Laser-cooled Atom Gravity Instrument Trends and Prospects for Future Applications

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Agenda

- Accelerometer Technologies
- What is Laser-cooled Atom Interferometry Technology (LAIT)?
- Comparison of Gravity Instruments
- NGA/NASA/NGS ABS GRAV Prototype Development
- Future Applications for Geodetic/Gravity Instruments

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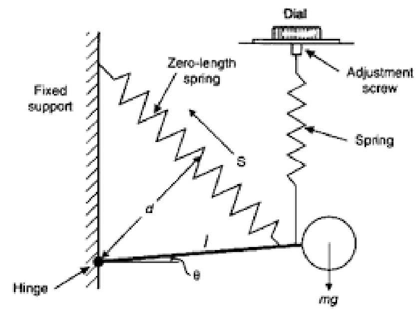
Mass-Spring Accelerometer

- LaCoste Romberg
  - Faithful Standard
  - Adjust dial to take measurement
- Lockheed-Martin - Gradiometers
  - Captive Proof Mass
  - Measures Capacitance
- Optomechanical
  - New Technology – Optical Cavity
  - Mass supported by two leaf springs – Hooke’s Law
  - Laser used to measure change in optical cavity



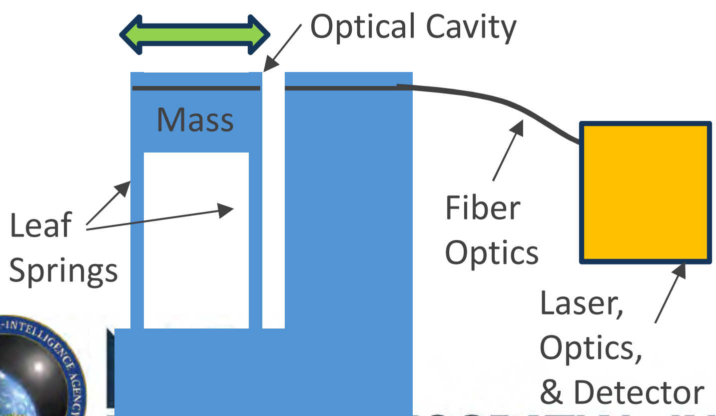
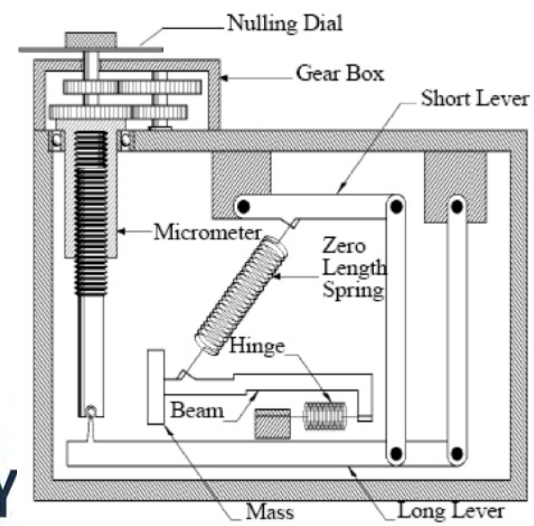


Image used with Lockheed-Martin Approval.



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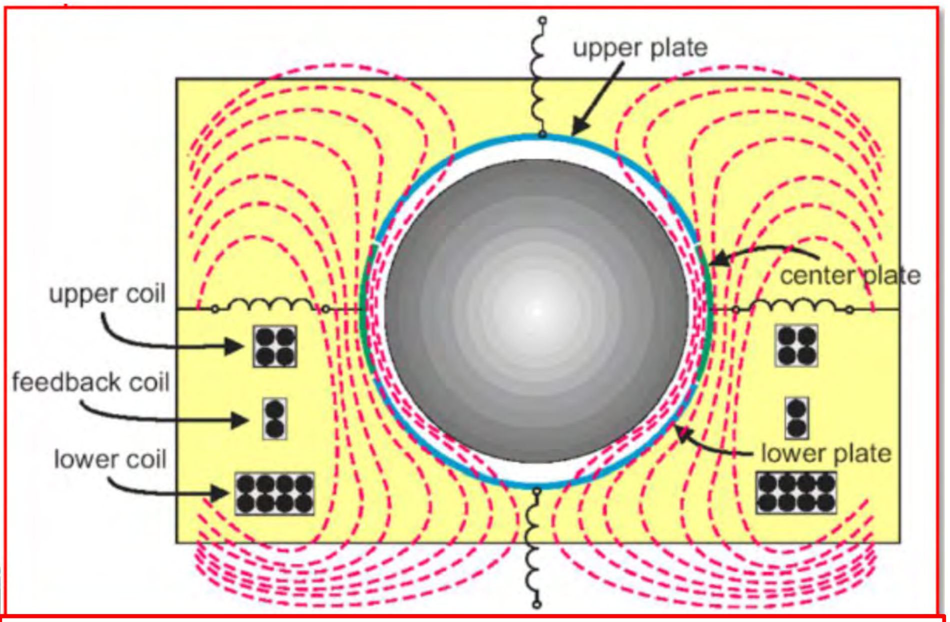
Levitated Mass

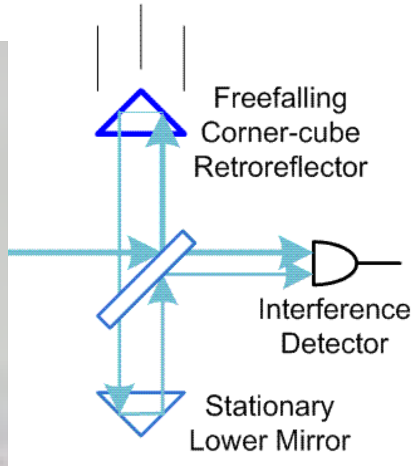
- GWR Superconducting
  - Nb Sphere levitated in chamber by magnetic fields
  - Upper and lower coils create a magnetic field to balance the force of gravity on the sphere at the center of a displacement transducer.
  - Requires liquid He to achieve 4° K.



Nb Test Mass Levitated in Magnetic Field

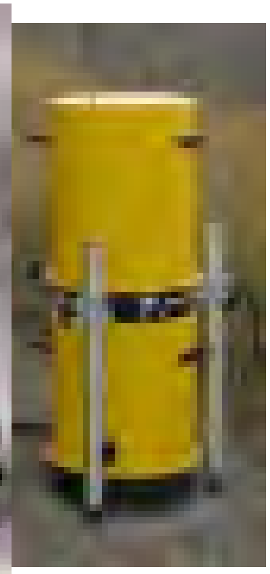
Images from GWR Website

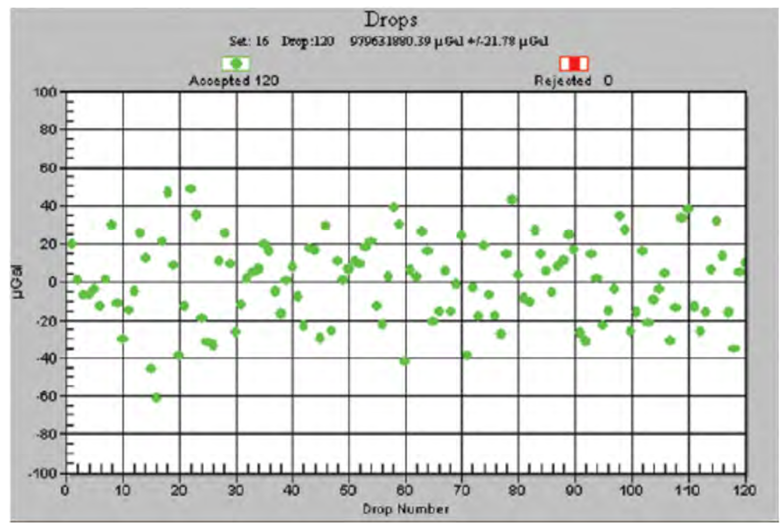
Free-Falling Mass



- A-10 or FG-5 Absolute Gravimeter
    - Falling Corner Cube in a vacuum
    - Laser used to measure acceleration
    - Interference resulting from the changing path length used for determining acceleration.
- Laser-cooled Atom Interferometer Technology (LAIT) based accelerometer
    - Measures acceleration with atoms.

So What is LAIT?





A-10 2 µGal averaging for 2 minutes

Images of NGA equipment and from Micro-g La Coste website and brouchers

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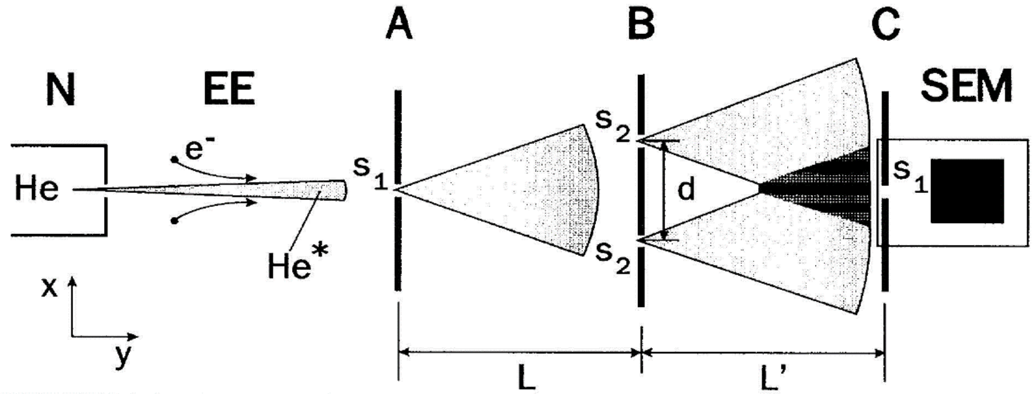
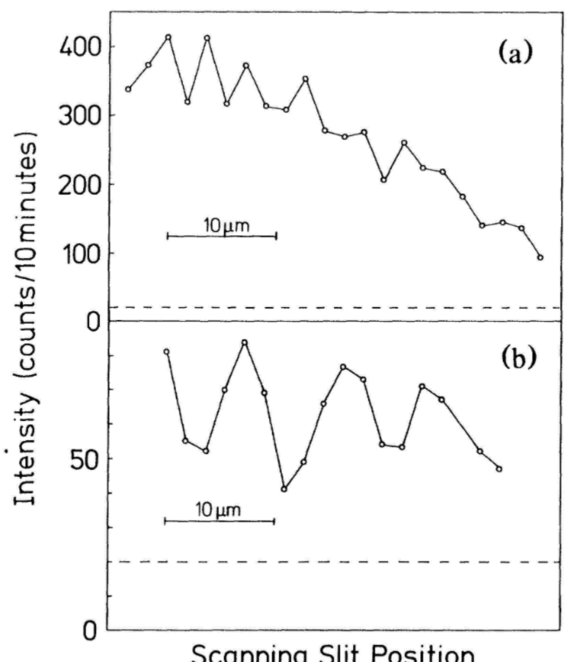
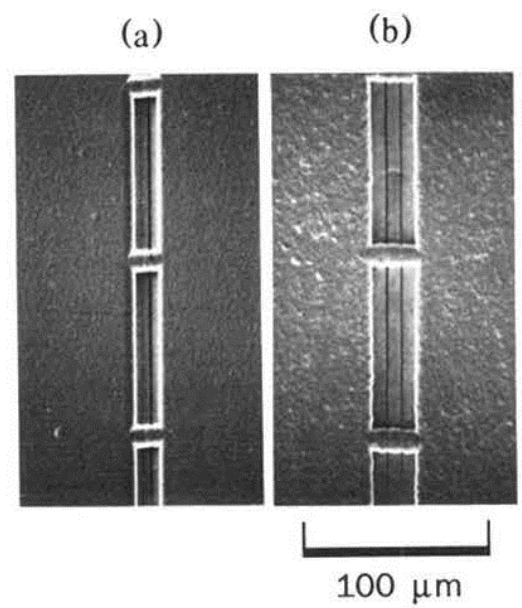
Wave Nature of Atom
(O.Carnal 1991)





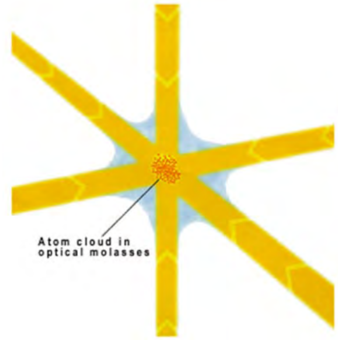


Beginning for Atom Optics

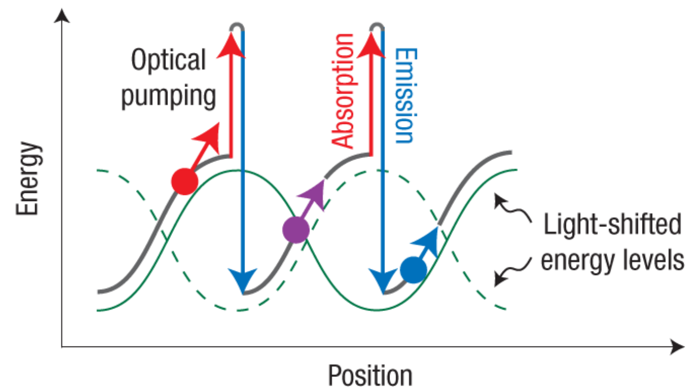
The Nobel Prize in Physics 1997

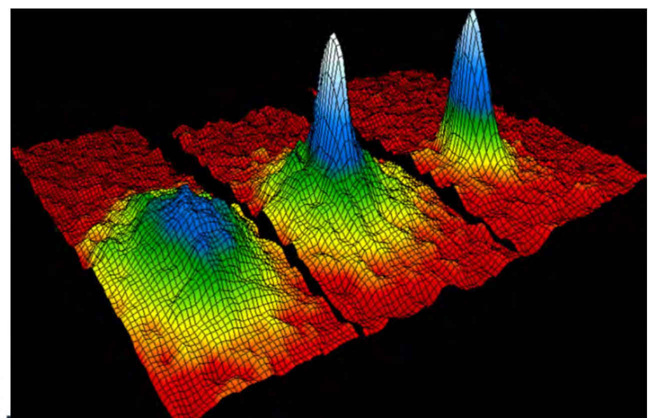
"for development of methods to cool and trap atoms with laser light"

Steven Chu	Claude Cohen-Tannoudji	William D. Phillips
USA	France	USA
Stanford University Stanford, CA, USA	Collège de France Paris, France and École Normale Supérieure Paris, France	National Institute of Standards and Technology Gaithersburg, Maryland, USA
1948 -	1933 -	1948 -



3D MOT for Laser-Cooling



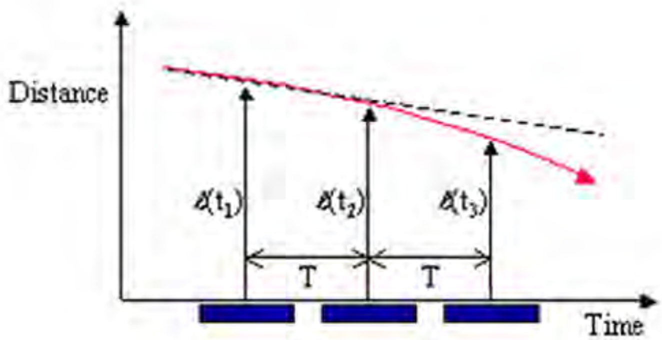


BEC

Images from NASA used with permission

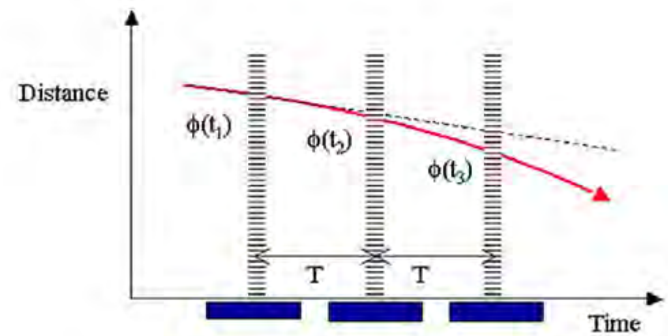
How to Measure Acceleration

Falling rock



- Determine trajectory curvature with three distance measurements $\ell(t_1)$, $\ell(t_2)$ and $\ell(t_3)$
- For curvature induced by acceleration **a**,
  a $\sim [\ell(t_1) - 2\ell(t_2) + \ell(t_3)]$

Falling atom



- Distances measured in terms of phases $\phi(t_1)$, $\phi(t_2)$ and $\phi(t_3)$ of optical laser field at position where atom interacts with laser beam
- Atomic physics processes yield
  a $\sim [\phi(t_1)-2\phi(t_2)+\phi(t_3)]$

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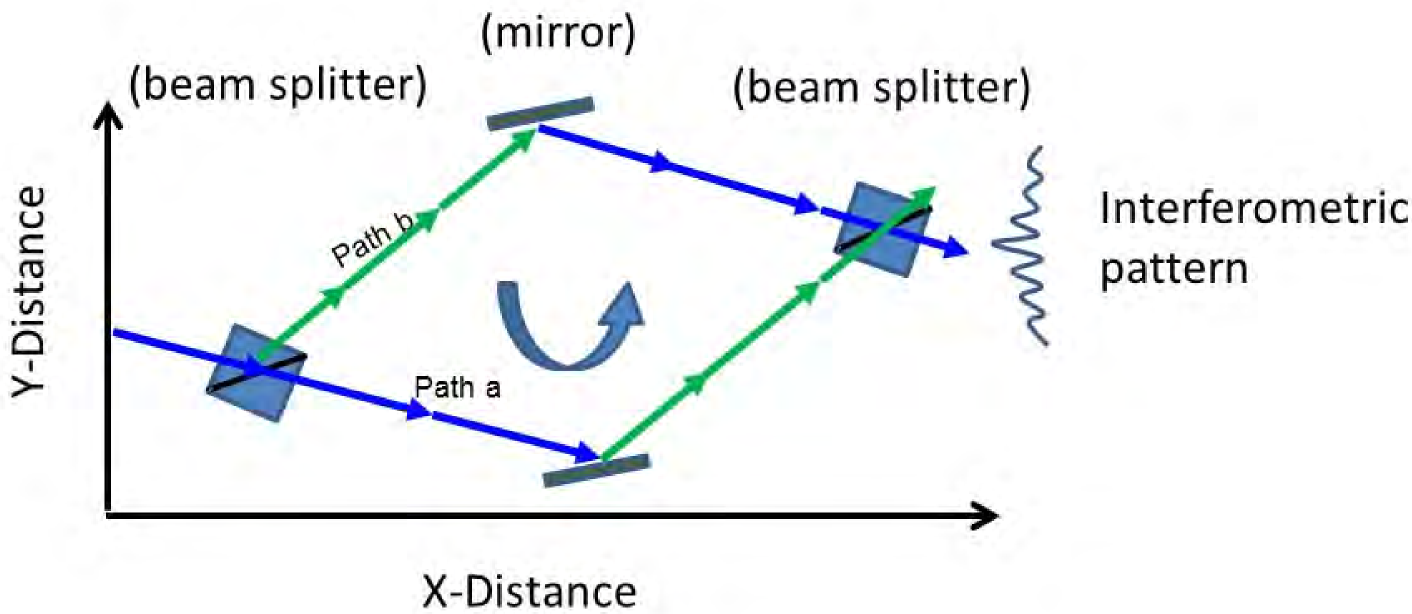
LAIT Accelerometer

Fundamental Concepts Regarding the Physics

Optical Interferometry



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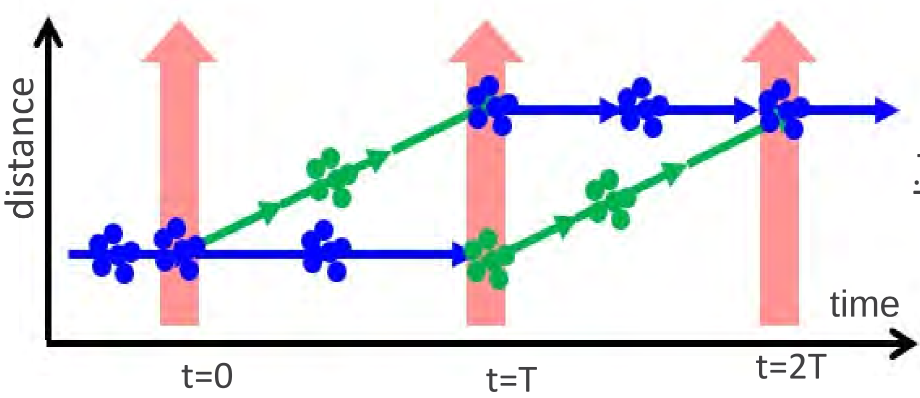
LAIT Accelerometer

Fundamental Concepts Regarding the Physics

Atom Interferometry
(analog of optical interferometry)

No *g*



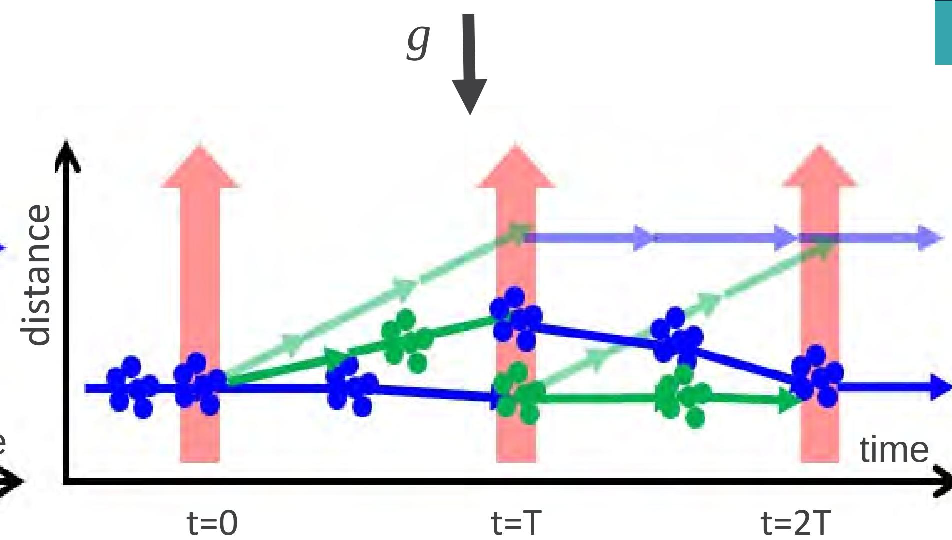
π/2
Raman Laser Pulse
(beam splitter)

π
Raman Laser Pulse
(mirror)

π/2
Raman Laser Pulse
(beam splitter)

For *No Gravity* path a is the same as path b

g



π/2
Raman Laser Pulse
(beam splitter)

π
aman Laser Pulse
(mirror)

π/2
Raman Laser Pulse
(beam splitter)

With Gravity, path a and path b have different lengths. This introduces a phase shift, ΔΦ, where ΔΦ is a function of ***g***.

Acceleration ~ Φ(t=0) - 2Φ(t=T) + Φ(t=2T)

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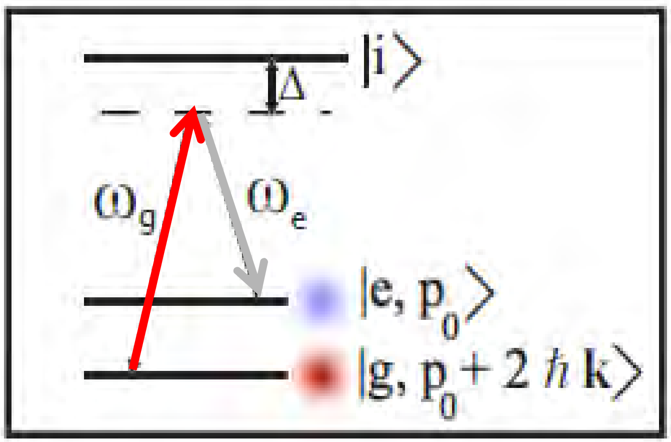
LAIT Accelerometer

Fundamental Concepts Regarding the Physics

Simulated Raman Transitions



An atom absorbs a photon of one frequency and emits another photon of another frequency.

Since Momentum is conserved and both photons carry a different amount of momentum, the atom receives a recoil momentum kick, related to

$$(\omega_g - \omega_e).$$

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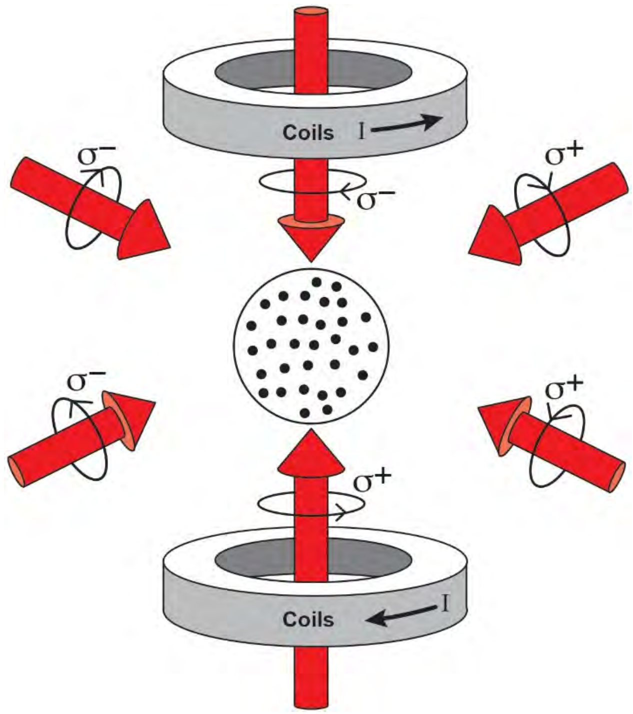
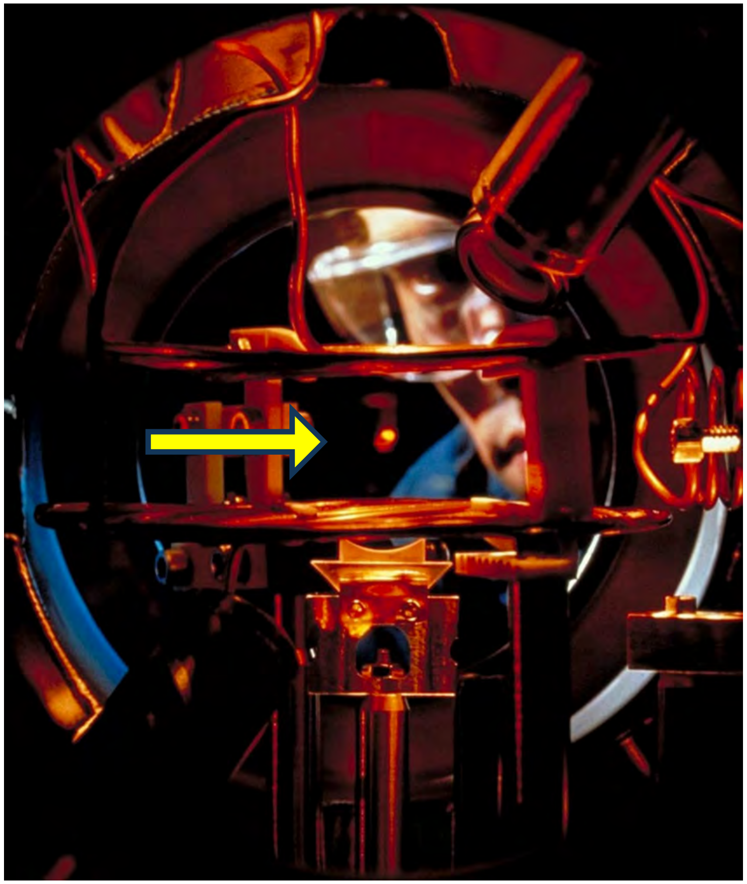
How to Generate Laser-Cooled Atom Clouds



3-D Magnetic Optical Trapp (MOT)



Sodium Atom Cloud in 3-D MOT

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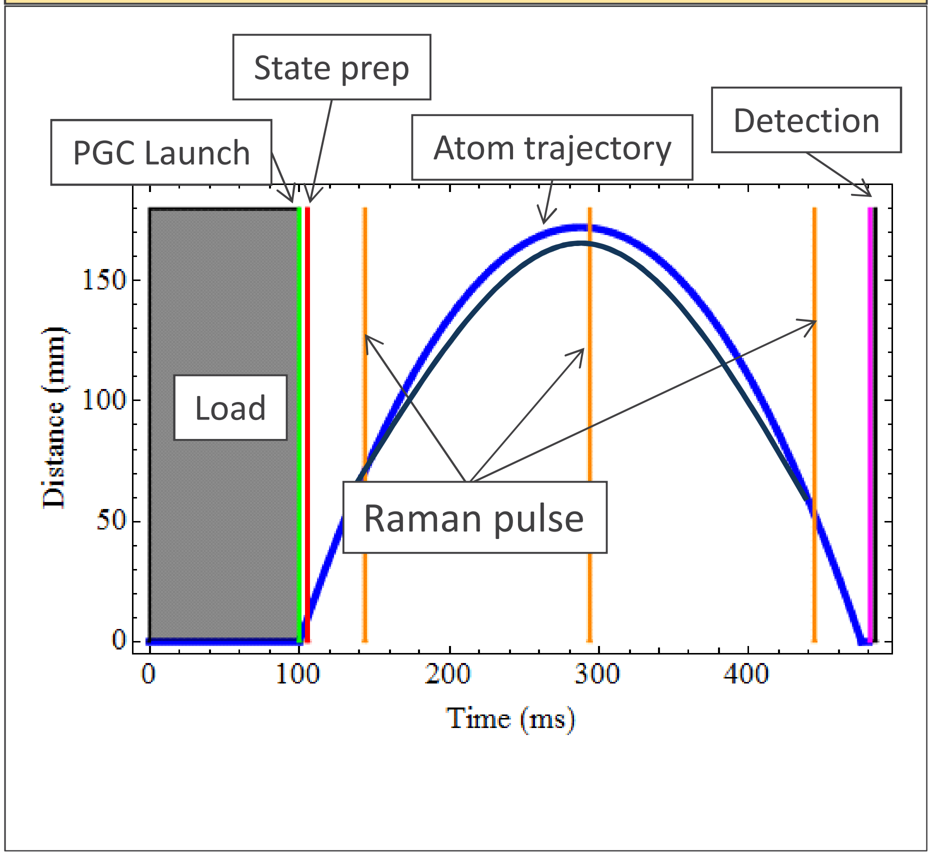
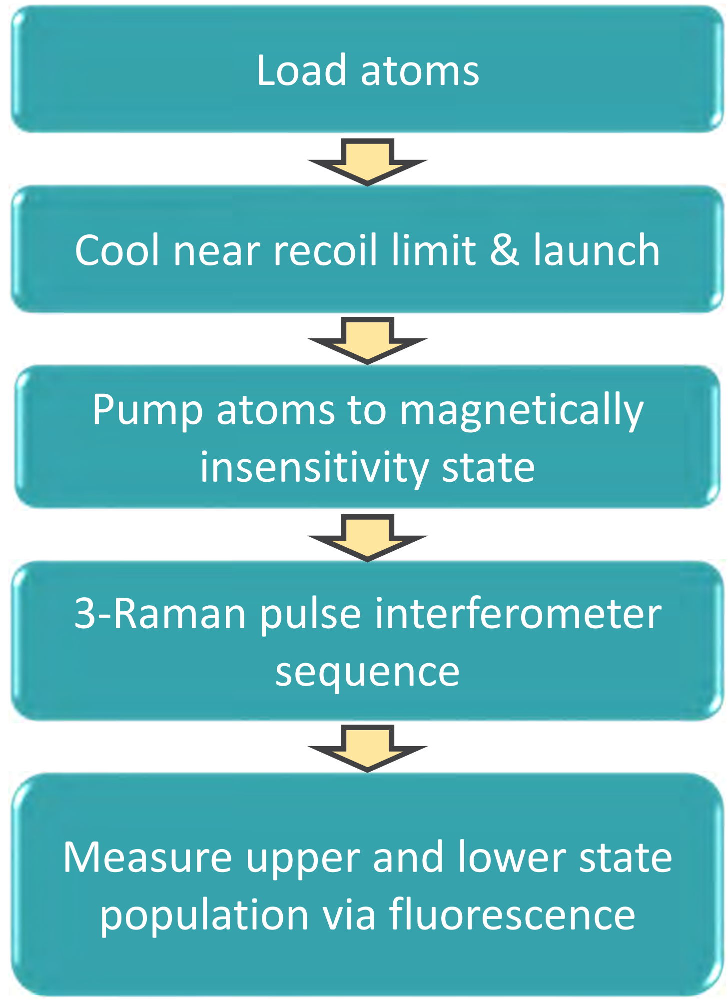
Gravimeter Timing Sequence

Single launch cycle gravimeter timing





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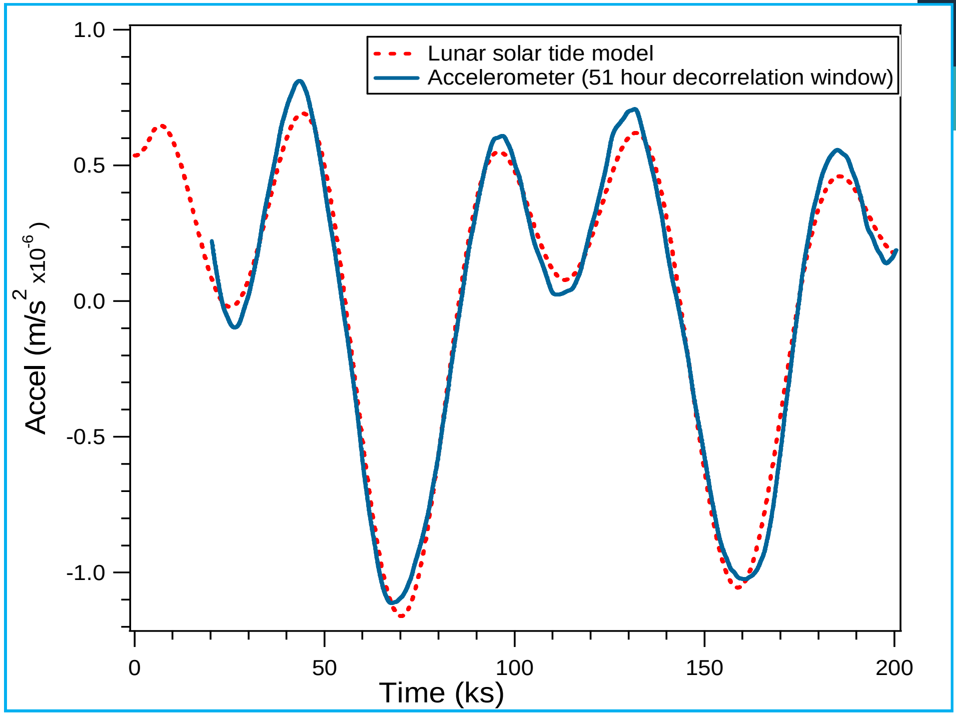
AOSense Commercial Gravimeter

AOSense commercial absolute gravimeter

- First commercial atom-optical sensor
- Precision: 0.7 mGal/Hz$^{1/2}$
- Shipped 11/22/10

2-Day Long Continuous Gravity Measurement
Observed By AOSense Gravimeter



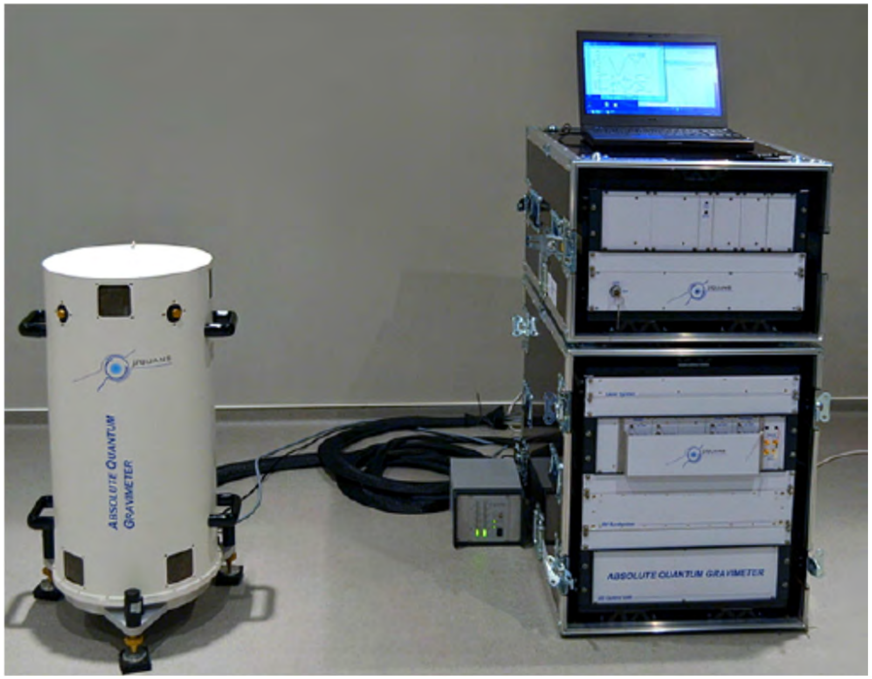
Lunar-solar variation due to variations in the relative positions of the sun and moon.

Images and Data used with permission of AOSense, Inc.

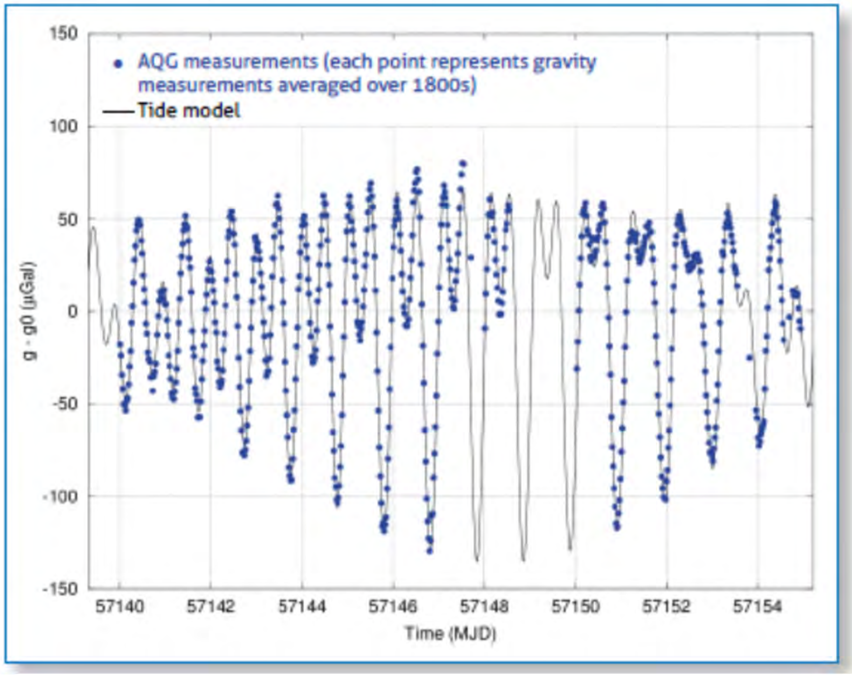
μQUANS Absolute Gravimeter

μQUANS AQG commercial absolute gravimeter

- Precision: 50 μGal/$Hz^{1/2}$
- Performance in a controlled environment
- Commercially available 2013 (?)



15-Day Long Continuous Gravity Measurement Observed By μQUANS Gravimeter



Lunar-solar variation due to variations in the relative positions of the sun and moon.

Images and Data used with permission of μQUANS.

Gillot, P. et al., Stability comparison of two absolute gravimeters at their best capabilities: optical versus atomic interferometers, Metrologia 51, L15-L17 (2014).

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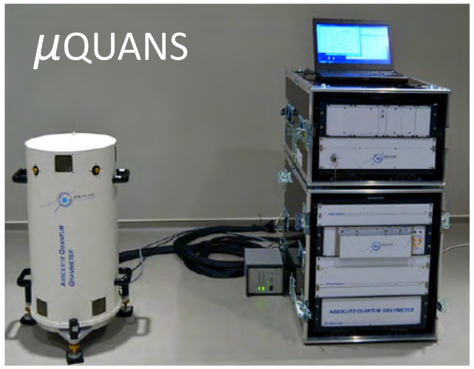
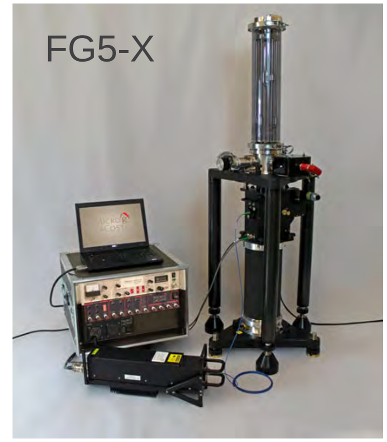
Comparison of Gravimeter Technologies



Laser-cooled Atom Interferometry



Falling Corner Cube

Absolute Gravimeters

Superconducting

gPhoneX

Spring systems

Relative Gravimeters

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Comparison of Existing Gravimeters

Manufacture/Model	Type	Absolute/ Relative	Volume/Weight	Sensitivity µGal/√Hz	Accuracy µGal	Drift µGal/mo.
AOSense Sensor	Laser-cooled Atom Interferometry	Absolute	45L/ 20 kg	700	>10 (?)	n/a
µQUANS AQG	Laser-cooled Atom Interferometry	Absolute	430L/ 100 kg	50	2.0-5.0	n/a
Micro-g LaCoste's **FG5-X**	Falling Corner Cube	Absolute	1500L / 320 kg	15	2	n/a
Micro-g LaCoste's **A-10**	Falling Corner Cube	Absolute	150L / 105 kg	100	10	n./a
GWR's iGrav	Superconducting	Relative	Dewar only, ~16L/ w/o LHe - 37 kg	0.3	0.3	0.5
GWR's OSG	Superconducting	Relative	Dewar only, ~16L/ w/o Liquid He - 150 kg	0.1	0.1-0.3	0.2
Micro-g LaCoste's gPhoneX	Zero-length Spring Suspension System	Relative	25L (Sensor)/ 48L (Electr.&Computer)/ 58kg	0.75	> 0.1	450
Scintrex's CG-5 (Canada)	Fused Quartz Spring System	Relative	14L / 8kg	< 1 (?)	1.0	600

Data used with permission or from manufacturer's open source website for educational purposes.

Why Absolute Gravimeter?

From the geodetic and geophysical perspective, absolute measurements have a clear advantage over relative measurements, due to their:

- lack of zero baseline ambiguity,
- calibration requirements, and
- drift.

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Reasons Why Current Absolute Gravimeters are Not Commonly Used?

- Acquisition cost differences between absolute and relative instruments;
- Maintenance costs, including user-provided maintenance, cleaning, and survey preparation;
- Survey support equipment costs (tents, generators, vacuum pumps, etc.);
- Costly in terms of transportation, setup, and operating time (days);
- Not Users Friendly (Limited number of skilled operators); and
- Environmental operating limits (power, site preparation, temperature, humidity, etc.)

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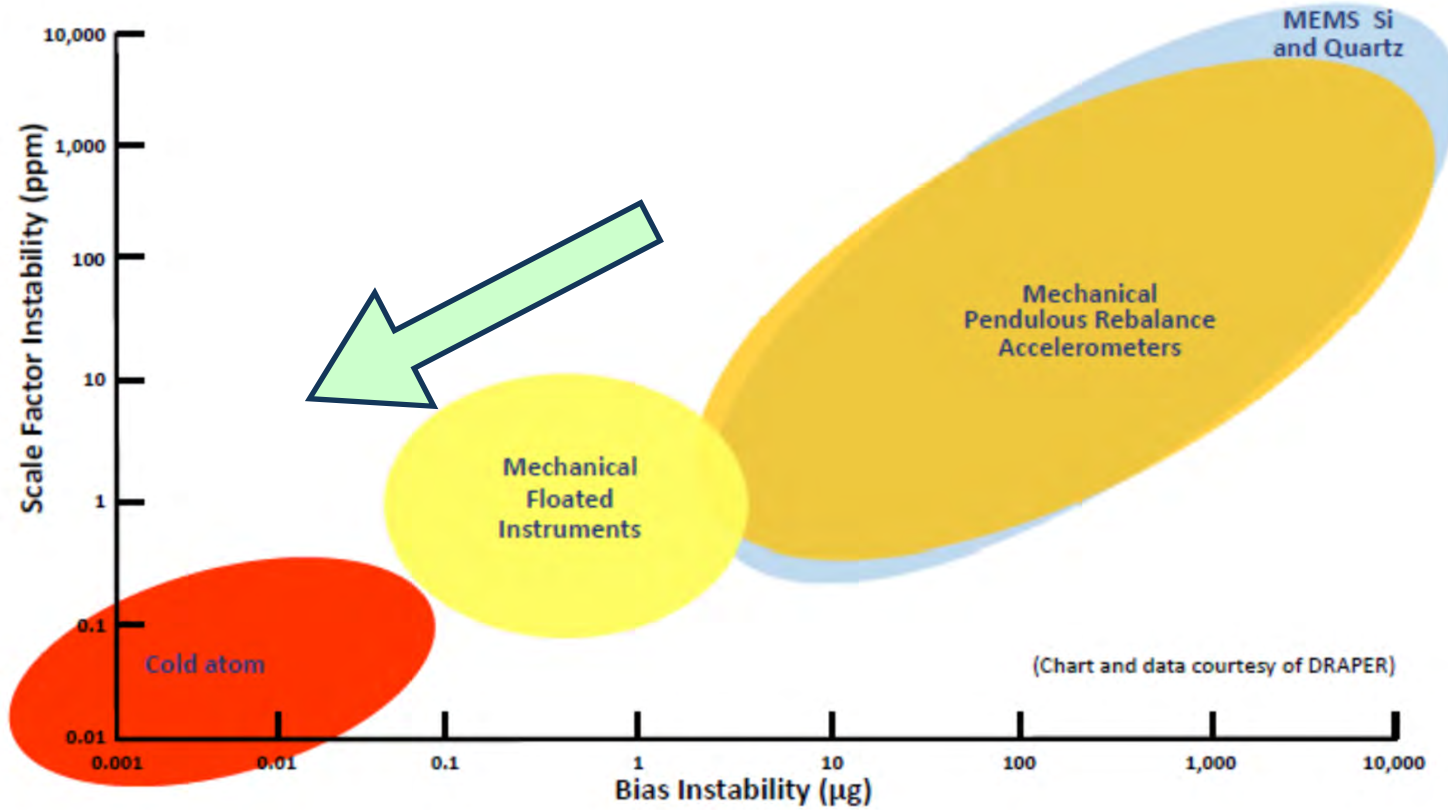
What is the Promise of LAIT?

- Greater Sensitivity and Higher Accuracies
- Promise of Lower Acquisition Costs;
- Lower Maintenance Costs, able to run unattended for months;
- Less survey support equipment costs (self contained);
- Single Person Portable (lower transportation/shipping costs);
- Less setup and operating time (less than an hour);
- User Friendly Operation; and
- Field able operations (lower power, wide range of temperature and humidity).

Accelerometer Performance Comparison



The Goal is to Realize the Promise of Cold Atoms

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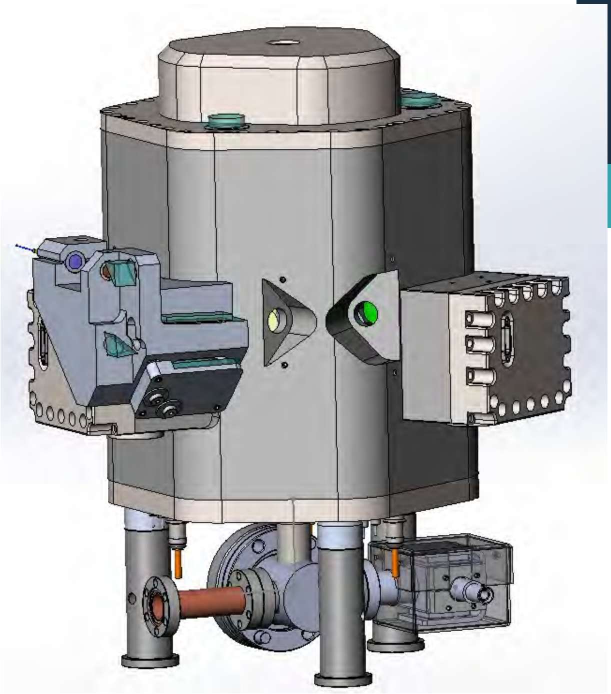
NGA/NASA/NGS Terrestrial Gravimeter

- **Designed for rapid terrestrial gravity survey.**
- Compared to state-of-the-art Micro-g FG5-X, AOSense design offers order-of-magnitude improvement in sensitivity and accuracy, start-up time, volume, and weight.
- Capable of sub 10 Eotvos gravity gradient measurement resolution.



NASA Contract #NNG14CR61C is supporting this work.

	N3T Gravimeter (projected)	FG5-X
Type	Atom interferometry	Falling corner cube
Volume	14 L sensor head/ 80 L electron. rack	1500 L
Weight	17 kg (38 lbs) sensor head/ 34 kg (75 lbs) electronics	320 kg
Resolution	0.1 μGal	~ 2 μGal
Sensitivity	0.3-3 $\mu\text{Gal}/\sqrt{\text{Hz}}$	15 $\mu\text{Gal}/\sqrt{\text{Hz}}$
Start-up time	~ minutes	~ hours
Site	noisy OK	quiet

Prototype #1: Begin testing soon, summer.

Prototype #2: Complete build next spring.

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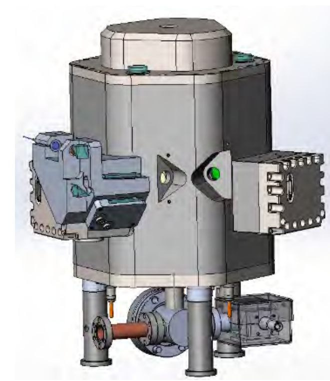
So What's in the Future, For Terrestrial Sensors?

- Decreases in the size and weight of the laser and electronic systems.
- A Sensor Head with magnetic shielding and thermal blanket that can work in the field and about size of a 5 gallon bucket.
- Accuracies better than a FG-5X with little to no maintenance.
- One person portable.
- Costs slightly higher than for a high performance relative gravimeters.



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So What's in the Future, For Terrestrial Gravity?

- How we do terrestrial gravity will be **REVOLUTIONIZED**.
- No longer will your sites be tied to an absolute station, every site can be measured with an absolute gravimeter.
- The ability to measure the vertical gradient of gravity at the same time at the 10 E level.
- A sensor capable of long term (several months) remote monitoring of sites.

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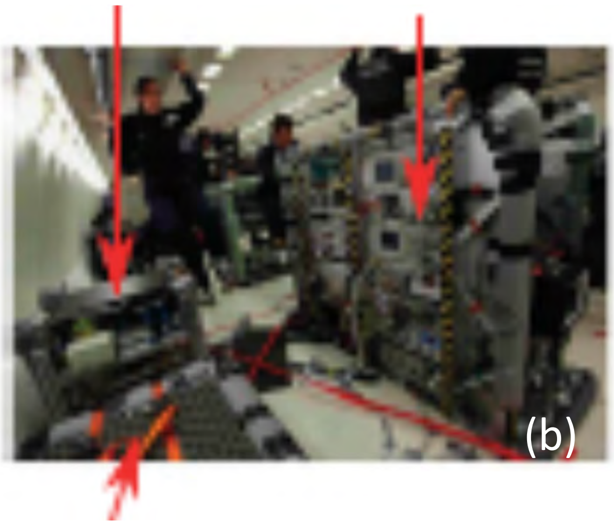
LAIT Airborne Tests

Institut d'Optique, CNRS & Observatoire de Paris. LNE-SYTRE with French Space Agency, CNES have already started testing.

Power Supply, laser amplifier, optical bench

Fiber laser sources, control electronics



3D MOT and fountain within magnetic shield

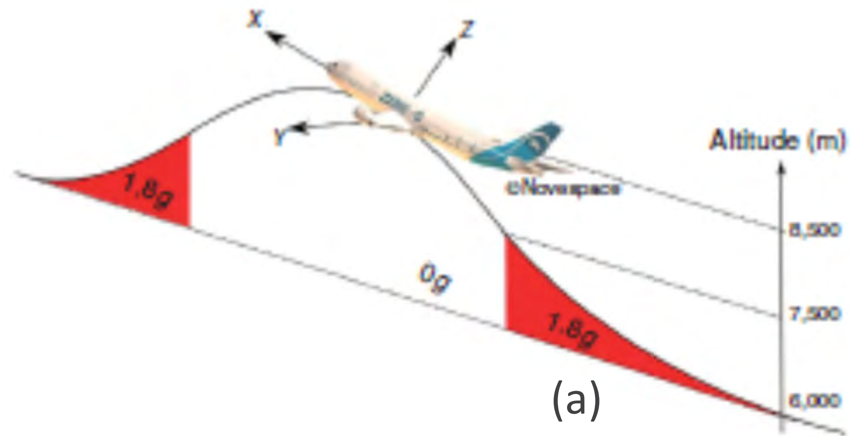


Figure 1 | Description of the experiment in the plane. (**a**) The parabolic manoeuvre consists of a 20 s pull-up hypergravity (1.8*g*) phase, the 22 s ballistic trajectory (0*g*) and a 20 s pull-out 1.8*g* phase. This manoeuvre is alternated with standard gravity (1*g*) phases of about 2 min and carried out 31 times by the pilots during the flight. (**b**) Picture of the experiment in the plane during a 0-g phase.

Claim to reach 0.02 Gal/√Hz

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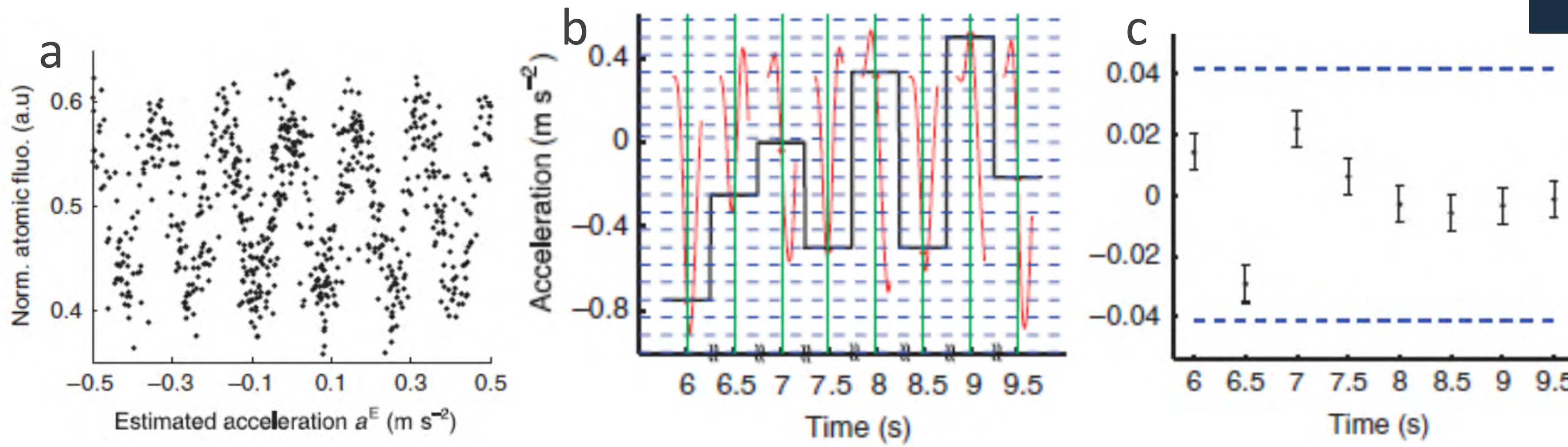
Geiger et al., Detecting inertial effects with airborne matter-wave interferometry, Nature Communications, 20 Sept. 2011.

Lessons Learn from Test

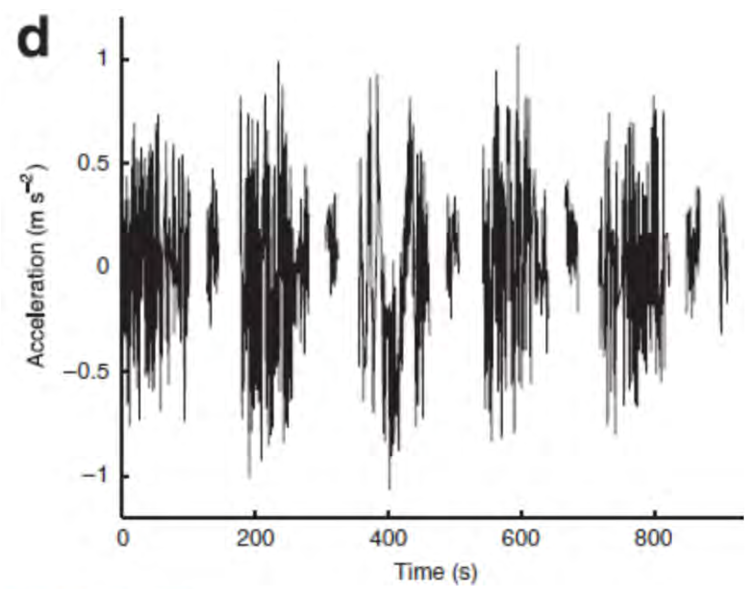


a) As sensor accelerates fringe under goes phase shift.

b) Mechanical accelerometer (MA) tracks accelerations (red) around measurement times (green) that supplies a coarse acceleration value (black line).

c) Then, the LAIT sensor can be used to determine the high resolution measurement within reciprocity region (between blue lines).

d) Coarse value from b and be added to c to determine accelerations shown in d.



- ➢ MA needed to keep track of fringe number.

Geiger et al., Nature Communications, 20 Sept. 2011.

What Does More Accurate Sensor Require?

It will require better modeling of gravity signals other than those associated with ground deformation, such as:

- **Hydrology:** This is, and will remain, the single largest contribution. However, the opportunity to detect and model hydrological effects. For a simple infinite slab model, a 1 μGal resolution would detect water table changes of 50 cm at 5% bulk porosity.
- **Ocean Loading:** The ocean loading tide is of order 5 μGal near coastlines. Improved earth rheology and ocean height models (including real-time satellite altimetry) would contribute too, and perhaps from, improved tidal models and observations.
- **Atmospheric Loading:** The nominal factor is 0.3 μGal/mBar. At the 1 μGal level, more detailed atmospheric model would be required.
- **Solid Earth Tides:** Better modeling of time varying solid earth tides.

*Thanks to Glenn Sasagawa (UCSD) for his comments on the topic.

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Summary

- LAIT Sensors for terrestrial gravity are already here, but they either not sensitivity enough or not one person portable.
- High sensitivity, lighter weight, smaller, low cost LAIT gravimeter are coming soon, within 5 years.
- LAIT based airborne gravimeter are in the works.
- Geodesists need to prepare for this new sensors with their higher accuracies.

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Thank You!

- Additional acknowledgement to Micro-g La Coste, and GWR for information off their websites.
- Miro Shverdin (AOSense, Inc.), Jean Lautier (μquans), and Pat Garten (Lockheed-Martin) for permission to use sensor information and images.
- Babak Saif (NASA/GSFC) for information and a couple slides.

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