



Jet Propulsion Laboratory
California Institute of Technology

Atom Interferometer Sensor Development And Applications In Space

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Atom Interferometer and its Applications

Key points:

- **Atomic particles as test masses**
- **Quantum matter-wave interferometer for high sensitivity measurement**
- **High intrinsic system stability**
- **Laser cooling without cryogenics**

Gravity sensors

for gravity field monitoring and 3D subsurface structure mapping

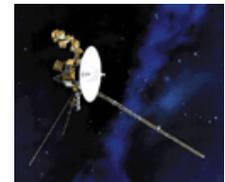
- Earth science observatory and geodesy
- Planetary gravity mapping and modeling
- Underground structure and resource detection



Inertial measurements

for navigation

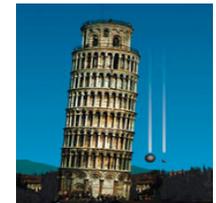
- Inertial guidance without GPS
- Precision accelerometers/gyros
- Drag-free assistance



Precision measurements

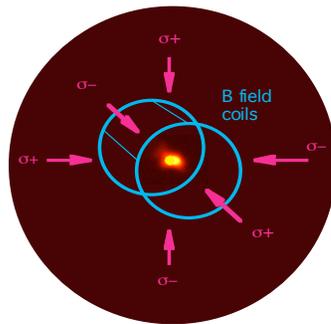
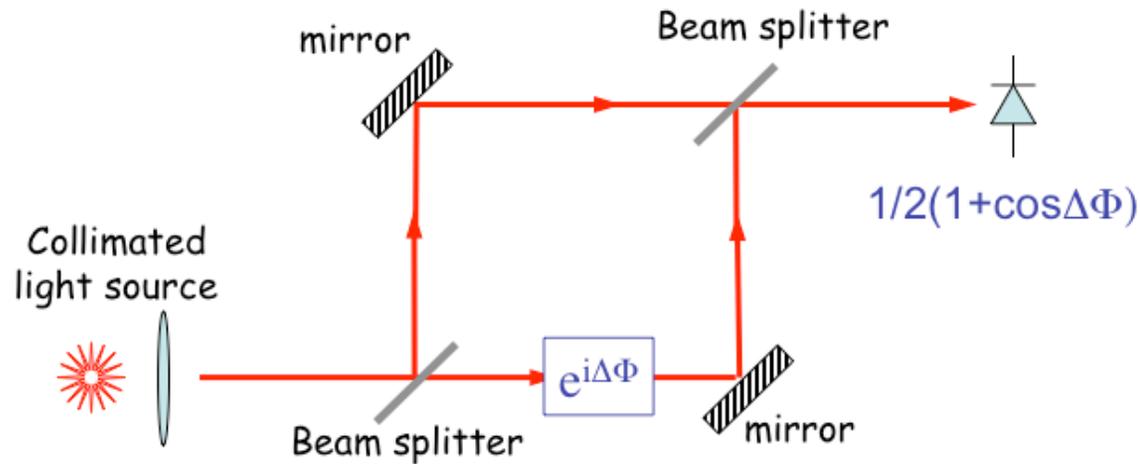
for advancement of science

- Test of Einstein's Equivalence Principle
- Frame-dragging test of the General Relativity Theory
- GW detector and spin-gravity coupling



Atom Interferometer Sensors

- Light and atom-wave interferometers



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

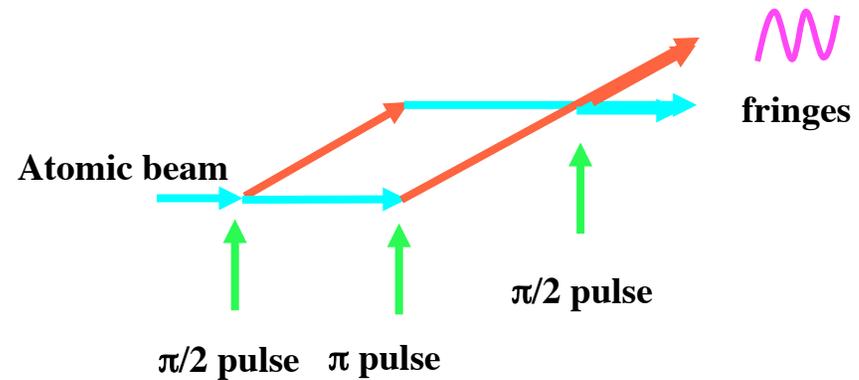
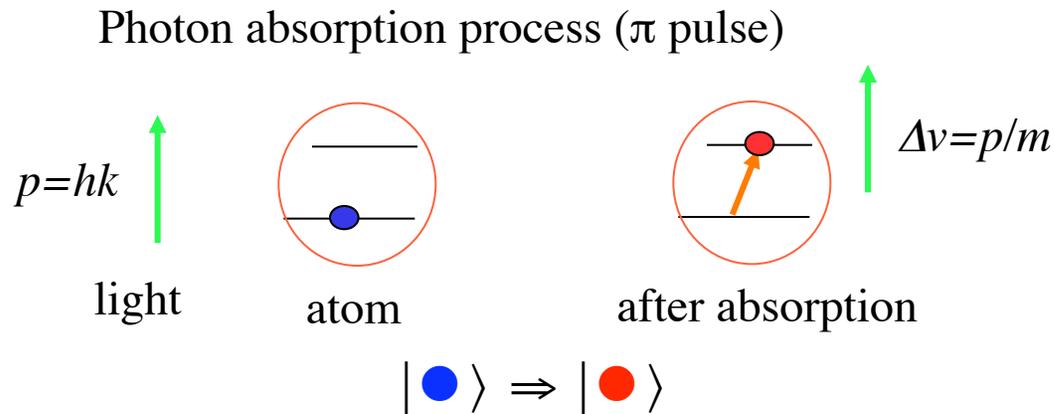


Illustration of Mach-Zehnder atom-wave interferometer, which is implemented by a sequence of laser pulses.

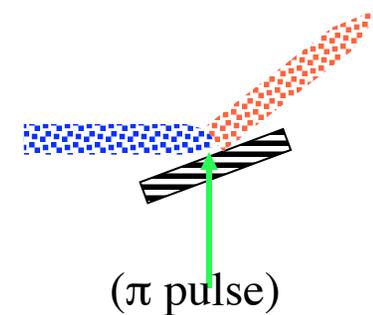
Atom Interferometer Sensors

- Atom optics using light pulses

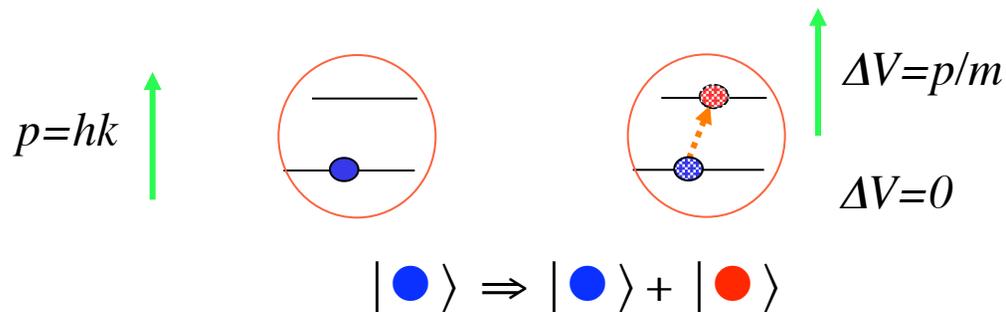
In the light pulse scheme, photon recoils are used to split and redirect atom beams



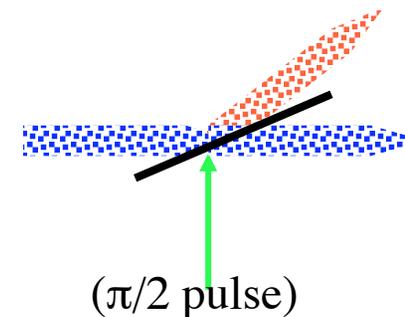
deflection (mirror)



Superposition state ($\pi/2$ pulse)

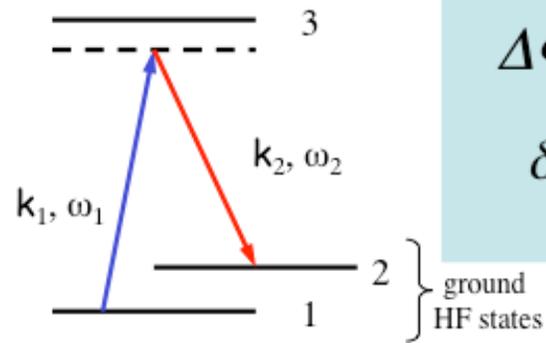
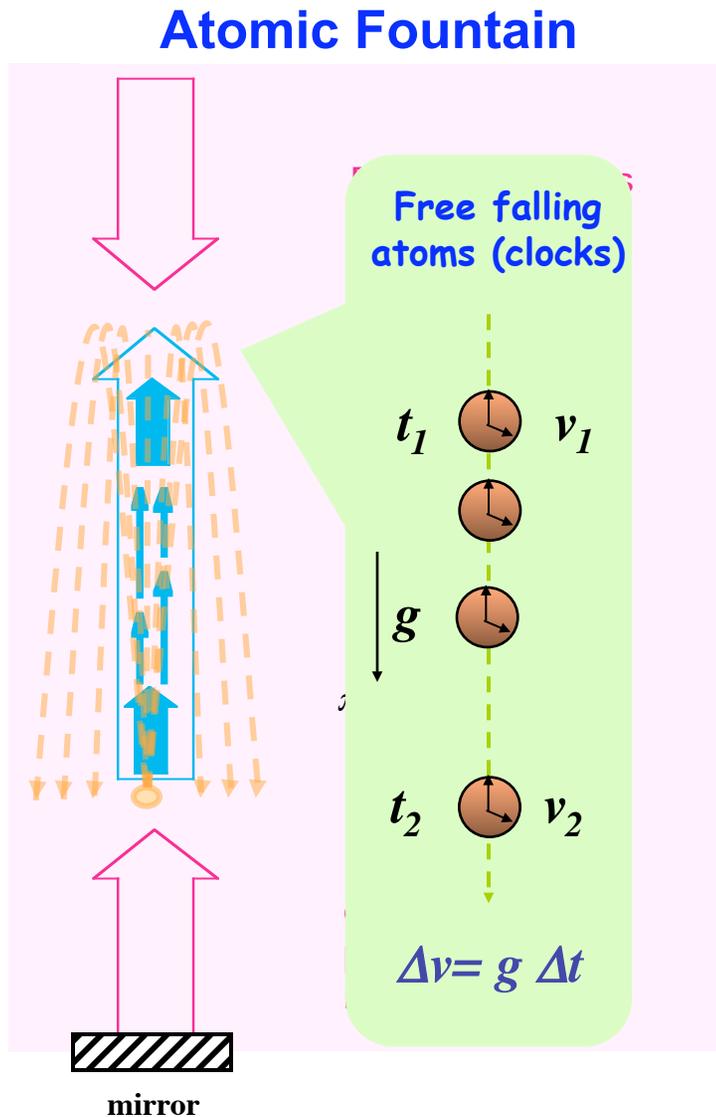


beam splitter



Atom Interferometer Sensors

- Atom interferometer as accelerometers



$$\Delta\Phi = 2 k g T^2$$

$$\delta g = \frac{1}{2kT^2} \frac{\pi}{SNR}$$

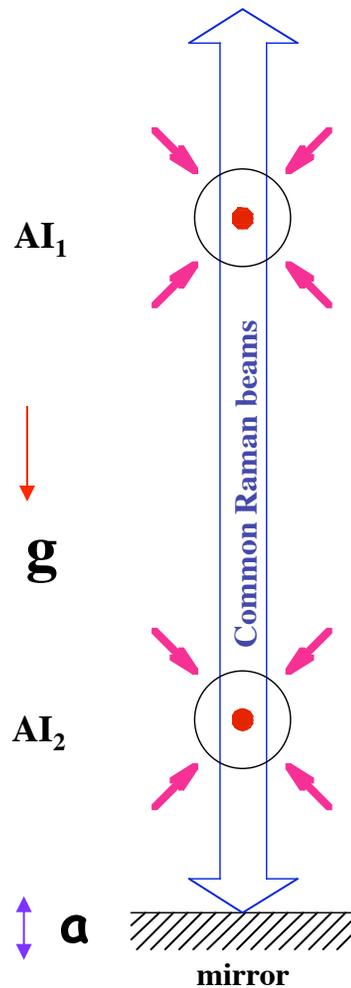
With over 10^6 detectable Cs atoms, the shot-noise limited SNR ~ 1000 . Per shot sensitivity $\approx 10^{-10}/T^2$ m/s², or about $10^{-11}/T^2$ g.

Great enhancement of the sensitivity can be gained in microgravity in space!

For example: in microgravity, 10^{-13} g Hz^{-1/2} possible with >10 s interrogation time.

Atom Interferometer Sensors

- Differential accelerometer (gravity gradiometer)



A gradiometer measures the difference in gravity, with the common local acceleration subtracted.

$$\left[(g(x_1) + a) - (g(x_2) + a) \right] / d = \Delta g_{12} / d$$

$$\Phi_1 = 2k(g_1 + a)T^2$$

$$\Phi_2 = 2k(g_2 + a)T^2$$

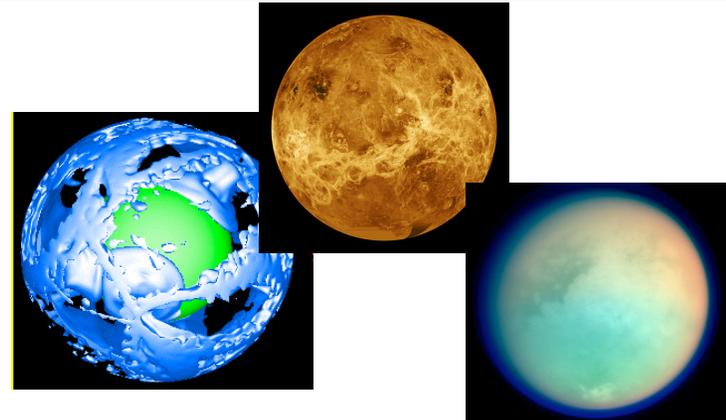
$$\Delta\Phi_{12} = 2k(g_1 - g_2)T^2$$

Many common mode errors are suppressed in the differential measurement to various degrees: vibration, laser phase error, AC stark shift, common optical path, magnetic fields,

Atomic Interferometer Sensor Applications in Space

- Advanced gravity mission for Earth and planetary sciences

- Cold atoms as truly drag-free test masses
- Gravity gradiometer (better resolution)
- Simpler mission architecture (single spacecraft)
- More flexible orbits and satellite constellation (more comprehensive data for data analyses)



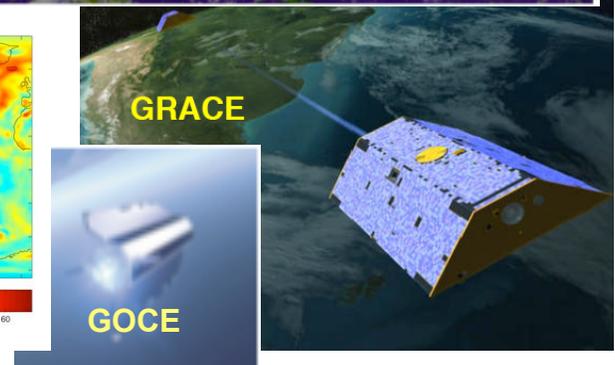
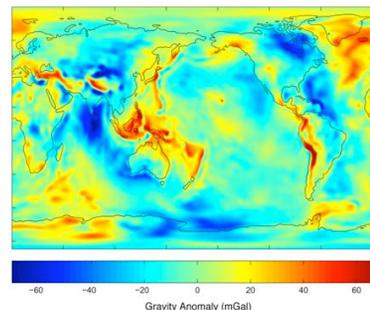
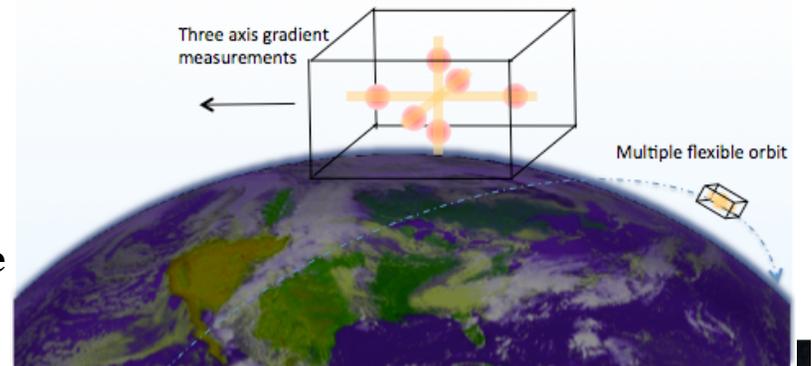
Geodesy

Earth and Planetary Interiors

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

Earth and Planetary Climate Effects

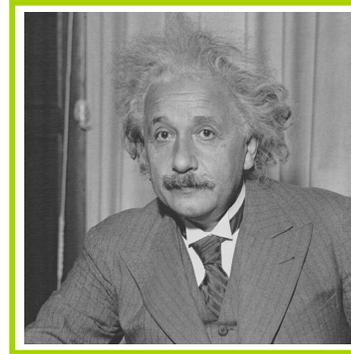
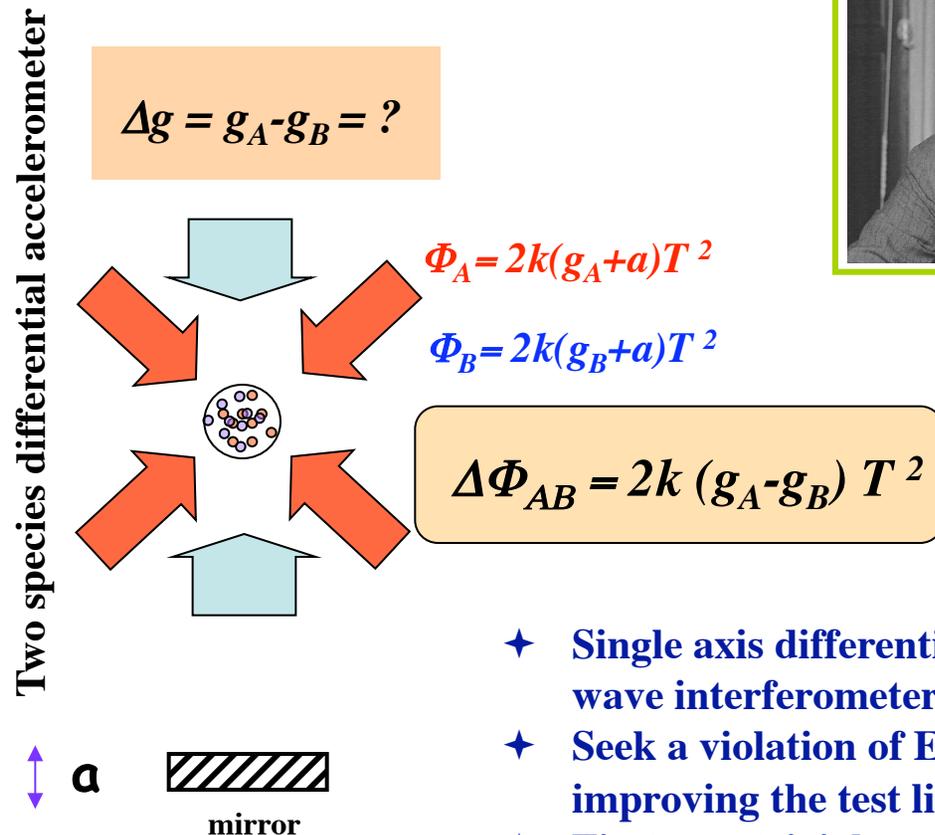
- Oceanic circulation
- Tectonic and glacial movements
- Tidal variations
- Surface and ground water storage
- Polar ice sheets
- Earthquake monitoring



Atom Interferometer Sensors

- Tests of Equivalence Principle with atomic particles

$d = 0$, overlapping atomic clouds



- ✦ Single axis differential acceleration of two co-located matter wave interferometers with different atomic species
- ✦ Seek a violation of Einstein's Equivalence Principle by improving the test limit by three orders of magnitude
- ✦ First non-trivial precision experiment of quantum particles under the influence of gravity, and may stimulate discussions of General Relativity in the framework of quantum mechanics.

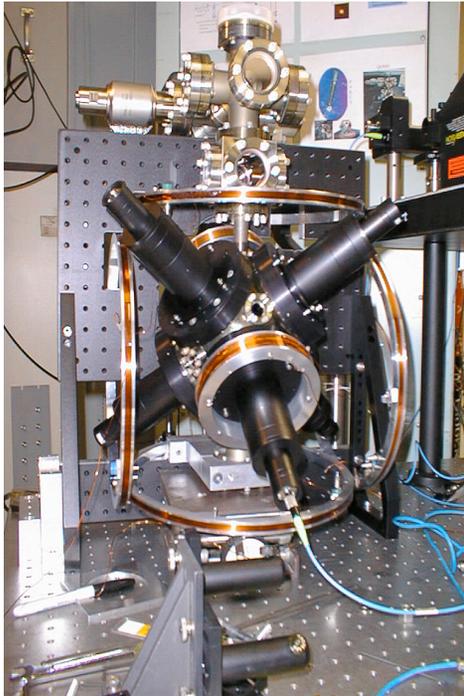
Unique Space Environment

- **Space offers freefall microgravity environment**
- **Large gravity variation possible**
- **Large spatial extent and velocity variations**
- **Minimal mechanical disturbance environment**

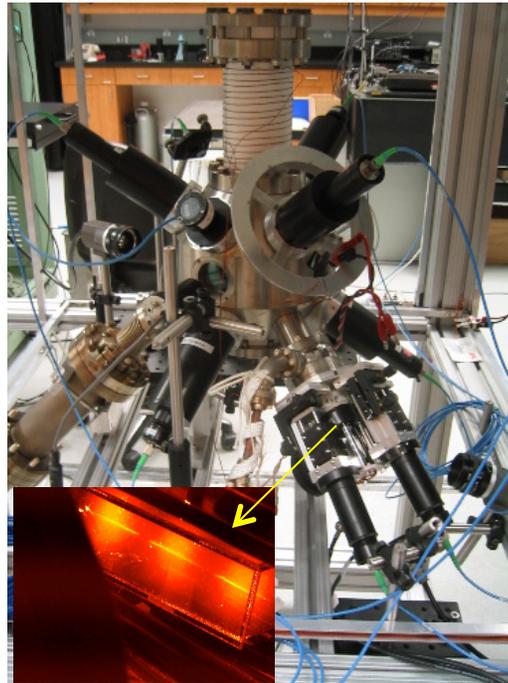


JPL Atom Interferometer Sensor Development

- From tabletop to transportable system



First tabletop experiment



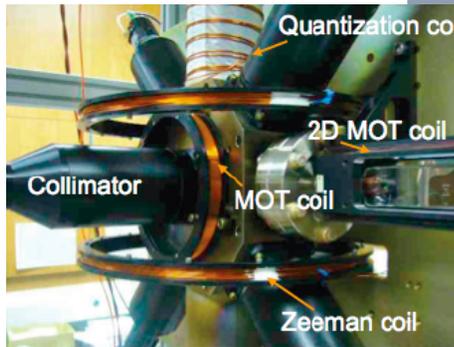
2nd generation laboratory system



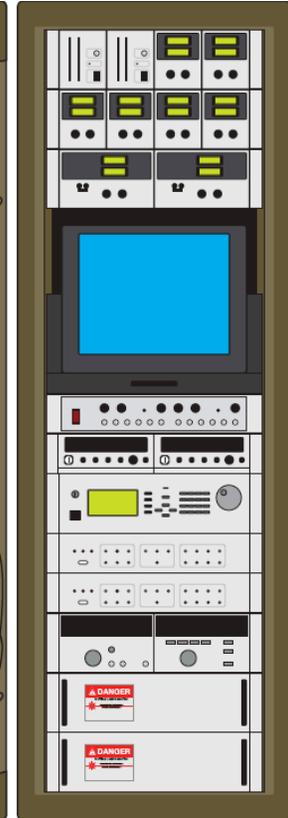
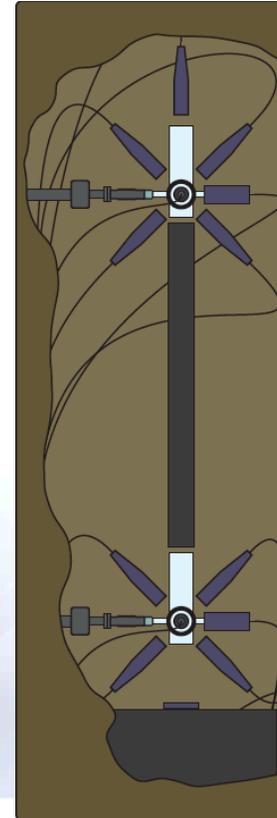
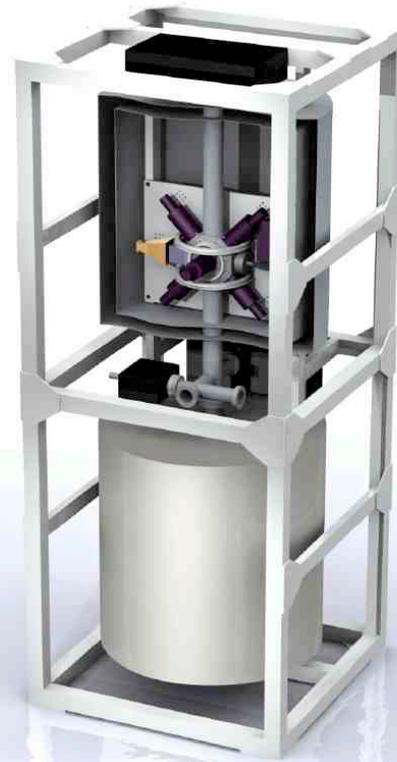
Transportable unit

Atom Interferometer Sensor Development

- Transportable atomic gradiometer instrument



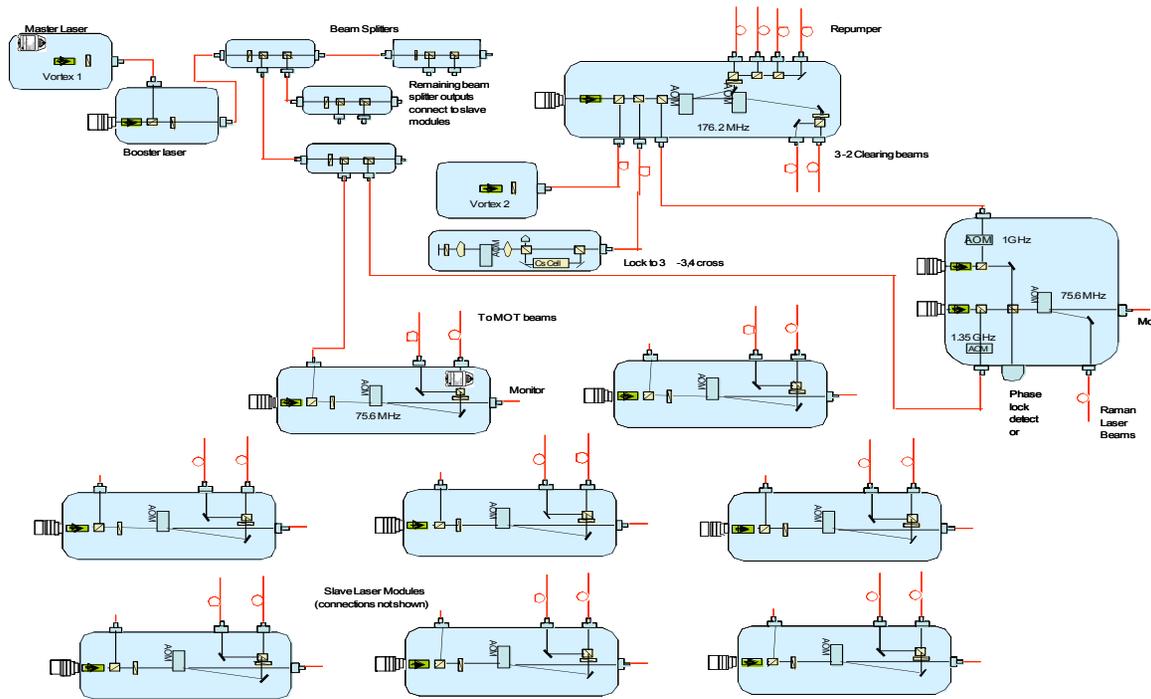
MOT and atomic source assembly



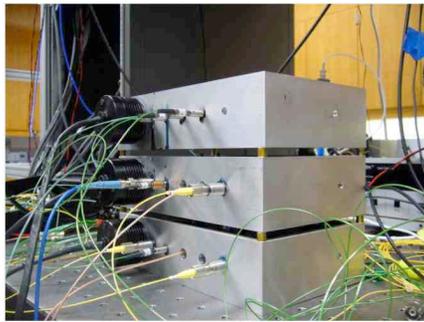
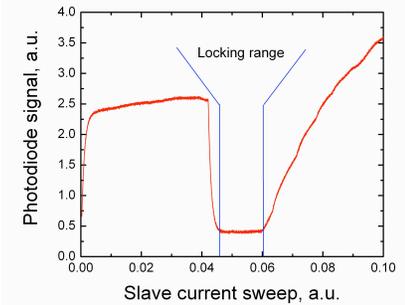
Design and actual atomic physics package

Atom Interferometer Sensor Development

- Laser and optical subsystem



Automated injection locking tracking



Laser and optics system

Eight injection-locked amplifiers for two 3D-MOTs and two 2D MOT sources. Frequency tuning through phase locking of two master lasers.

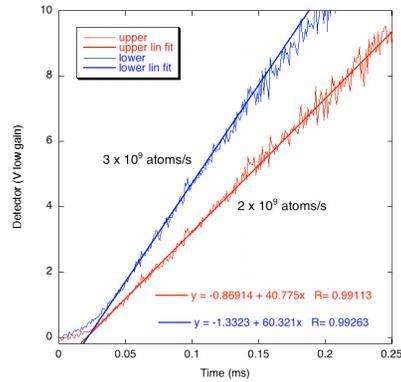


Absorption cells for locking

Atom Interferometer Sensor Development

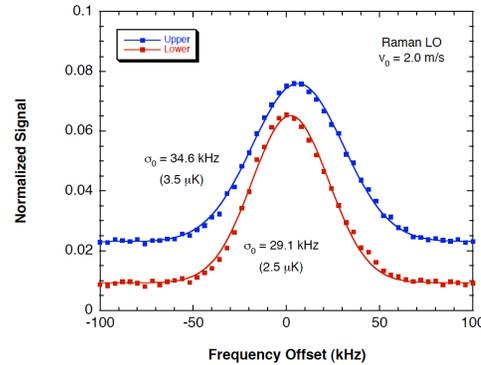
- Experimental results

loading



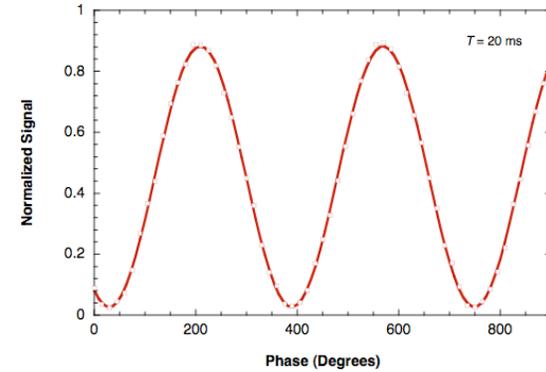
loading rate $2-5 \times 10^9$ atoms in one second.

temperature



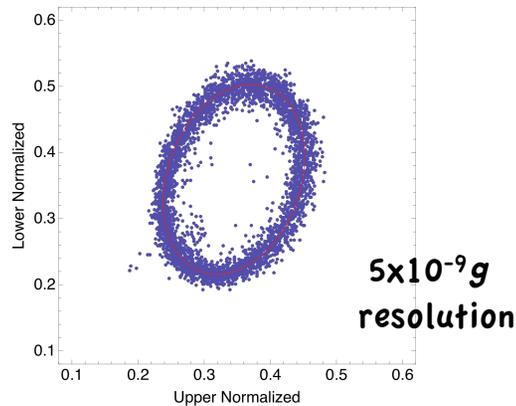
Atomic fountain launch temperature.

detection



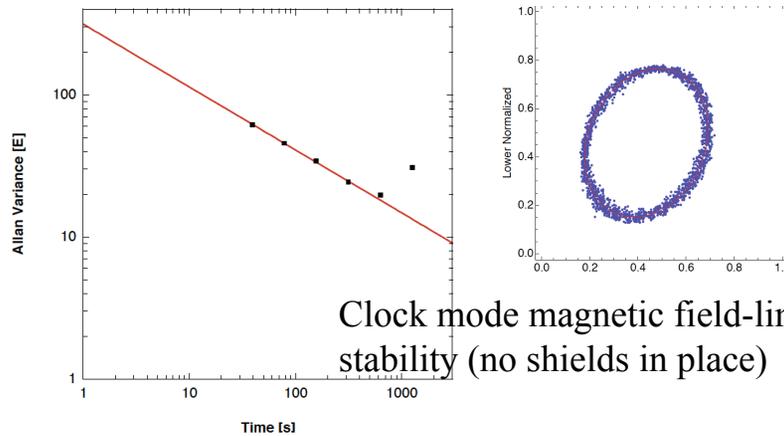
Ramsey interferometer fringes showing the fringe contrast 86% and the SNR 185.

Gradiometer signal



300 ms interrogation time (2T) each point

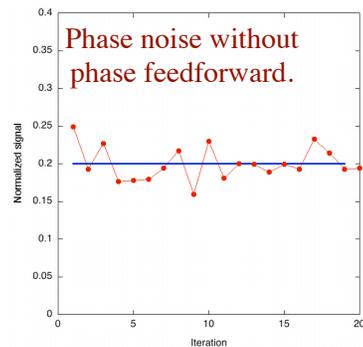
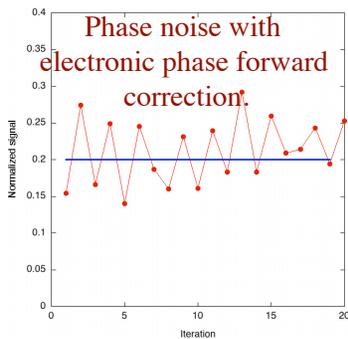
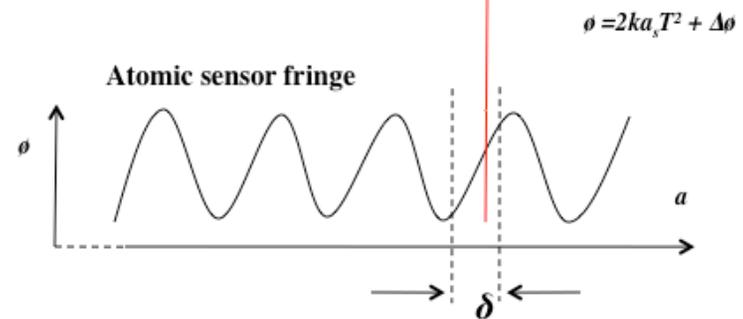
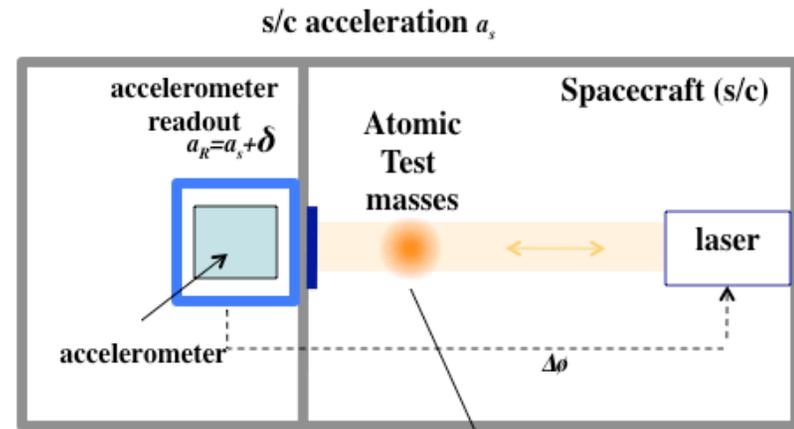
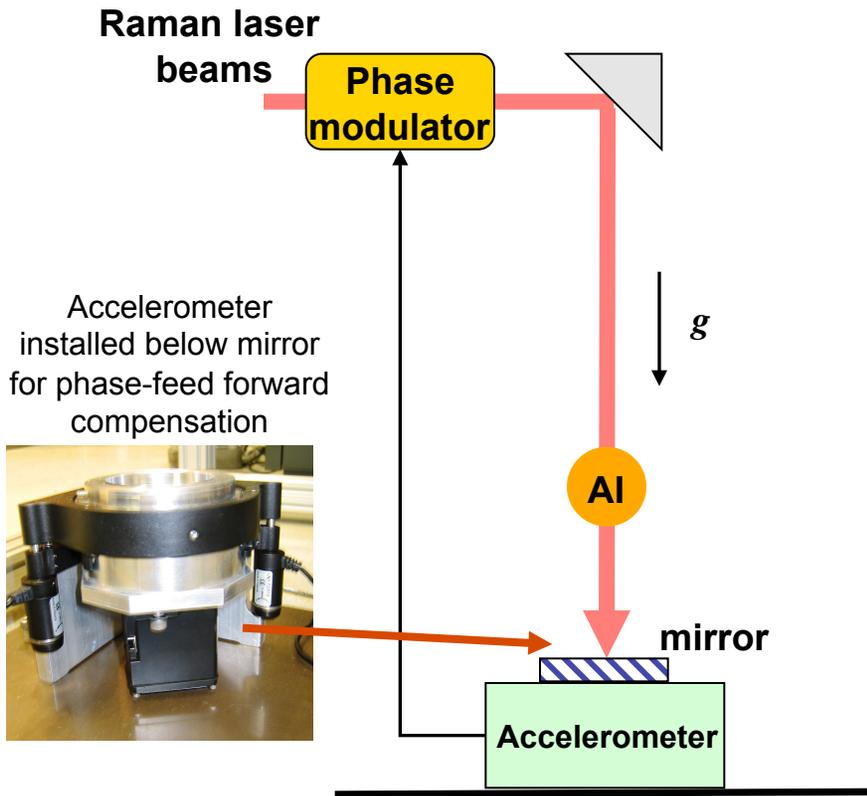
B field stability



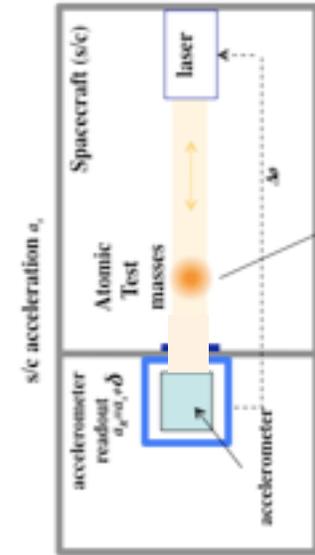
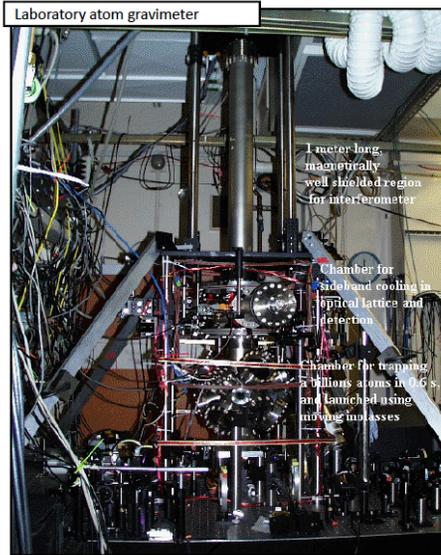
Clock mode magnetic field-limited stability (no shields in place)

Atom Interferometer Sensor Development

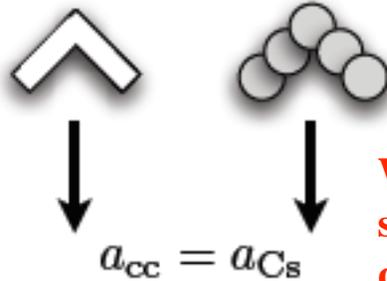
- Dynamic Range of Atomic Sensor



Universality of Free Fall (UFF) and Redshift in AI

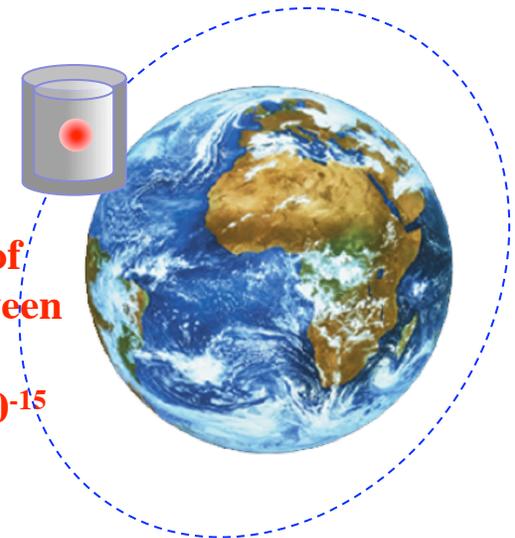


Courtesy H. Mueller



We propose a new concept of space UFF experiment between quantum and classical test masses to the precision $< 10^{-15}$

- a) Test of EEP
- b) Redshift in AI



Thoughts on possible collaborations

- Science objectives and significances
- Definition of the baseline mission concept and subsystem design
- Technology risk reductions



Acknowledgement:

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