Prospects for Improved Accuracy in the Determination of G using Atom Interferometry

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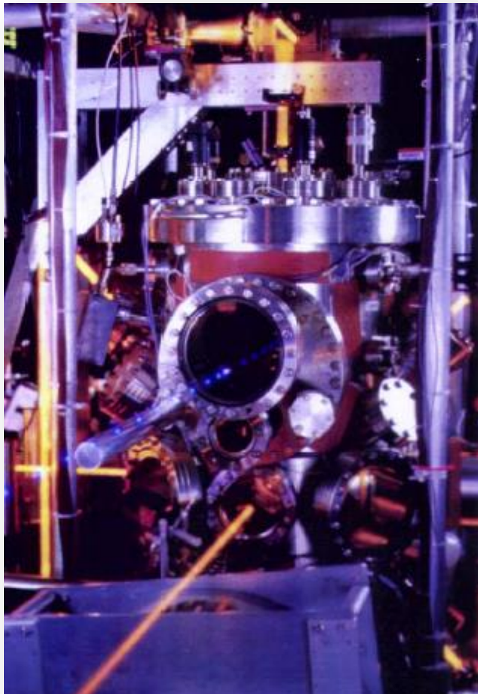
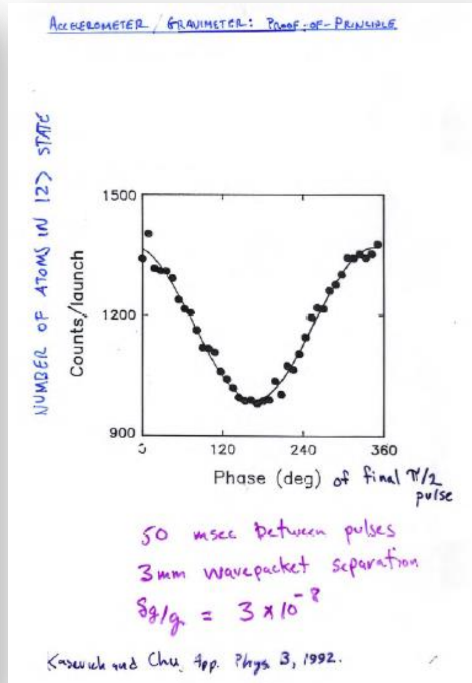
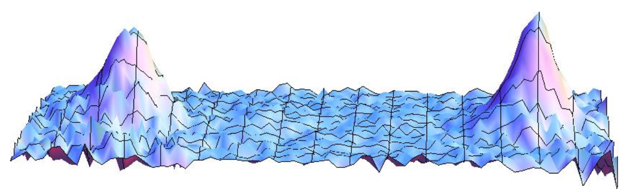
Light-pulse atom interferometer



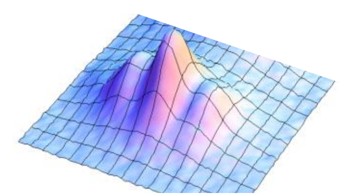


1991 demonstration of an atom interferometer gravimeter

2014 laboratory sensor, atomic wavepackets separate by 8 cm before interfering, 5e-13 g resolution* after 1 hr.



Atoms imaged in middle of interferometer

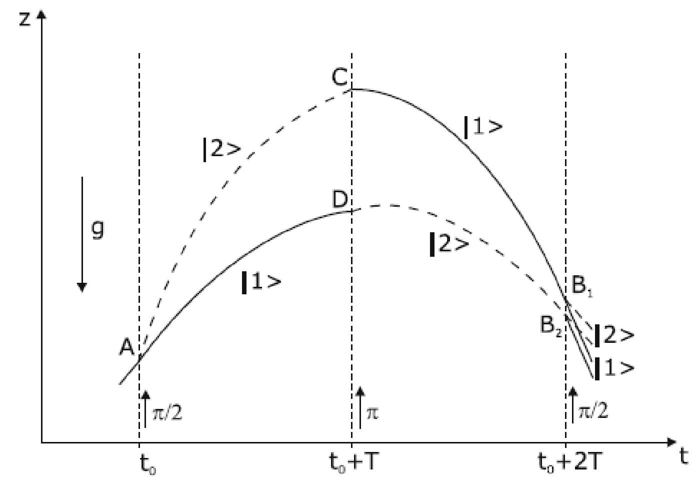


Interference at output

Semi-classical approximation

Three contributions to interferometer phase shift:

$$\Delta\phi_{\text{total}} = \Delta\phi_{\text{prop}} + \Delta\phi_{\text{laser}} + \Delta\phi_{\text{sep}}$$



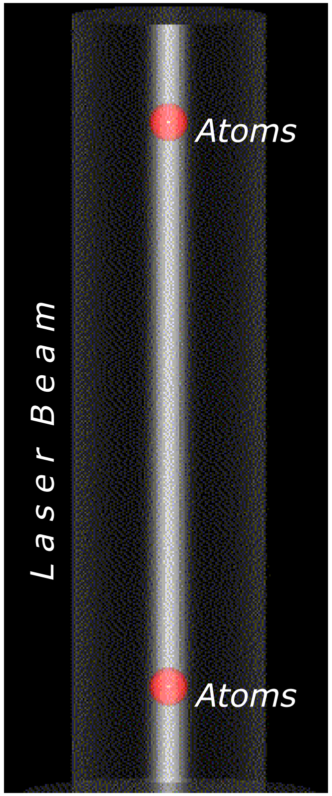
Propagation shift: $$\frac{S_{\text{cl,B}} - S_{\text{cl,A}}}{\hbar}$$

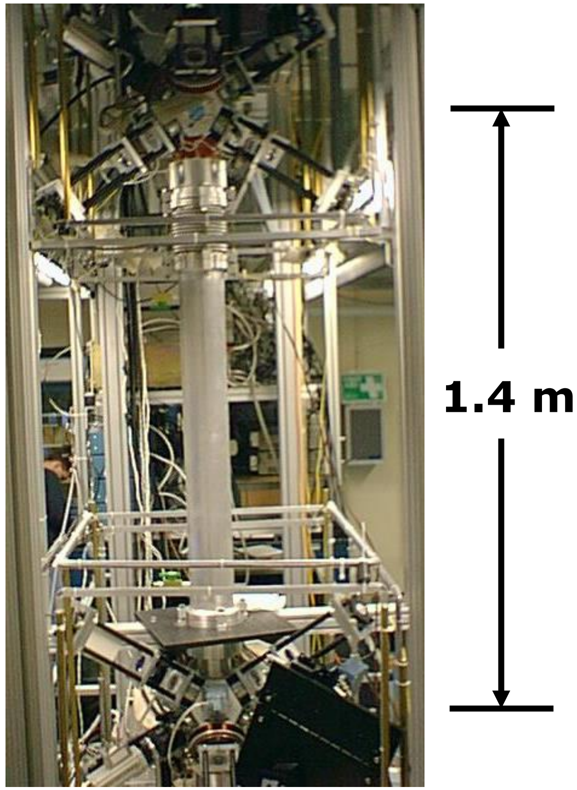
Laser fields (Raman interaction): $$k(z_c - z_b + z_d - z_a) + \phi_I - 2\phi_{II} + \phi_{III}$$

Wavepacket separation at detection: $$\vec{p} \cdot \Delta\vec{r}/\hbar$$

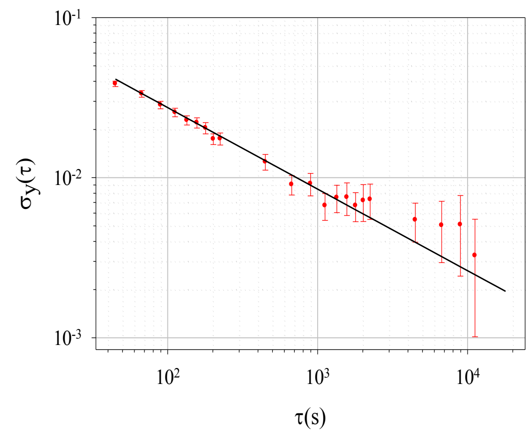
For example, Bongs, App. Phys. B, 2006;
with Gen. Rel., Dimopoulos, PRD, 2008.
Graham lectures

Laboratory gravity gradiometer (1997-2002)





Use laser cooled ensembles in atomic fountain configuration for high sensitivity/accuracy



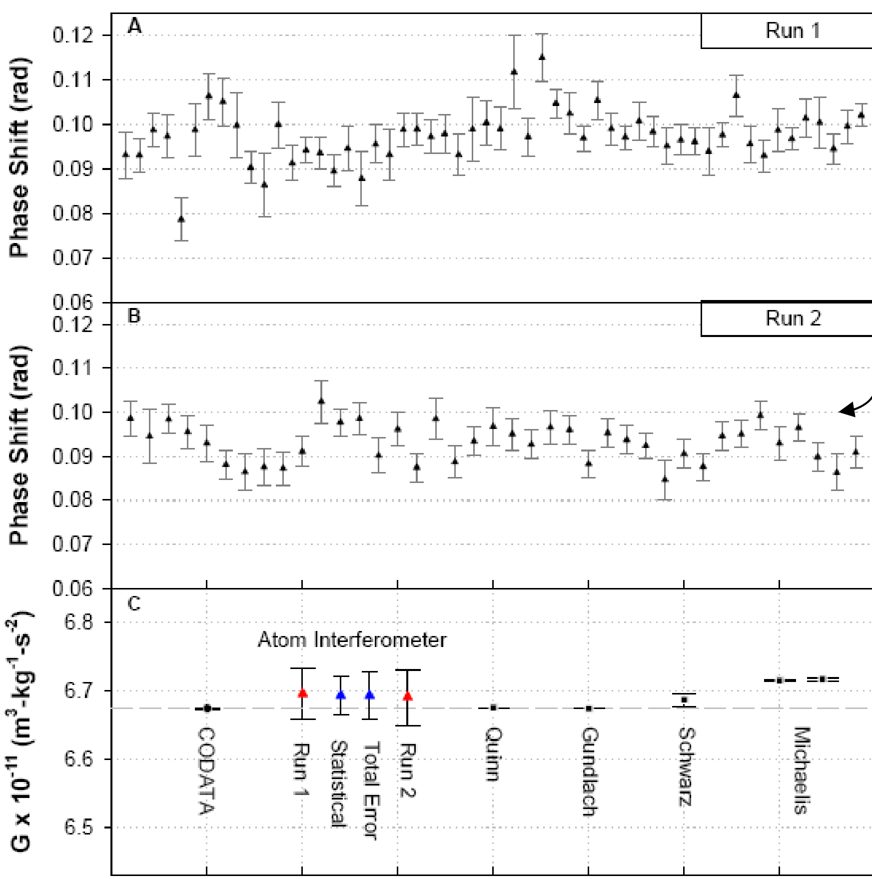
Distinguish gravity induced accelerations from those due to platform motion with differential acceleration measurements.

Demonstrated differential acceleration sensitivity (McGuirk, PRA 2001): $4x10^{-9}$ g/Hz$^{1/2}$

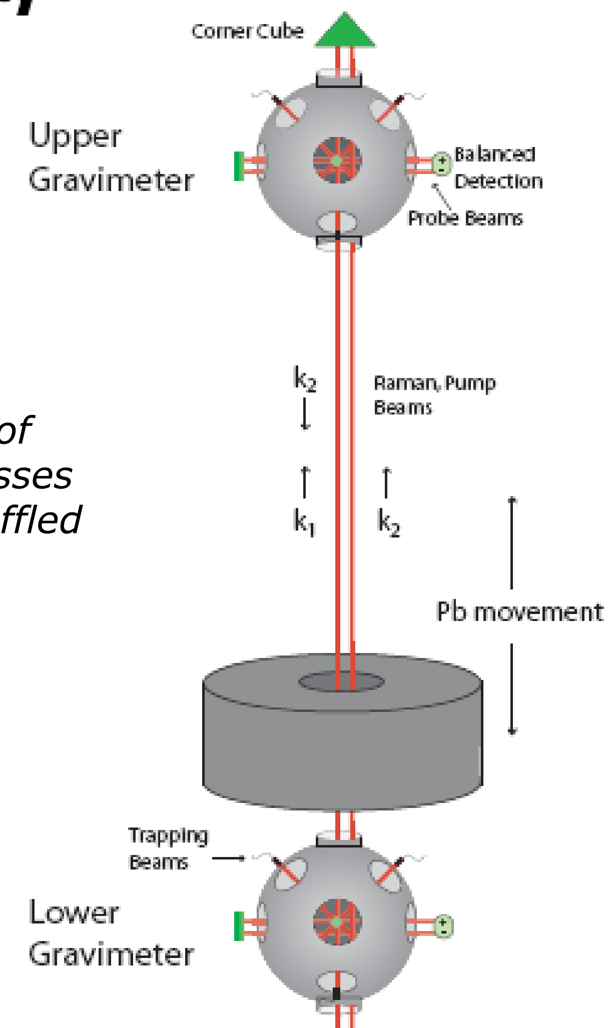
Measurement of G (2003/7)

Atom Interferometer Measurement of the Newtonian Constant of Gravity

J. B. Fixler,[1] G. T. Foster,[2] J. M. McGuirk,[3] M. A. Kasevich[1]*

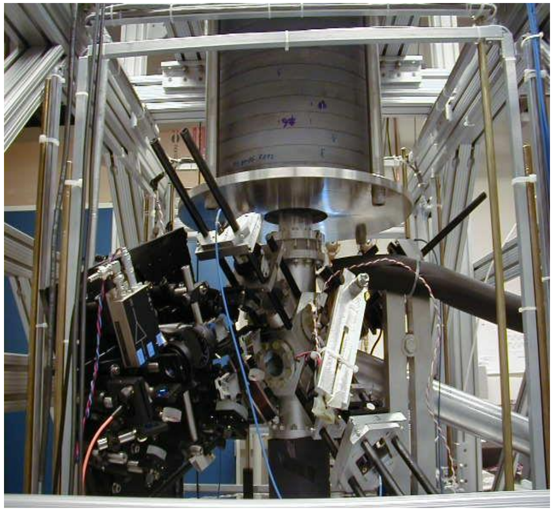


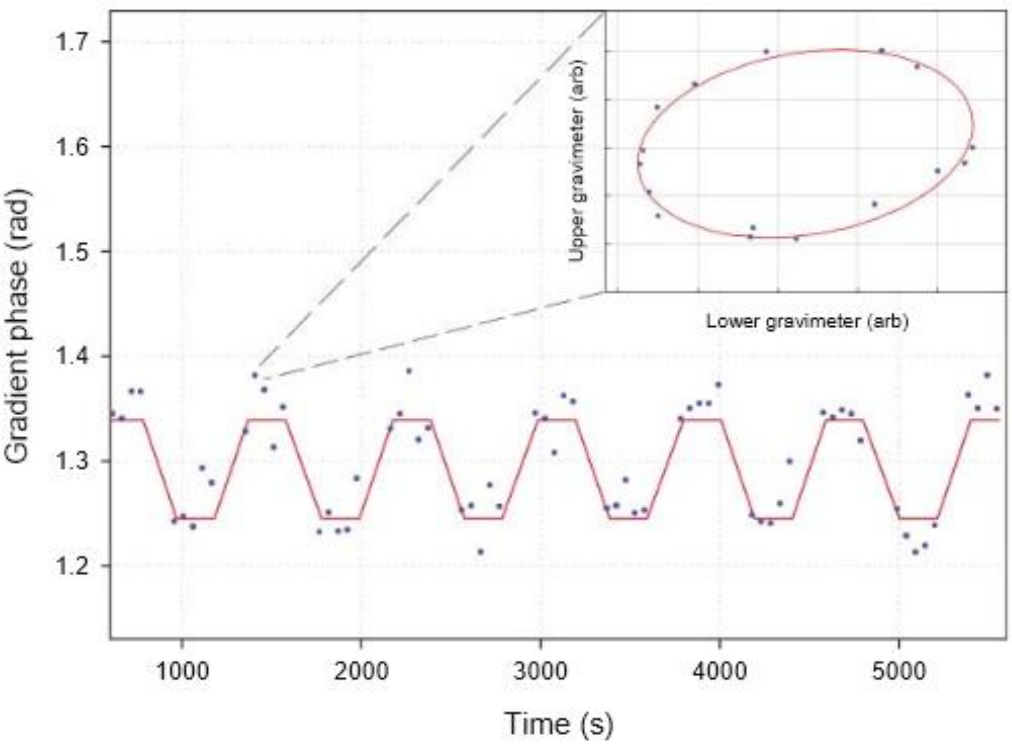
Proof masses shuffled



Fixler PhD thesis, 2003; Science 2007.

Measurement procedure





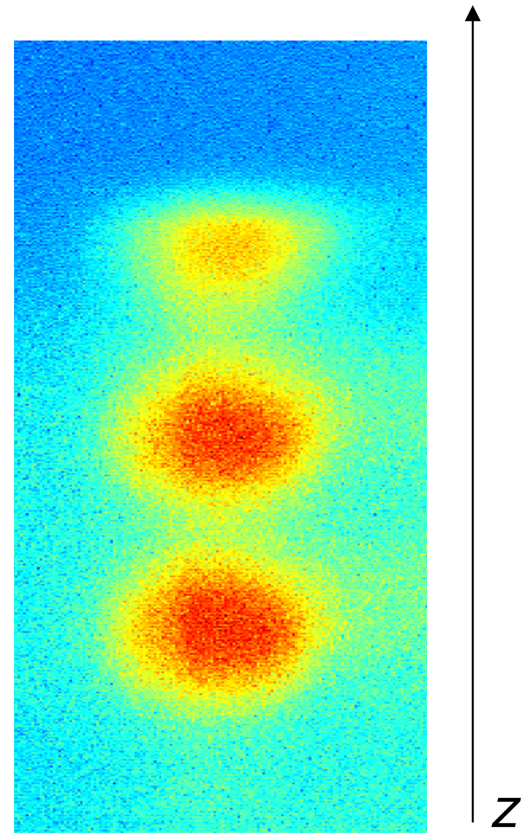
Errors

Systematic	$\delta G/G$
Initial atom velocity	1.88×10^{-3}
Initial atom position	1.85×10^{-3}
Pb magnetic field gradients	1.00×10^{-3}
Rotations	0.98×10^{-3}
Source positioning	0.82×10^{-3}
Source mass density	0.36×10^{-3}
Source mass dimensions	0.34×10^{-3}
Gravimeter Separation	0.19×10^{-3}
Source mass density inhomogeneity	0.16×10^{-3}
Total	3.15×10^{-3}

Systematic error sources dominated by initial position/velocity of atomic clouds.

$$\partial v = 2\times10^{-3}\, m/s \quad \Rightarrow \quad \frac{\partial G}{G} \sim 1\times10^{-3}$$

$$\partial z = 3\times10^{-4}\, m \quad \Rightarrow \quad \frac{\partial G}{G} \sim 1\times10^{-3}$$

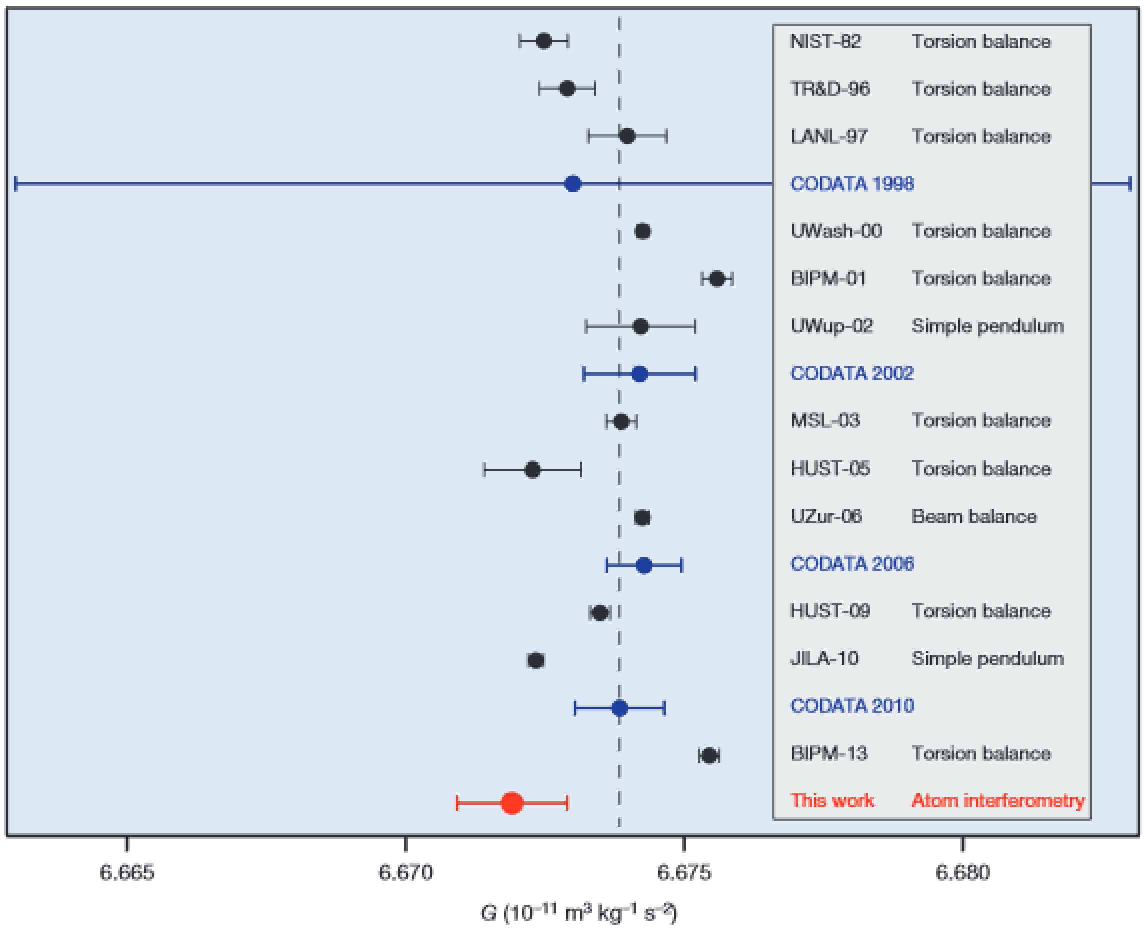


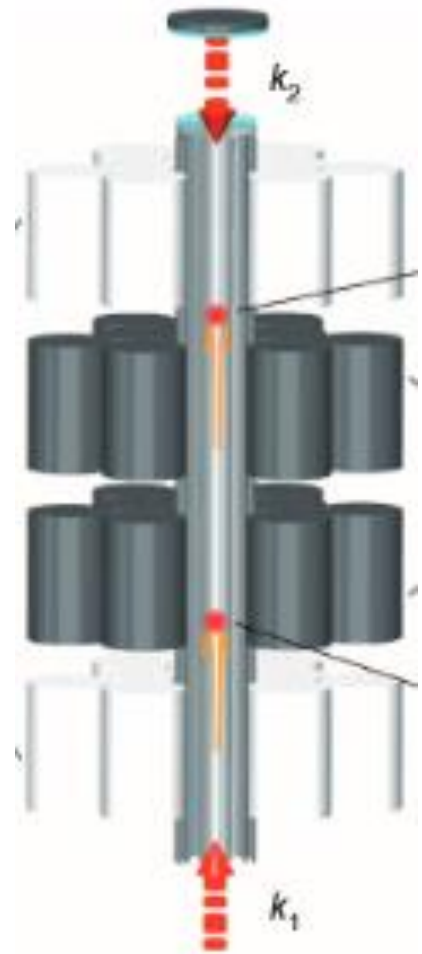
Time lapse images of atoms during launch

LENS (Tino), 2014

Precision measurement of the Newtonian gravitational constant using cold atoms

G. Rosi[1], F. Sorrentino[1], L. Cacciapuoti[2], M. Prevedelli[3] & G. M. Tino[1]





LENS, Measurement of G, 2014

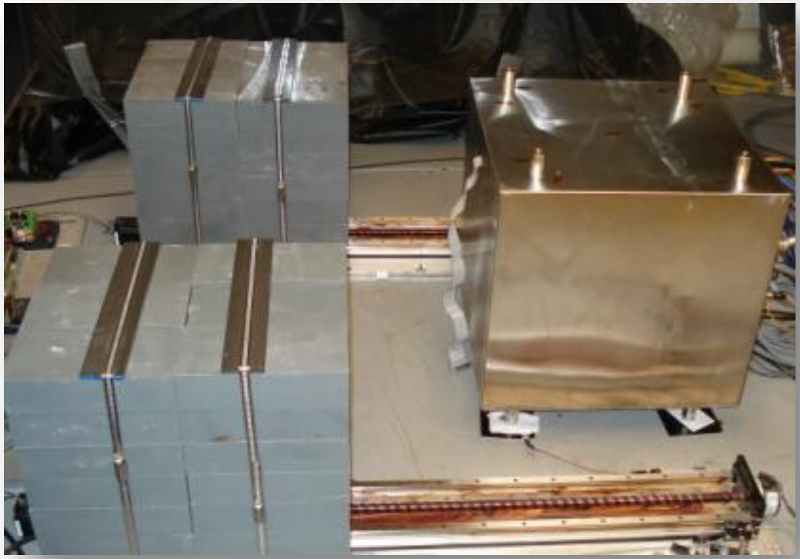
Table 1 | Effects, relative corrections and uncertainties considered in our determination of *G*

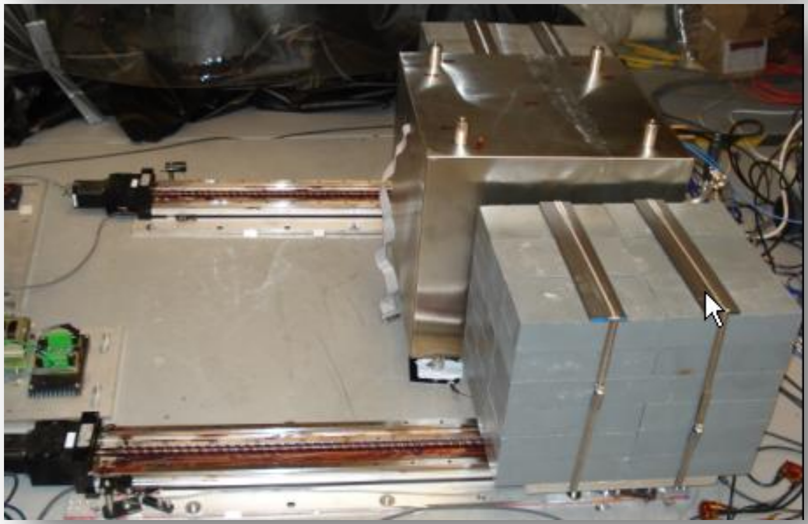
Parameter	Uncertainty in parameter	Relative correction to G (p.p.m.)	Relative uncertainty in G (p.p.m.)
Air density	10%	60	6
Apogee time	30 µs	—	6
Atomic cloud horizontal size	0.5 mm	—	24
Atomic cloud vertical size	0.1 mm	—	56
Atomic cloud horizontal position	1 mm	—	37
Atomic cloud vertical position	0.1 mm	—	5
Atom launch direction change C/F	8 µrad	—	36
Cylinder density homogeneity	10^{-4}	91	18
Cylinder radial position	10 µm	—	38
Ellipse fit	—	−13	4
Size of detection region	1 mm	—	13
Support platform mass	10 g	—	5
Translation stage position	0.5 mm	—	6
Other effects	—	<2	1
Total systematic uncertainty	—	—	92
Statistical uncertainty	—	—	116
Total	—	137	148

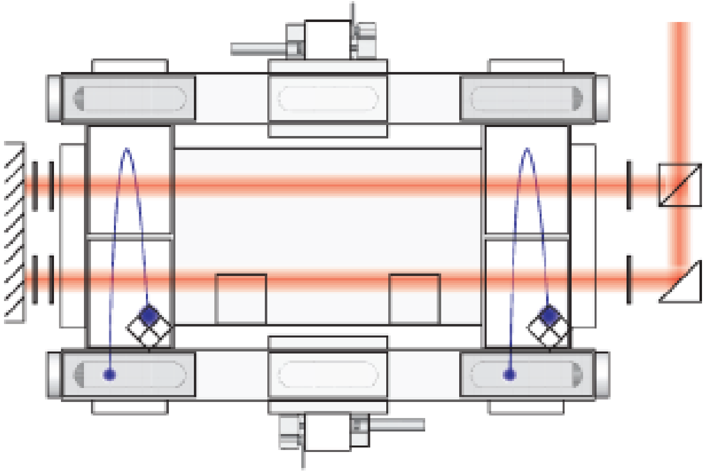
Uncertainties are quoted as one standard deviation. The third column contains the corrections we applied to account for effects not included in the Monte Carlo simulation. The bias and systematic error from ellipse fitting are evaluated by a numerical simulation on synthetic data. Other effects include cylinder mass, cylinder vertical position, gravity gradient, gravity acceleration, Raman mirror tilt, Raman *k* vector and timing.

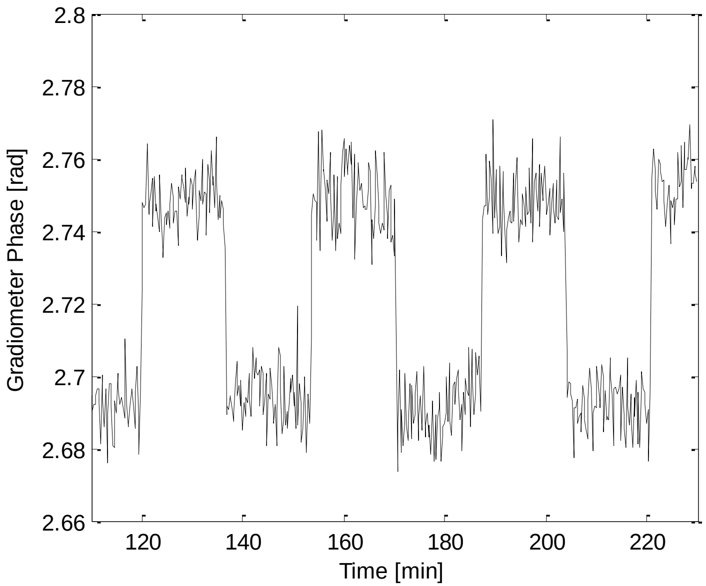
Measurement limited by knowledge of atomic trajectories.

Gravity gradiometer for SSBN navigation

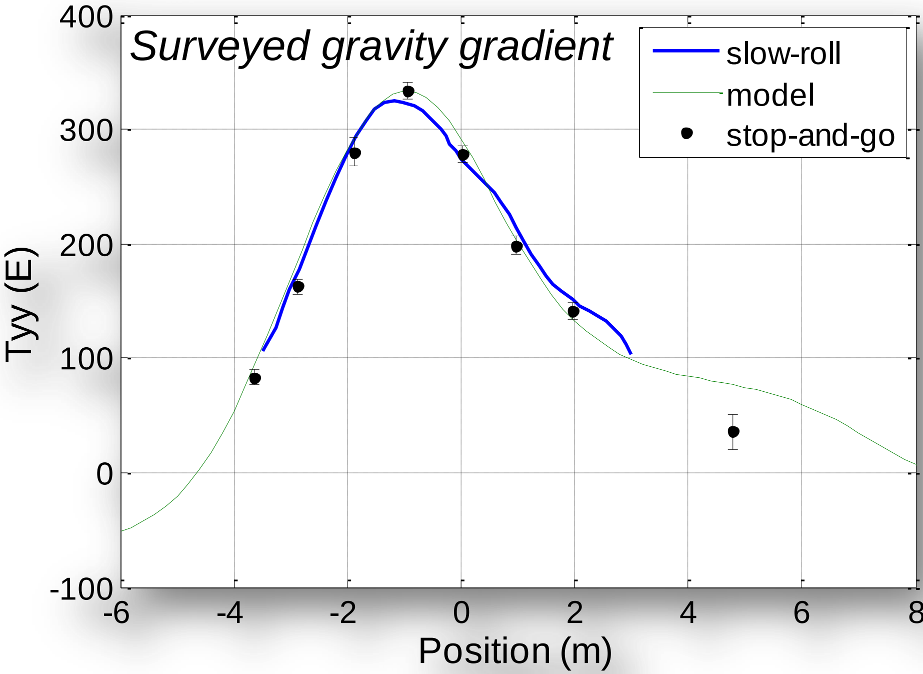


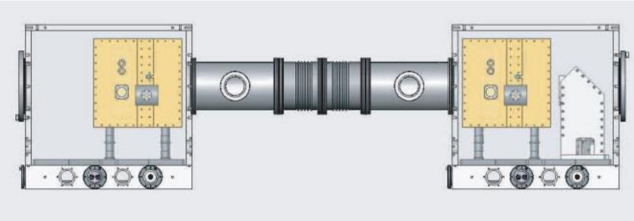




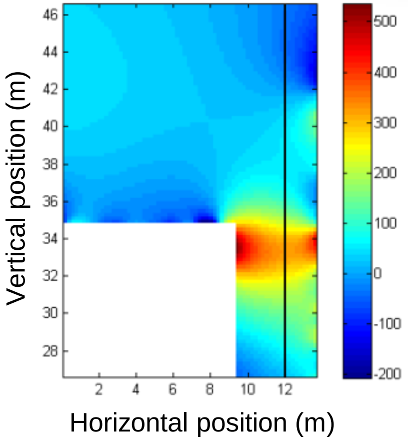


Moving-base gravity gradiometer



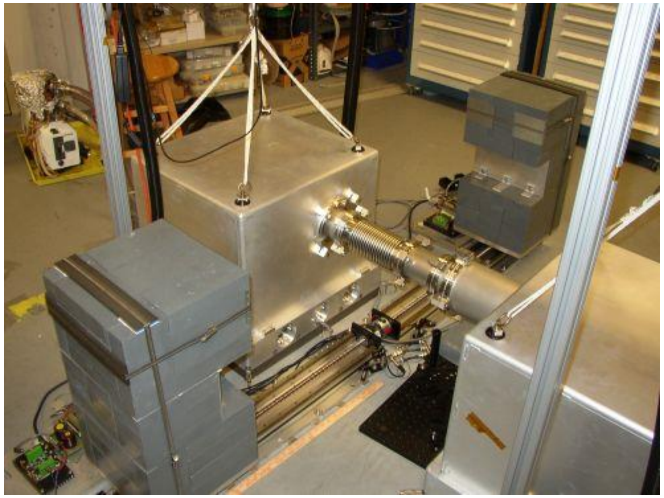


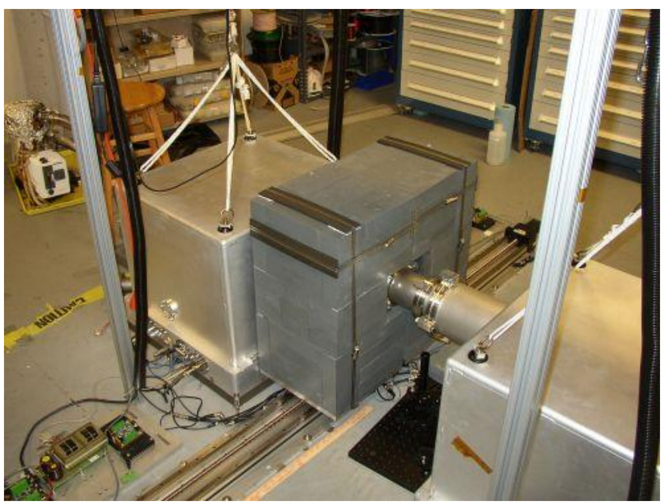
Atom interferometric gravity gradiometer on-board

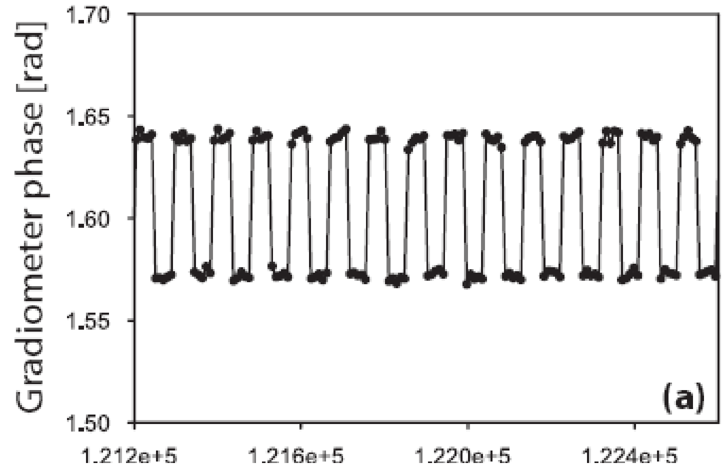


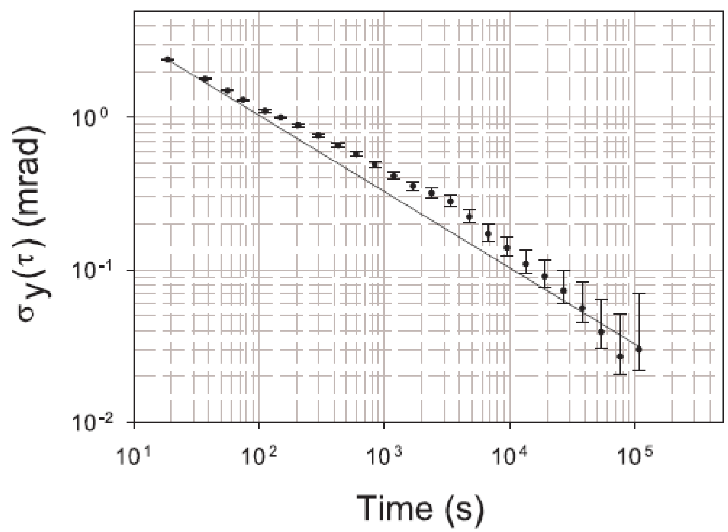
Calculated gravity gradient along survey path

Moving-base gravity gradiometer







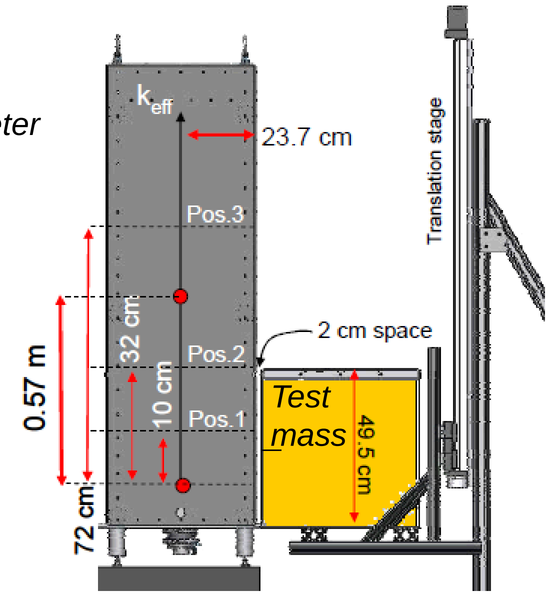


Demonstrated accelerometer resolution: ~10^{-11} g.

Gravitational portal detector

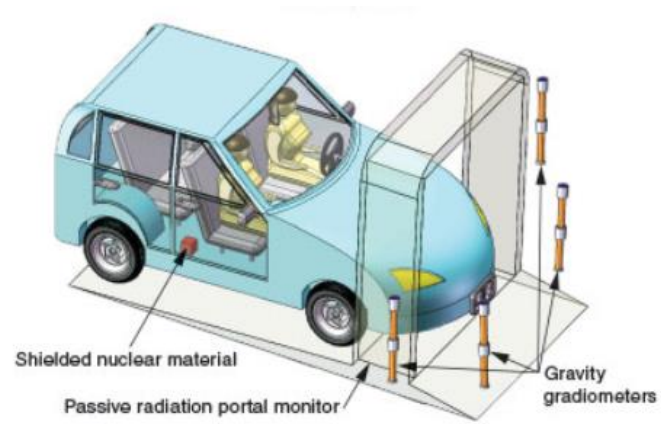
Proof-of-concept

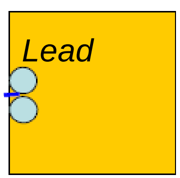
Gravity Gradiometer



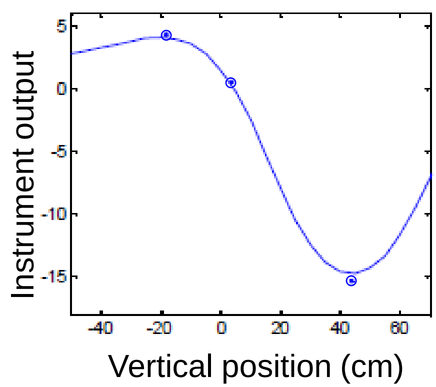
AOSense Gradiometer

Envisioned portal





Test mass detail



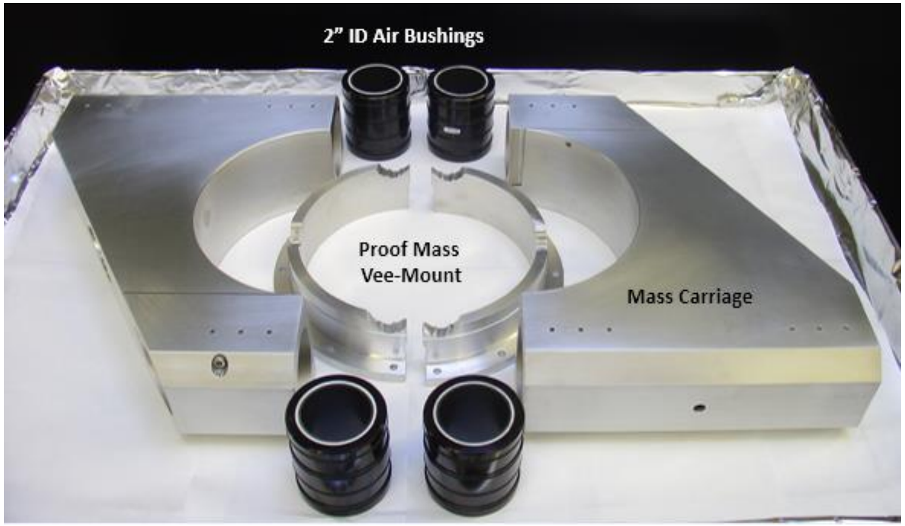
Discover high mass objects through their gravitational signature

AOSense/LLNL collaboration. (www.aosense.com)

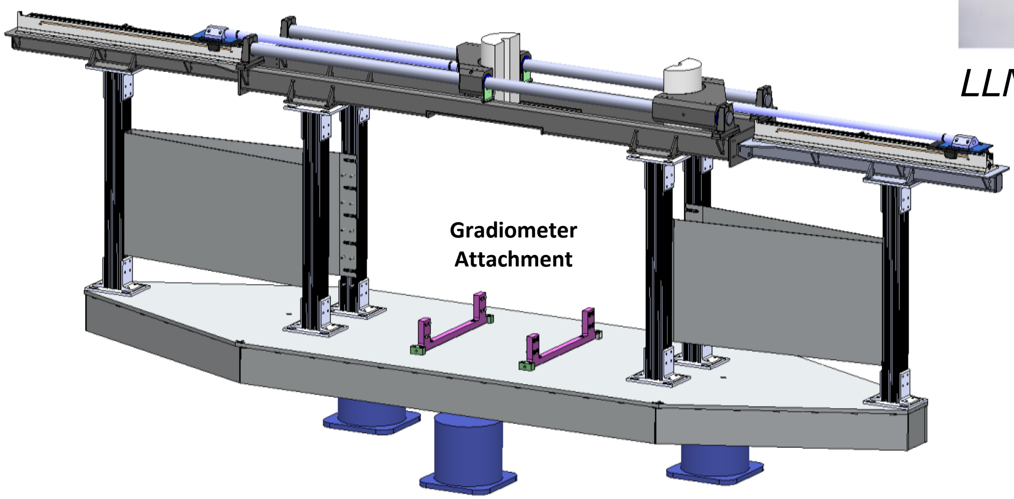
Joint LLNL/AOSense/Stanford G Measurement

LLNL: Proof mass metrology (co-I S. Libby)
AOSense: Gravity gradiometer (co-I T. Loftus)

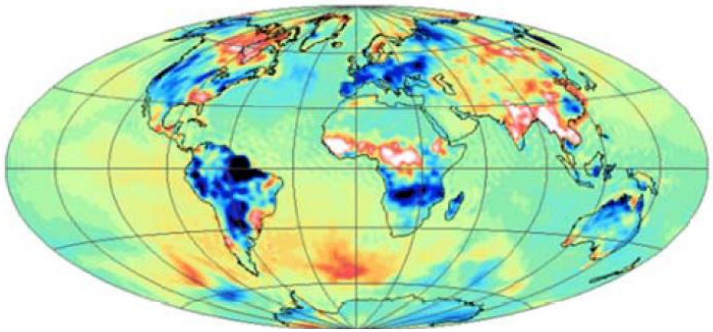
Objective: $\delta G/G \sim 1e\text{-}4$

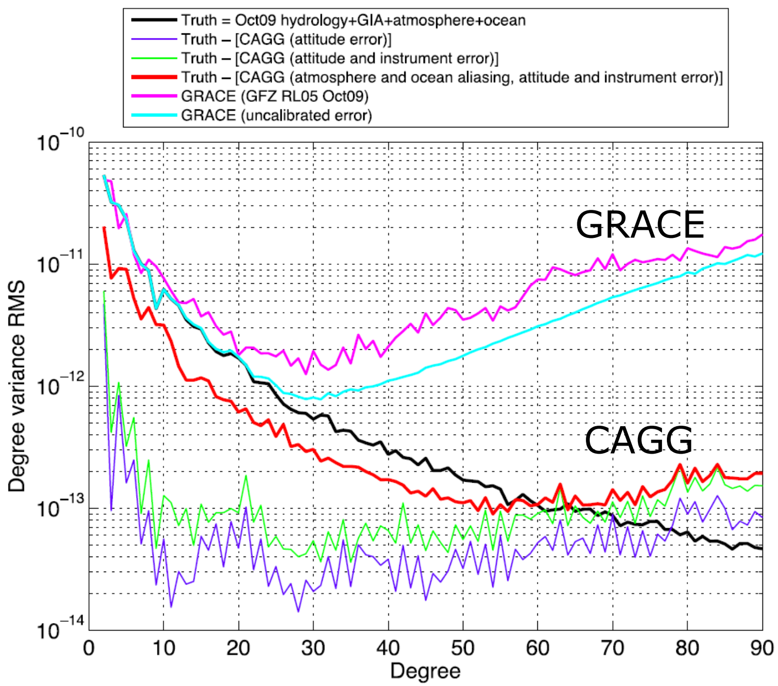


LLNL precision machined fixtures



Prototype gradiometer for satellite geodesy





Analysis from S. Luthke, GSFC

Simulation of hydrology map from space-borne atom interferometer gravity gradiometer.

~ 1 cm equivalent water height resolution.

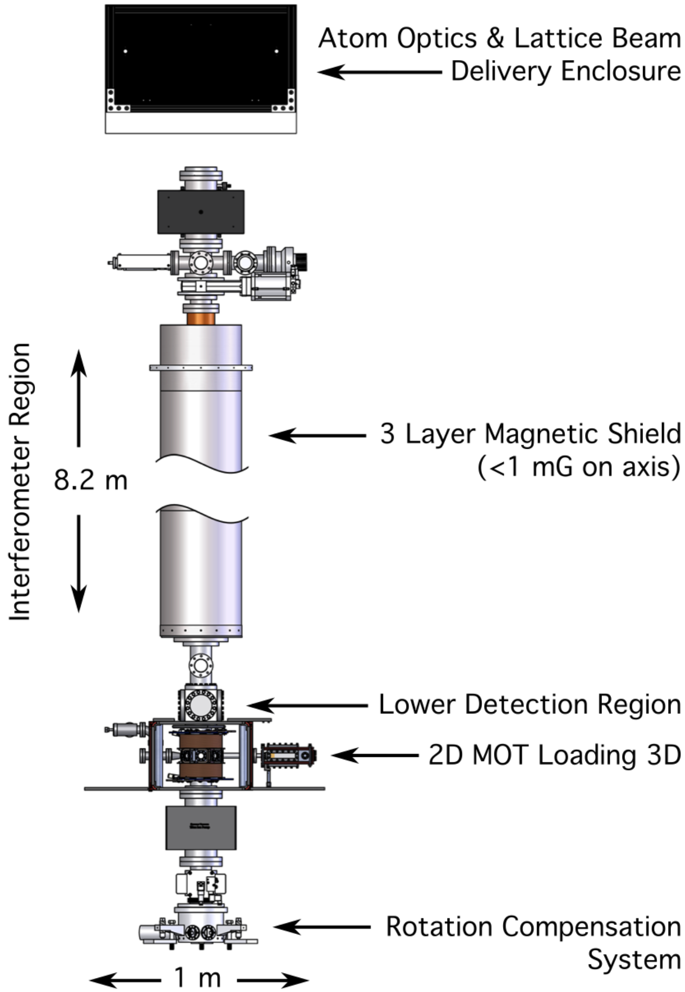
Instrument:
- 1 m baseline
- single-axis
- rotation compensation

Development of prototype recently funded by NASA IIP (Saif, PI); Instrument to be built by AOSense, Inc.

Defense sensors

- High accuracy AI gradiometers will become commercially available in the next 5 years (subject to ITAR).
- Will support G determination at the < 1e-5 accuracy level.
- Error models and noise performance understood across generations of instruments.
- Proof-mass metrology and personnel salary likely the dominant expense in performing a G measurement with this hardware class.

2014 Stanford 10 m baseline interferometer



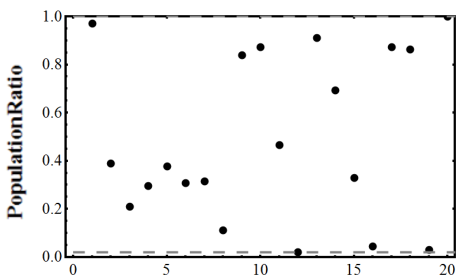
Current demonstrated statistical resolution, ~5e-13 g in 1 hr (87Rb)

Gravitational acceleration from 40 cm dia. sphere (10 g/cm^3), 40 cm from center of sphere is ~5e-8 g.

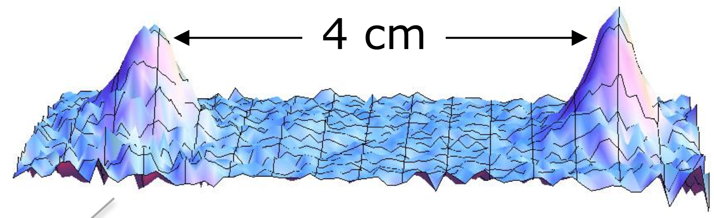
Suggests feasibility of ppm class measurements.

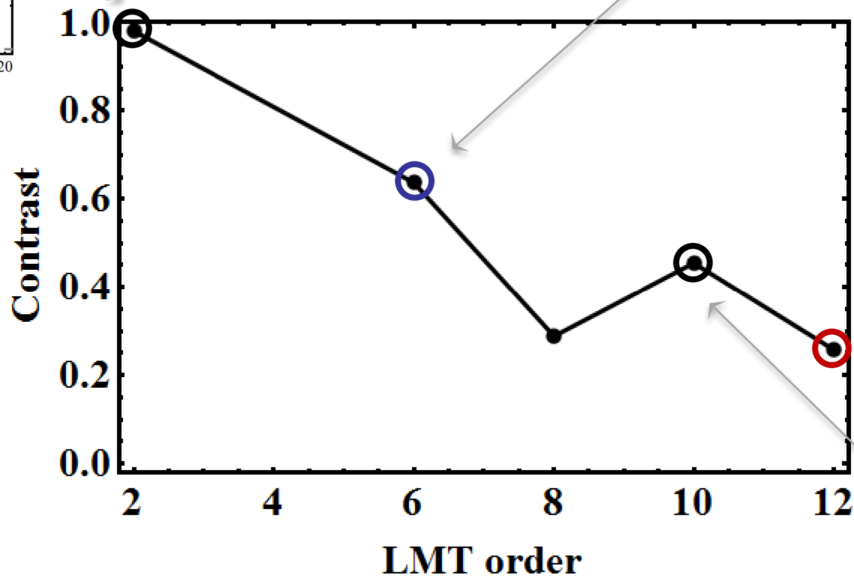
Large wavepacket separation

Sequential Raman transitions with long interrogation time.

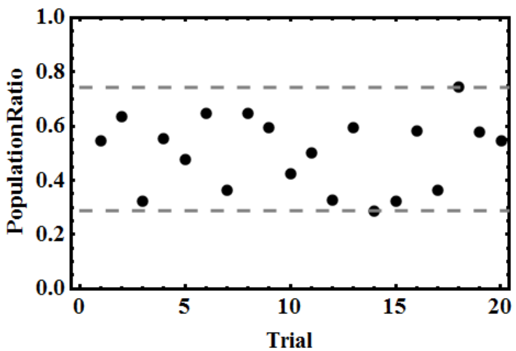


>98% contrast



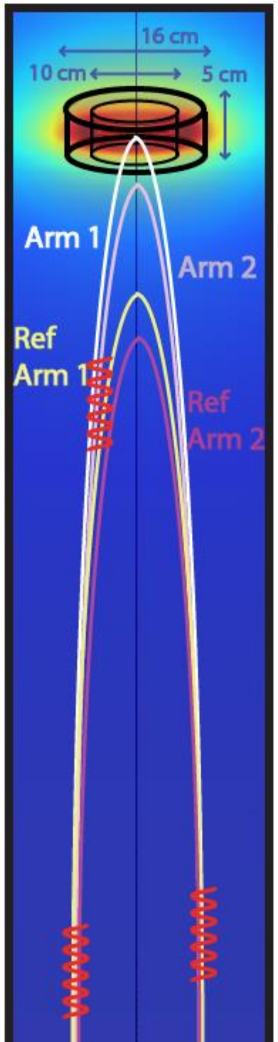


8 cm wavepacket separation

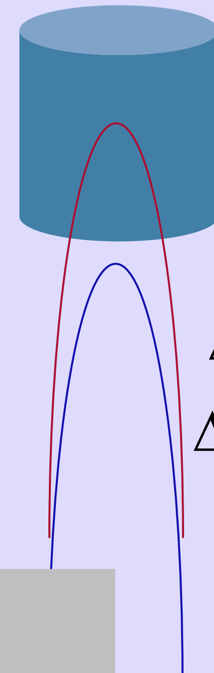


LMT demonstration at 2T = 2.3 s
Contrast loss consistent with spontaneous emission

G in the 10 m tower



$$\Delta\phi_{tot} \approx 700 \text{ mrad}$$



$$\Delta\phi_{las} \approx 54 \text{ mrad}$$

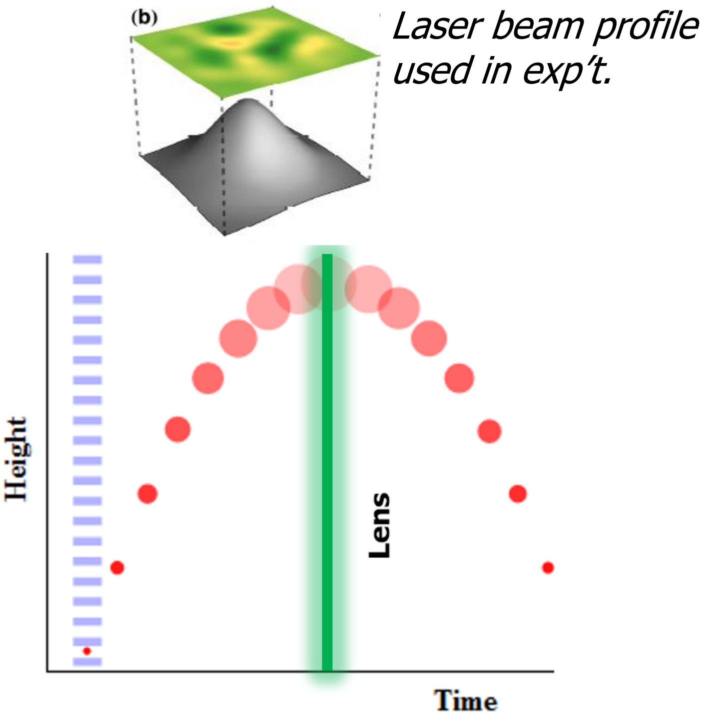
$$\Delta\phi_{prop} \approx 1400 \text{ mrad}$$

Sample 8ħk interferometer simulation with T = 1.2 s

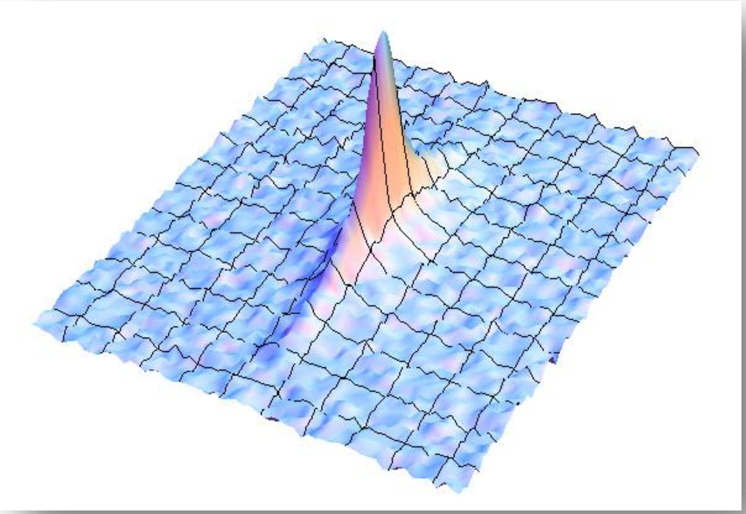
Ultra-ultra cold atoms

Dramatically improved control over atom velocity distributions.

A lens for atom clouds is realized using a laser beam:



Atom cloud refocused to <200 microns (resolution limited) after 2.6 seconds drift.

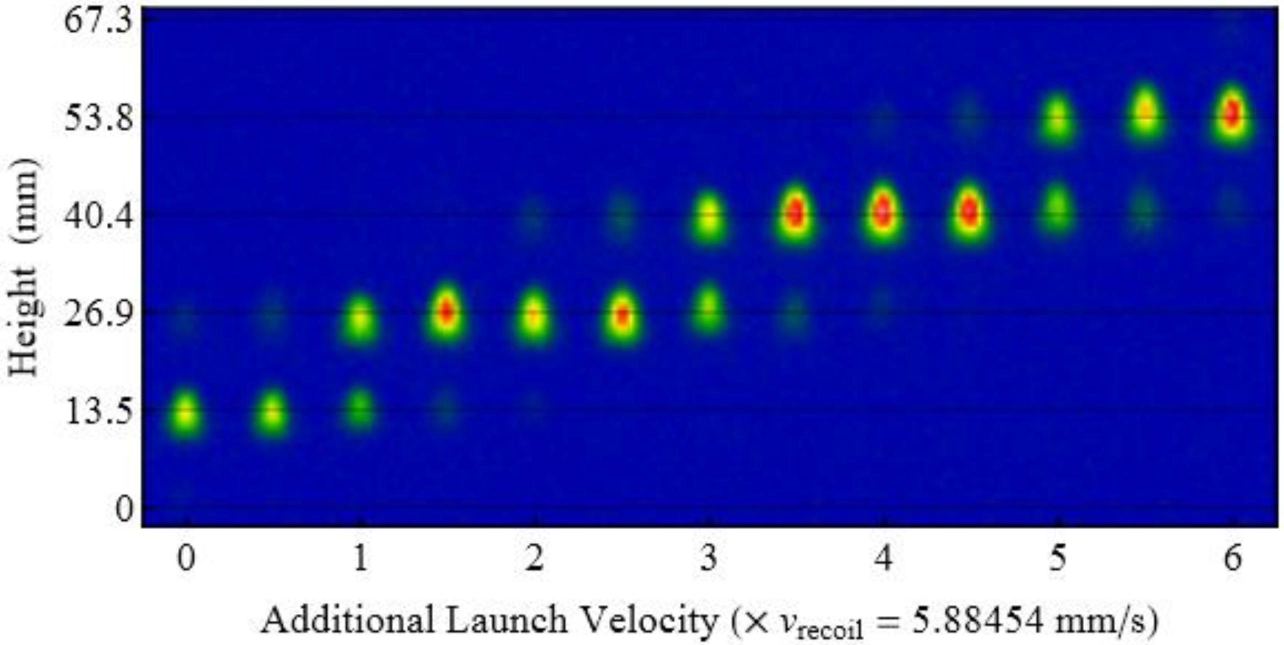


Collimated cloud has inferred effective temperature of 50 picoKelvin

Kovachy, et al., arXiv 1407.6995

Vertical velocity determination

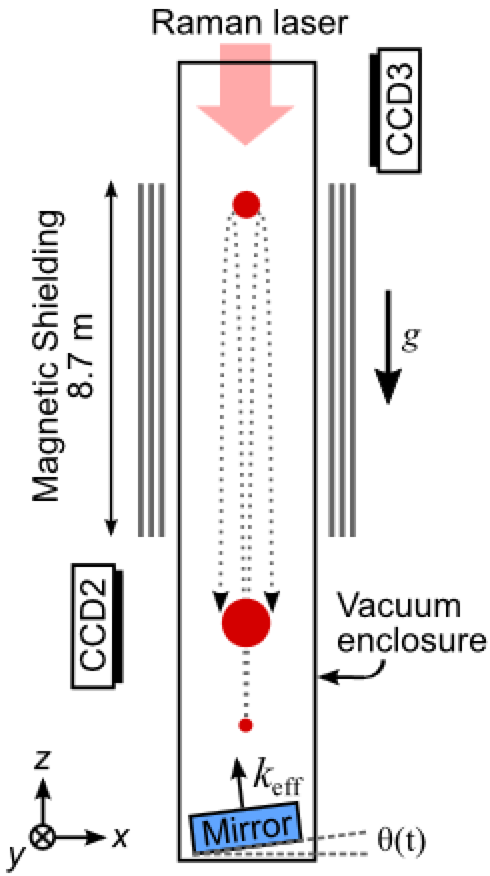
Excellent control over the mean vertical velocity using delta-kick cooled atomic source and an optical lattice launch.

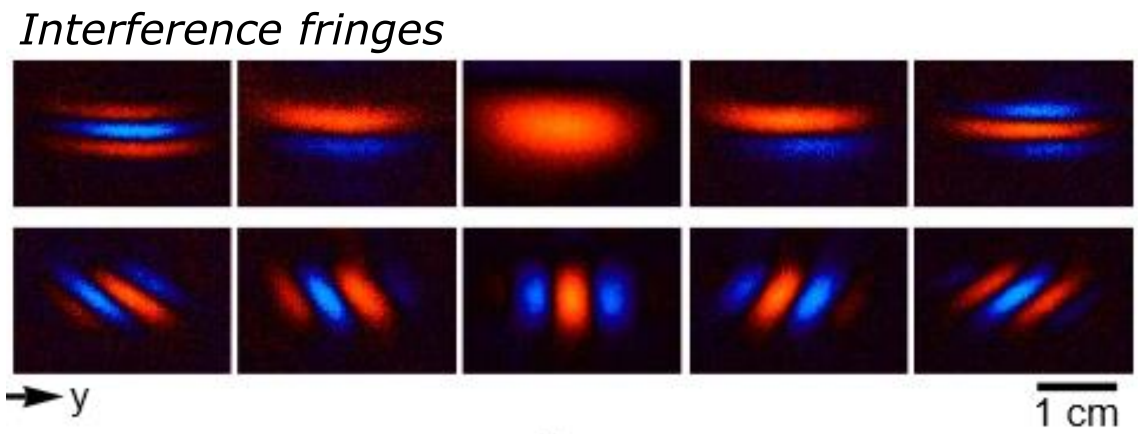


>2000 photon recoils to launch to top of tower.

Momentum transferred in 2 photon recoil increments.

Point source interferometry/spatial readout





Exploit point-source geometry to directly detect phase shift as a function of atomic trajectory.

Avoids signal integration errors from previous instruments.

G Measurement at Stanford

- Trade exceptional instrument sensitivity for proof-mass homogeneity.
- Measurement in a regime where quantum (recoil) phase shift terms dominate.
- Proof-of-concept in FY15.
- Pathway to < ppm sensitivity.

Thanks

Stanford:

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Tim Kovachy
Christine Donnelly
Chris Overstreet

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Tom Loftus
Bent Young
Mike Matthew
Miro Sverdin
Boris Dubetsky
Alan Zorn

LLNL:

Steve Libby
John Taylor
Vijay Sonnad
Pete Fitsos
Pete Davis
Stan Edson
Michael Johnson