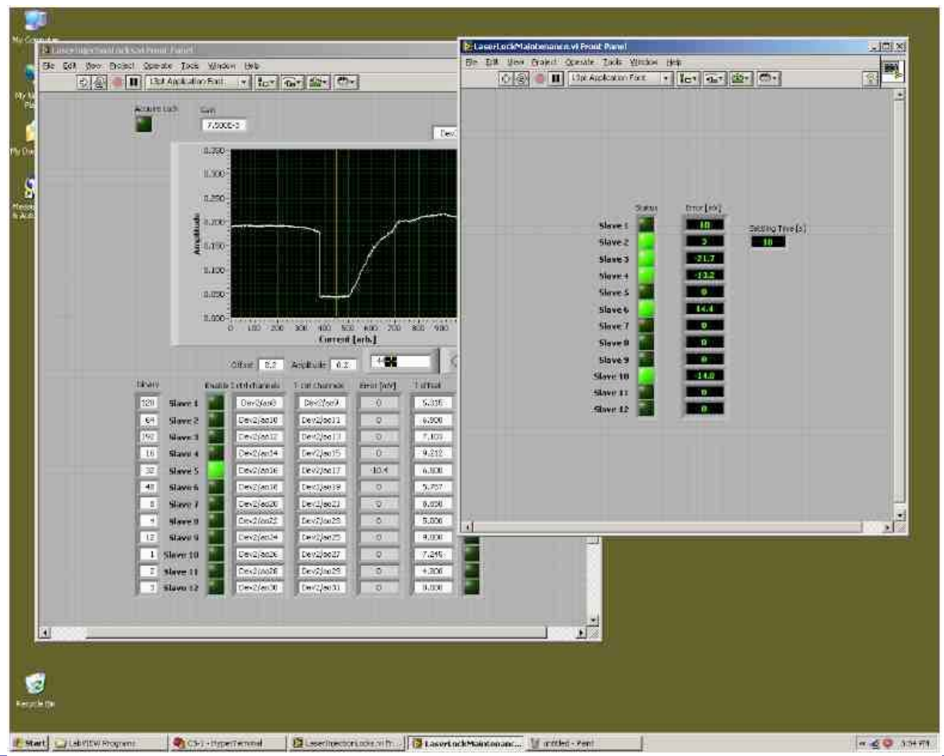
Automated Frequency and Injection Locking

A software utility has been developed to automatically recognize the desired saturation absorption peak and lock the master laser to it. Once locked, it will monitor the lock circuit operation and adjust the master laser parameters to prevent railing and unlocking. At the same time, slave laser injection locking conditions are periodically monitored and adjusted for continuous operations.

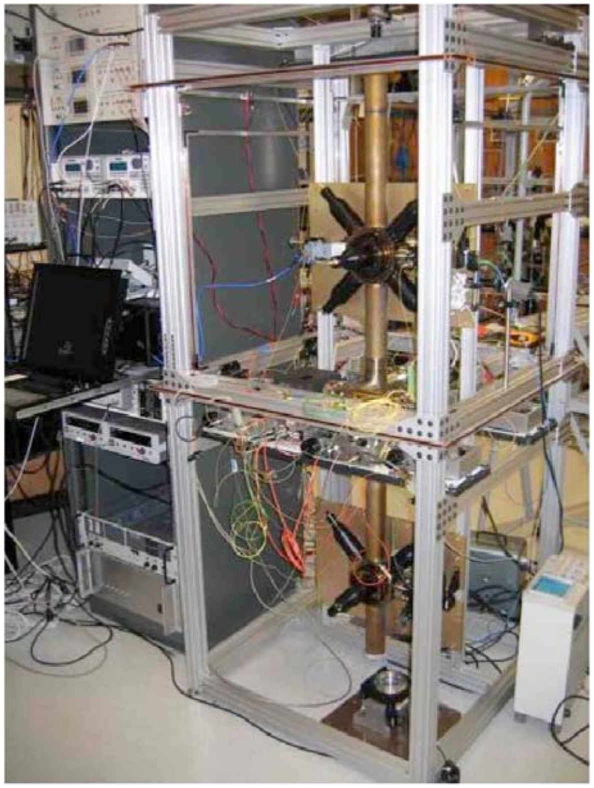


Left: atomic saturation fringes for master laser locking;

Right: slave laser current scan for absorption conditions.



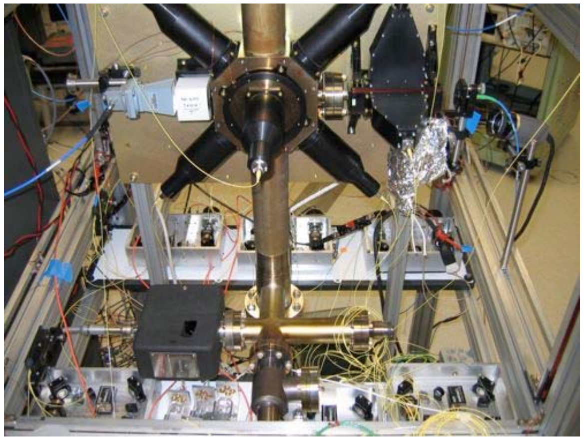
Integrated APP and LOS on Instrument Rack



Atomic physics package rack with laser and optics modules installed.

Laser modules viewed from the top

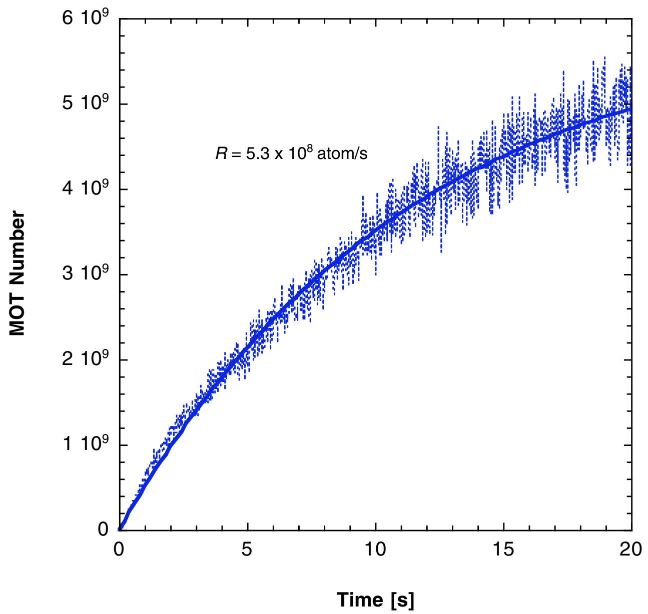
Middle laser module platform closeup

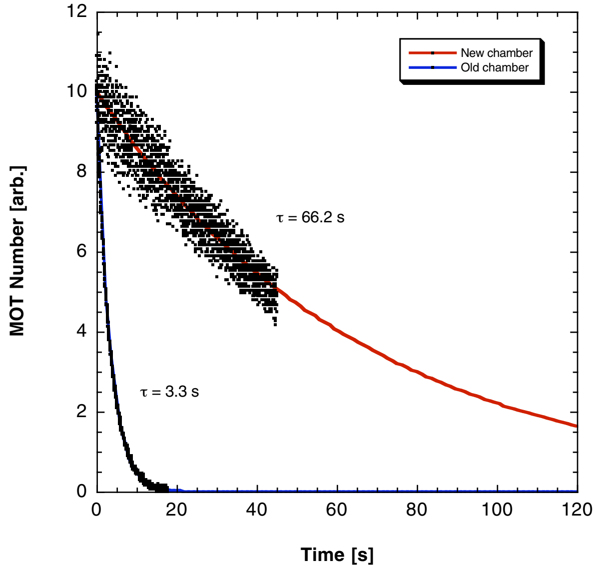


MOT Atom loading and Lifetime

The UHV MOT (*right*) collects atoms from a cold atom beam generated by a separate vapor cell 2D-MOT. Initial measurements give a loading rate of up to 7×10^8 atom/s and static MOT numbers of 6×10^9 atoms.

The lifetime of the UHV MOT is greater than 60 s — this is a factor of 20 better than the previous system and is indicative of the much lower background pressures in the current system.

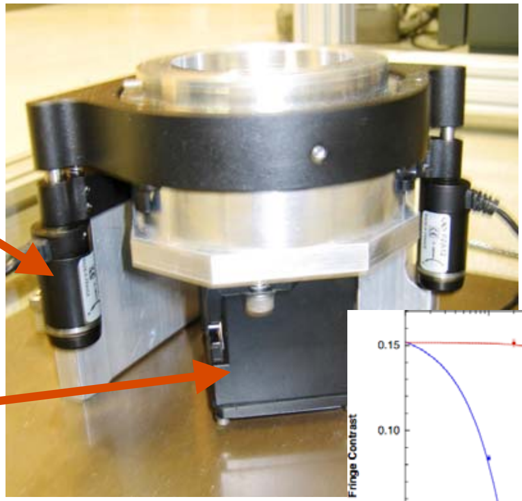


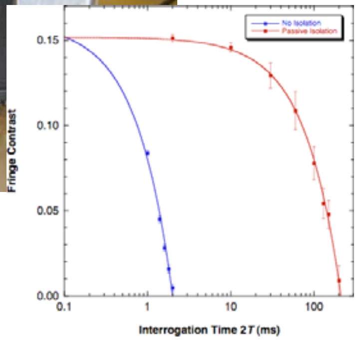


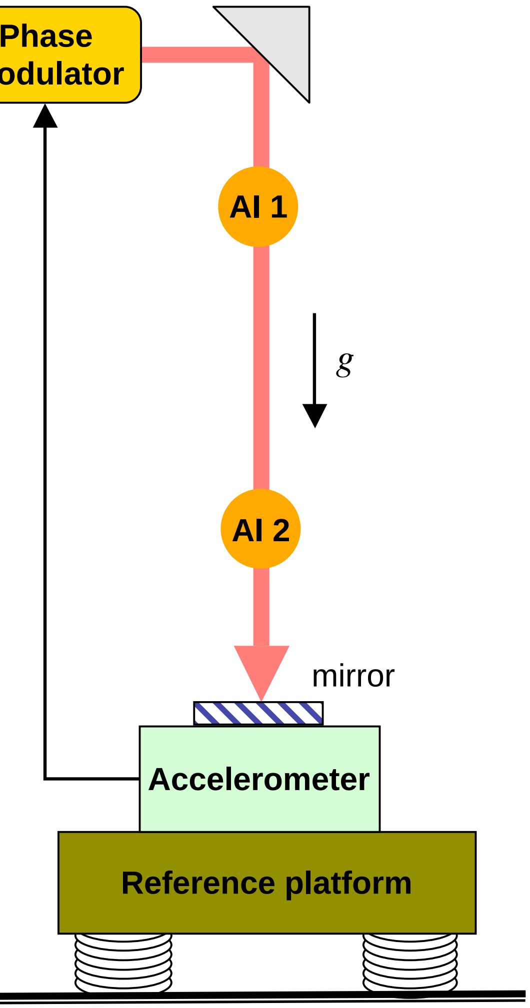
Vibration Compensation Scheme

Retro-optic mirror mount designed and fabricated with motorized piezo-actuators for automated alignment of Raman laser beams

Accelerometer installed below mirror for phase-feed forward compensation







Vibrations of the reference platform can be actively compensated via electronic feedback from an **accelerometer** mounted on the platform [2] …

[2] F. Yver-Leduc *et al.*, J. Opt. B **5**, S140 (2003).

Summary

- We are developing a transportable gravity gradiometer based on atom-wave interferometry. Atom interferometry is an enabling technology that employs a matter-wave interference measurement with individual atoms as proof masses for inertial sensing. Following a laboratory version of this instrument demonstrated, and the current effort has been to further the maturity of this technology by developing a transportable instrument for measurements in the field. This is an important developmental step towards a new class of space-borne instruments which can contribute to NASA's global gravity field mapping and monitoring efforts.

- All major subsystems of the transportable instrument have been implemented. The completed subsystems include the physics package with titanium UHV chambers and high quality optical window, the laser and optics system with more than 15 functional modules, inertial platform, and control and electronics. The instrument is current in the process of integration and testing. Initial atom loading and trapping showed exceptional good lifetime associated with UHV. We expect to achieve the full atom interferometer operation soon and perform initial science measurements in the next three months.

- The follow-on development efforts would include field science measurement validation, micro gravity operation validation, science instrument definition study, and technology maturity advancement to higher TRL level.

- With sustained development effort, atom interferometer-based gradiometer instrument will be a competing gravity measurement approach that will offer higher stability and resolution. It can also provide multi-axis measurements. In addition, it may be alternatively used in enhancing GRACE type satellite ranging measurements.