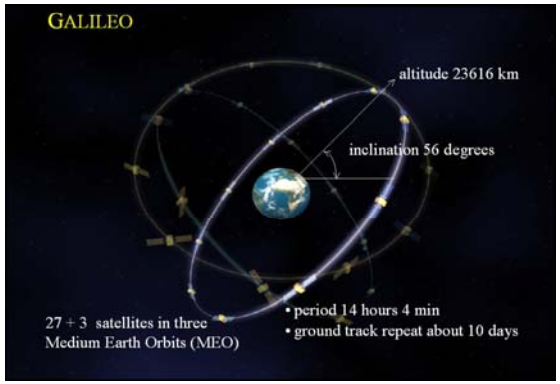
Cold Atom Navigation Sensors

Atom Interferometry Group
Stanford Center for Position, Navigation and Time
Mark Kasevich

Navigation strategies

- Radio navigation
  - Radio reference signals allow trajectory determination (eg. GPS)
- Inertial navigation
  - Trajectory determination with accelerometers and gyroscopes
  - “Black-box”
- Integrated Radio/Inertial
  - System initialization with radio
  - Inertial sustains navigation solution over radio lapses



Galileo constellation

HG 1900 series IMU

Next generation integrated INS/GPS

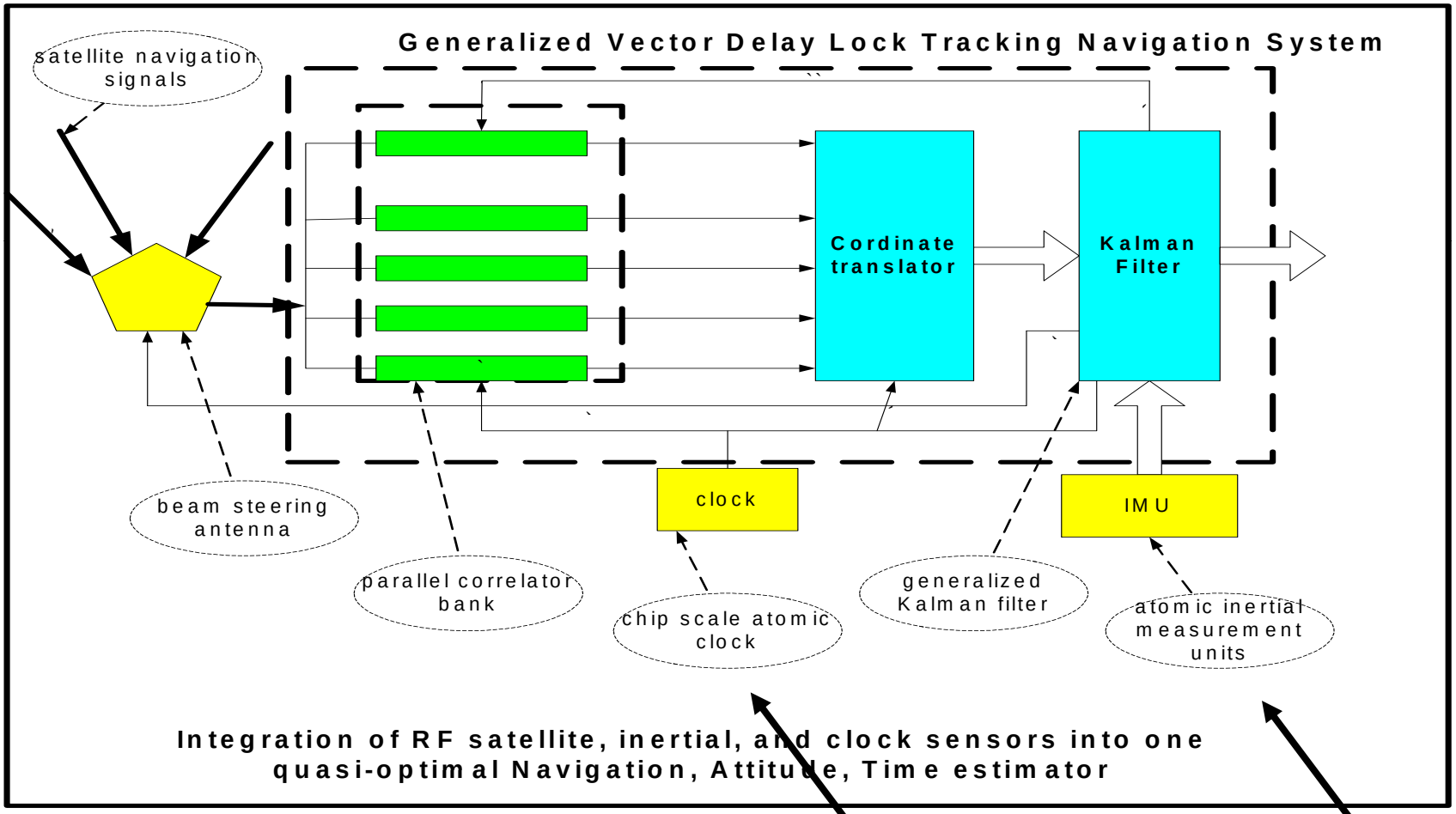


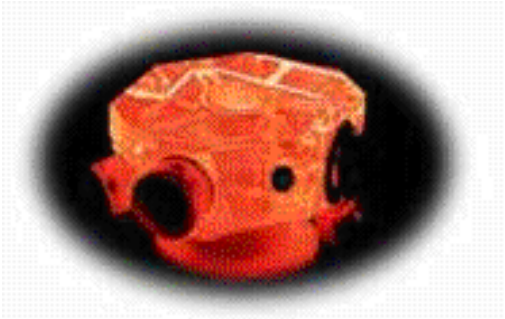
Diagram courtesy of Jim Spilker

Atomic physics contributions

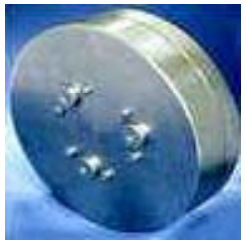
Navigation & physics

- Early in 20th century, prominent physicists argued against INS, citing Equivalence Principle
  - "problem of the vertical"

- Best inertial sensors are mechanical
  - MEMS, ring-laser and fiber-optic gyro have yet to be incorporated in very high performance systems



Ring-laser gyroscope



Fiber-optic gyroscope

Physics of space-time

- GP-B
  - gravitational warping of space-time
- LIGO
  - gravitational waves
- LISA
  - space-based gravity wave antenna
- ...

GP-B experiment;

Physics packages for these experiments have superb sensors.

Sensors are unsuitable for navigation.

And yet ....

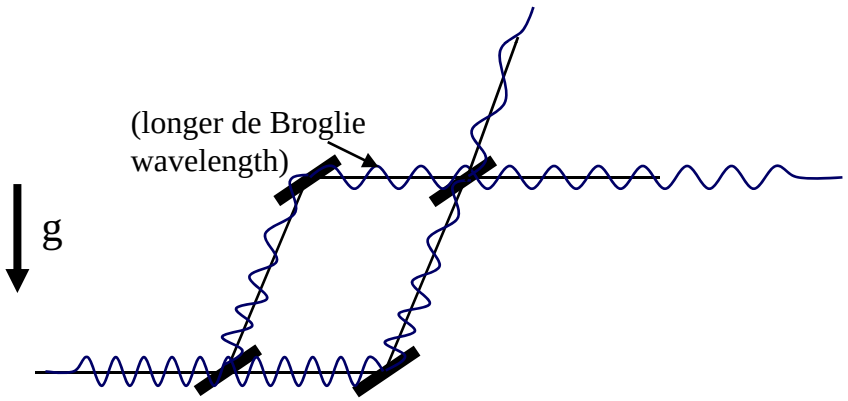
- Atomic physics community is evolving a new class of inertial sensors based on de Broglie wave interference which appear to enable

  low cost, robust, high accuracy INS

de Broglie wave sensors

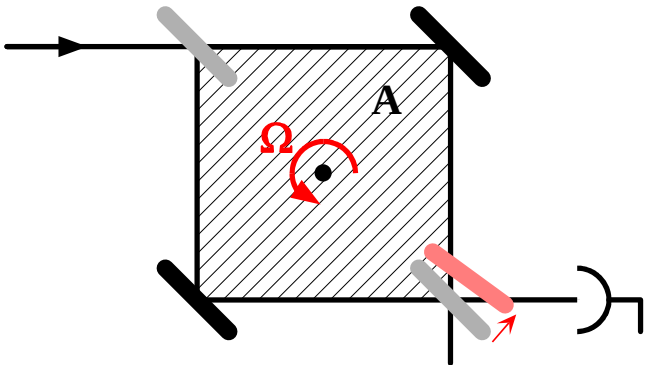
Gravity/Accelerations

As atom climbs gravitational potential, velocity decreases and wavelength increases



Rotations

Sagnac effect for de Broglie waves



Current ground based experiments with atomic Cs:

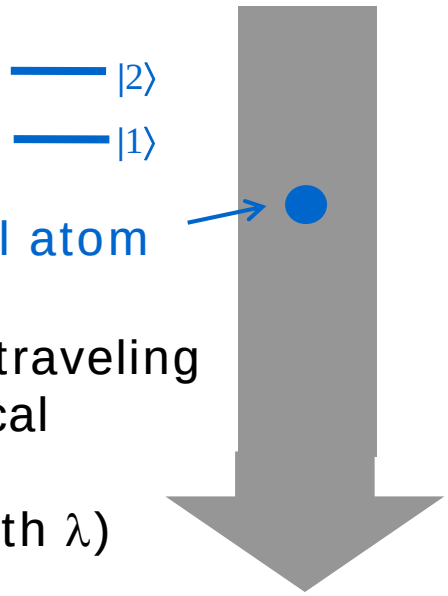
Wavepacket spatial separation ~ 1 cm,

Phase shift resolution ~ 10^{-5} rad

1 rad phase shift for 10^{-7} g acceleration or 0.1 Earth rate rotation

(Light-pulse) atom interferometry

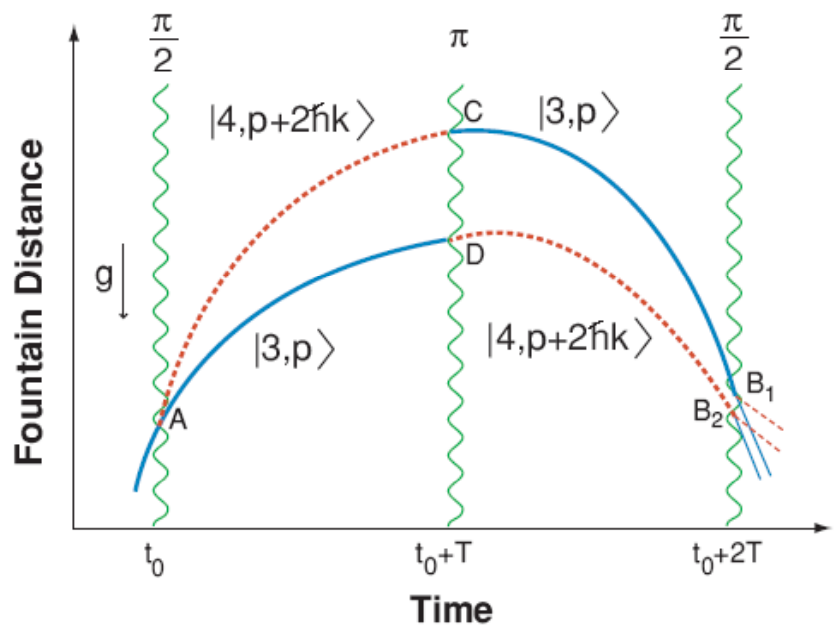
Resonant optical interaction



Resonant traveling wave optical excitation, (wavelength λ)

Recoil diagram

Momentum conservation between atom and laser light field (recoil effects) leads to spatial separation of atomic wavepackets.



Enabling Science: Laser Cooling

Laser cooling techniques are used to achieve the required velocity (wavelength) control for the atom source.

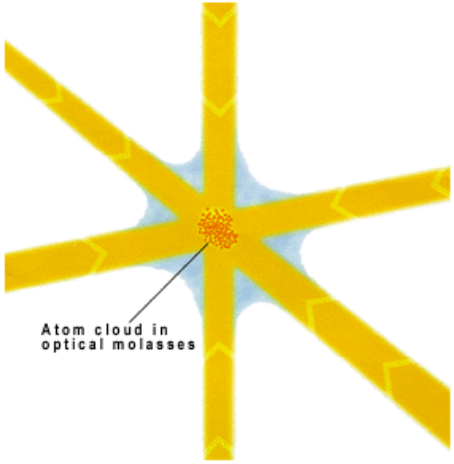
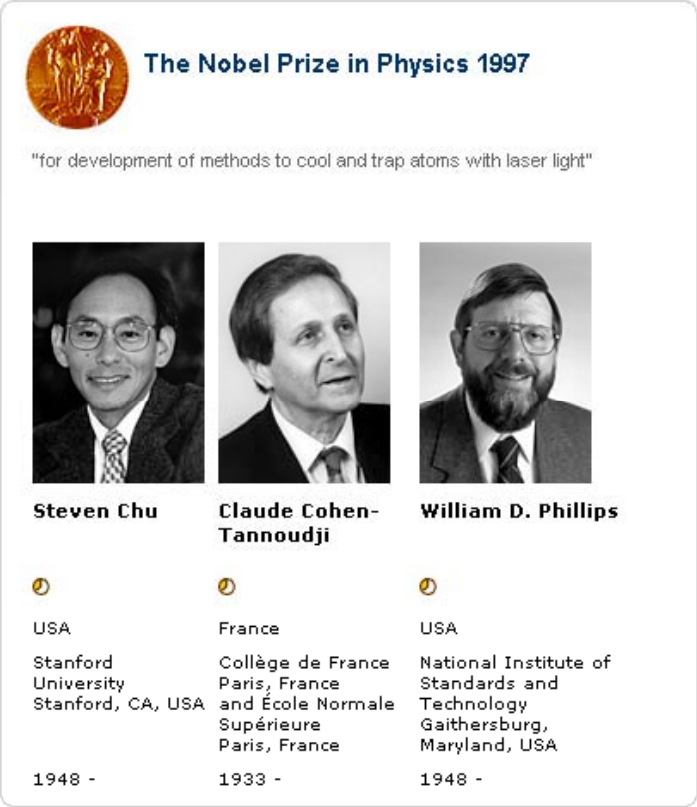


Image source:www.nobel.se/physics

Laser cooling: Laser light is used to cool atomic vapors to temperatures of ~10^{-6} deg K.



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 -

Light pulse sensor attributes

Atom is in a near perfect inertial frame of reference (*no spurious forces*).

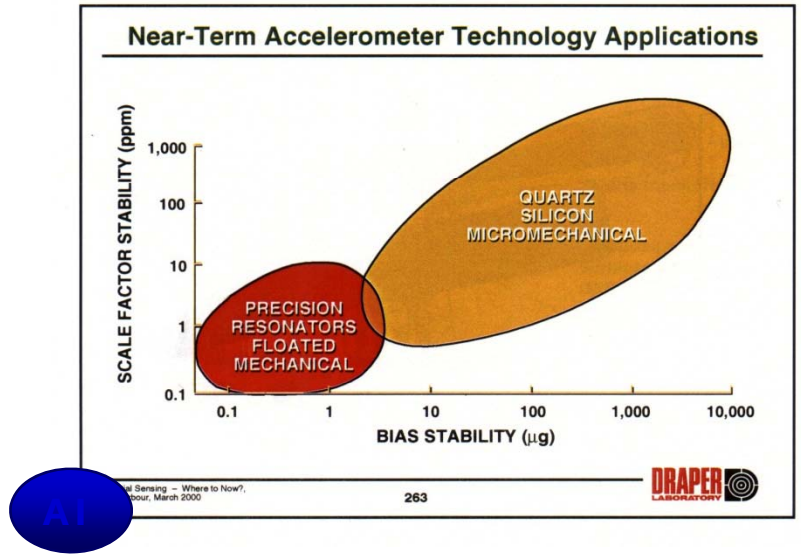
Laser/atomic physics interactions determine the the relative motion between the inertial frame (*defined by the atom deBroglie waves*) and the sensor case (*defined by the laser beams*).

Sensor accuracy derives from the use of optical wavefronts to determine this relative motion.

Sensor characteristics

Light-puse AI accelerometer characteristics

- Bias stability: $<10^{-10}$ g
- Noise: 4×10^{-9} g/Hz$^{1/2}$
- Scale Factor: 10^{-10}



Light-puse AI gyroscope characteristics

- Bias stability: <60 μdeg/hr
- Noise (ARW): 3 μdeg/hr$^{1/2}$
- Scale Factor: <5 ppm

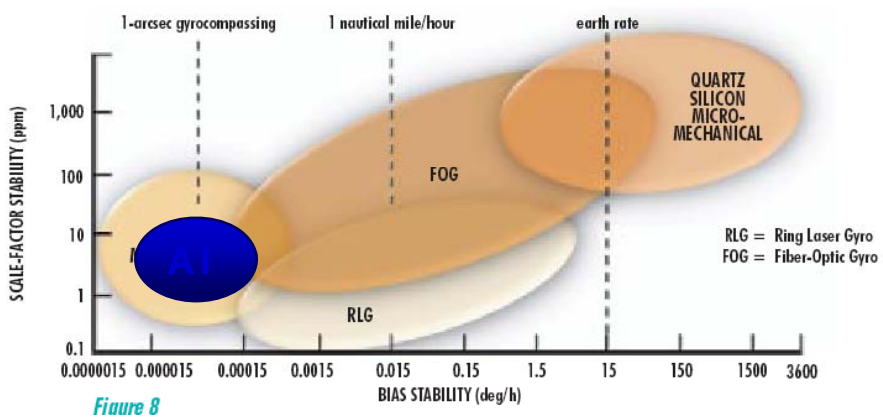
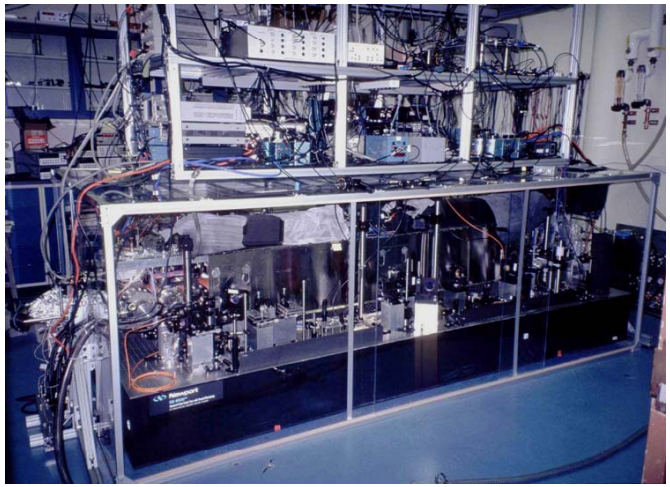


Figure 8

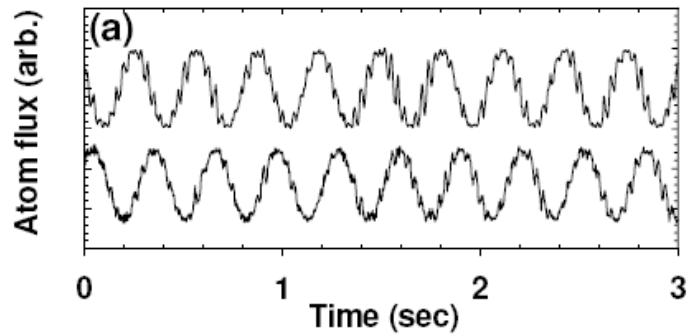
Source: Proc. IEEE/Workshop on Autonomous Underwater Vehicles

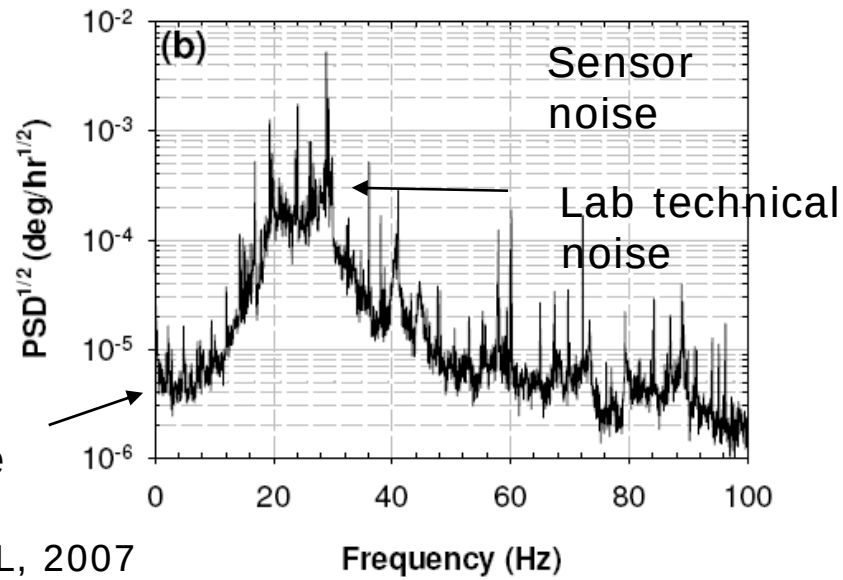
Laboratory gyroscope (1997)



AI gyroscope

Gyroscope interference fringes:





ARW	**3 μdeg/hr$^{1/2}$**
Bias stability:	**< 60 μdeg/hr**
Scale factor:	**< 5 ppm**

Gustavson, et al., PRL, 1997; Durfee, et al.,PRL, 2007

Gravity gradiometry and high accuracy navigation

Gravity gradiometer enables real-time discrimination of gravity-induced accelerations from platform accelerations.

Required for high accuracy navigation in near (un-mapped) gravity anomalies.

Gravity Gradiometry

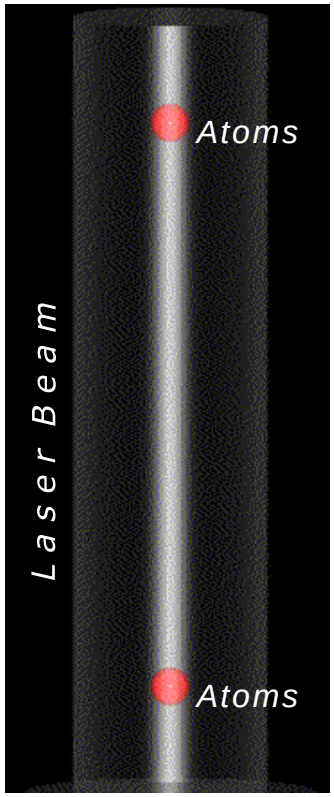
SOMETHING NEW IN INERTIAL NAVIGATION

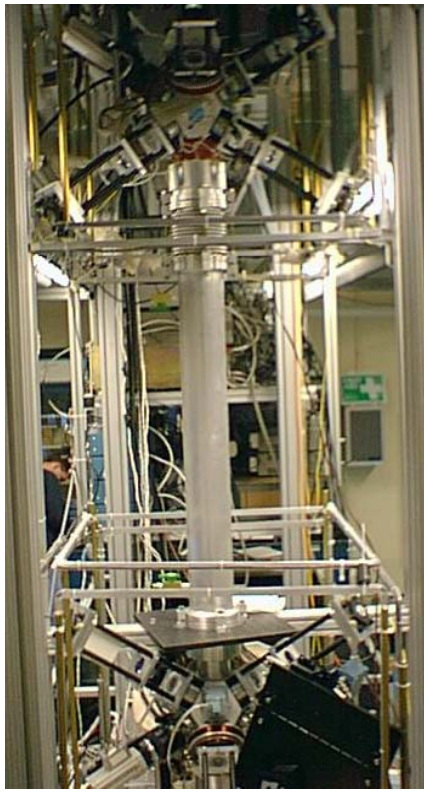
By MARK A. GERBER
The Charles Stark Draper Laboratory

gravitational accelerations. An inertial navigator must have a mathematical model of the gravity field in order to separate inertial and gravitational effects (F-1A). Early inertial systems and present-day commercial versions realized their full potential using the simple reference ellipsoid to describe the Earth's gravity field; but as the precision of inertial components has improved, the need for more detailed knowledge of gravity has increased. *Further advances in inertial navigation performance cannot be made without a solution to the gravity problem.*

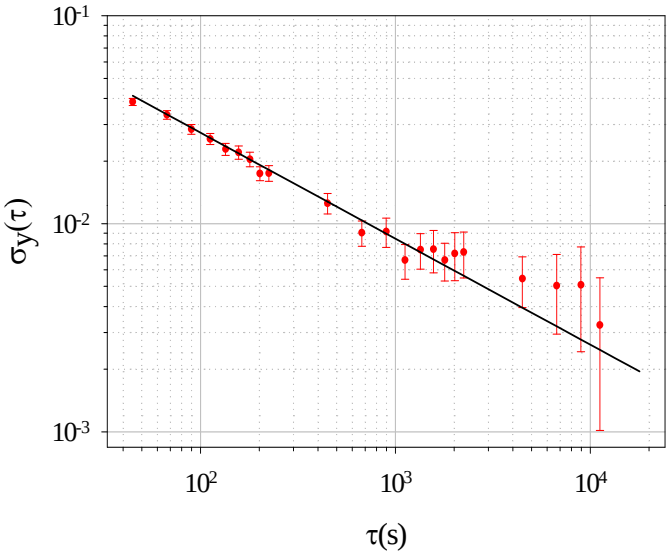
From Astronautics&Aeronautics (CSDL), May 1978

Laboratory gravity gradiometer (2002)





1.4 m



Demonstrated differential acceleration sensitivity:

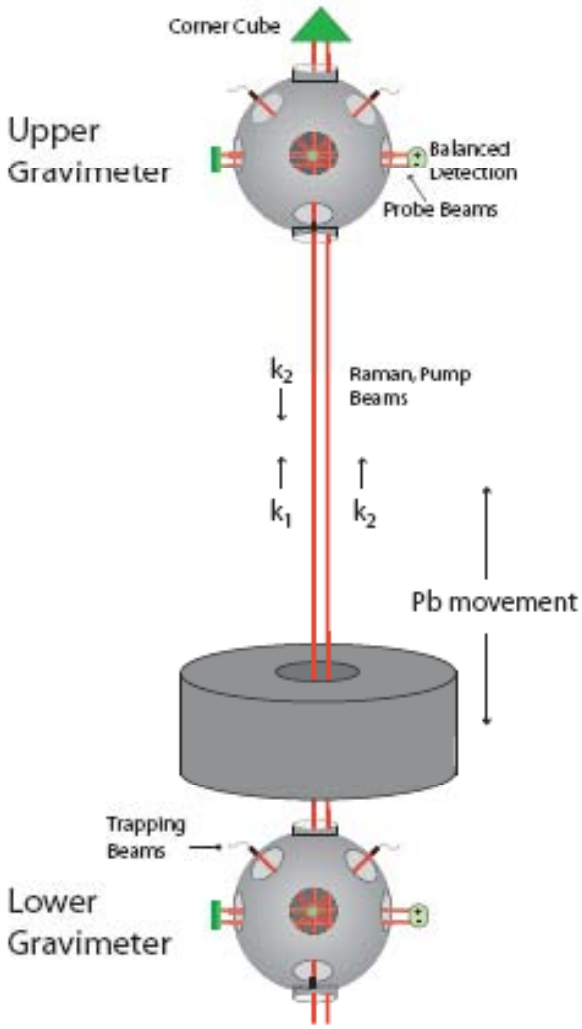
4×10^{-9} g/Hz$^{1/2}$

(2.8×10^{-9} g/Hz$^{1/2}$ per accelerometer)

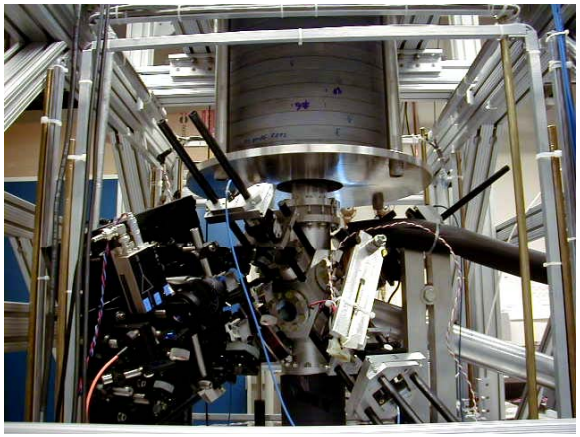
(McGuirk, et al., PRA, 2002)

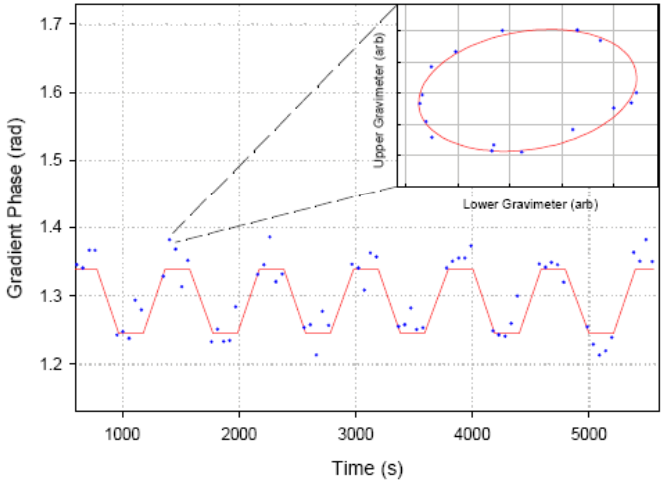
Distinguish gravity induced accelerations from those due to platform motion with differential acceleration measurements.

Measurement of Newton's Constant

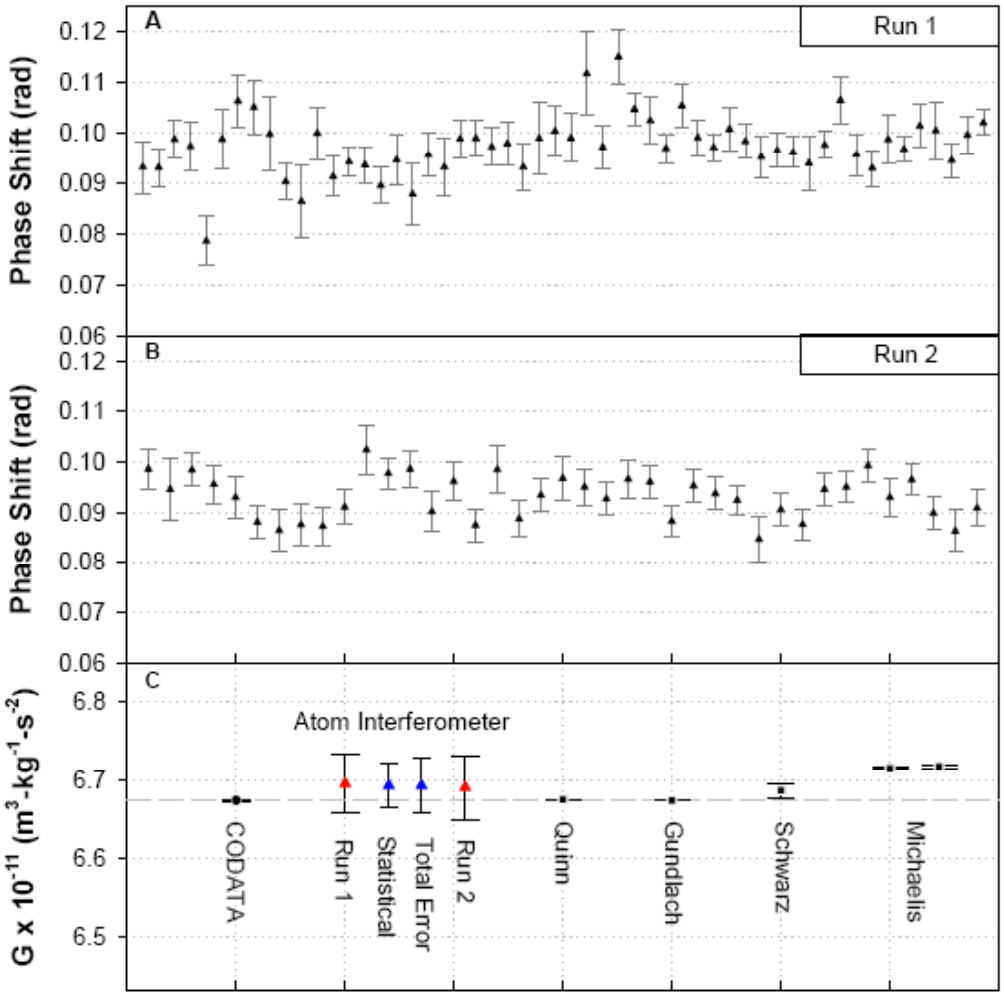


Pb mass translated vertically along gradient measurement axis.





Measurement of G



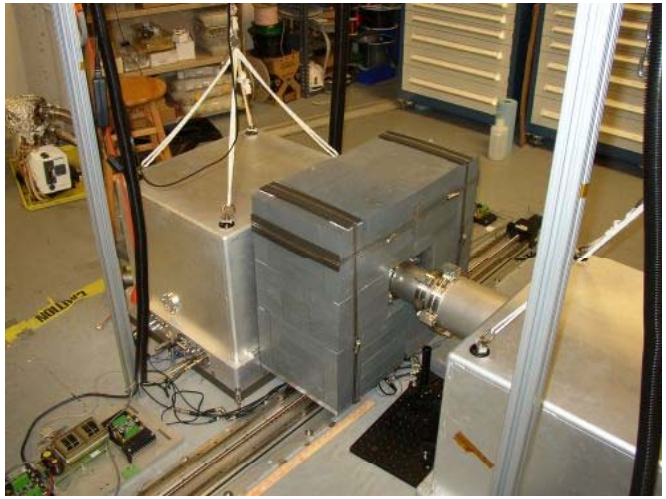
Systematic	$\delta G/G$
Initial Atom Velocity	1.88×10^{-3}
Initial Atom Position	1.85×10^{-3}
Pb Magnetic Field Gradients	1.00×10^{-3}
Rotations	0.98×10^{-3}
Source Positioning	0.82×10^{-3}
Source Mass Density	0.36×10^{-3}
Source Mass Dimensions	0.34×10^{-3}
Gravimeter Separation	0.19×10^{-3}
Source Mass Density inhomogeneity	0.16×10^{-3}
TOTAL	3.15×10^{-3}

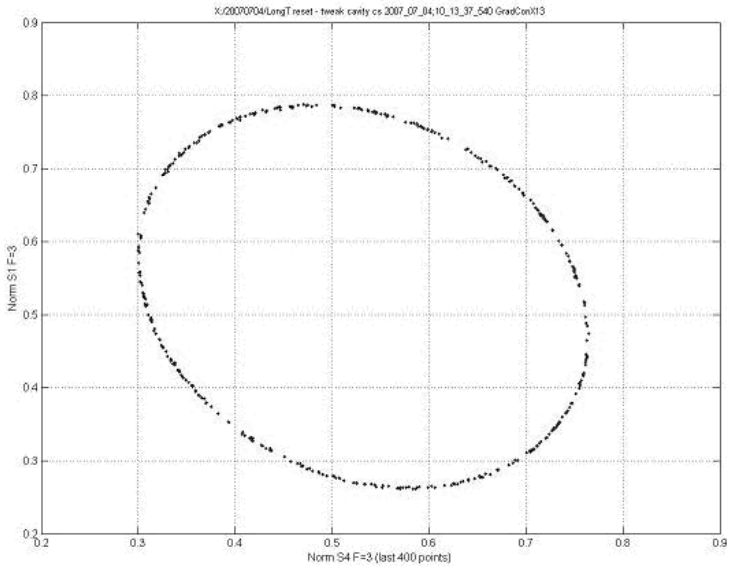
Systematic error sources dominated by initial position/velocity of atomic clouds.

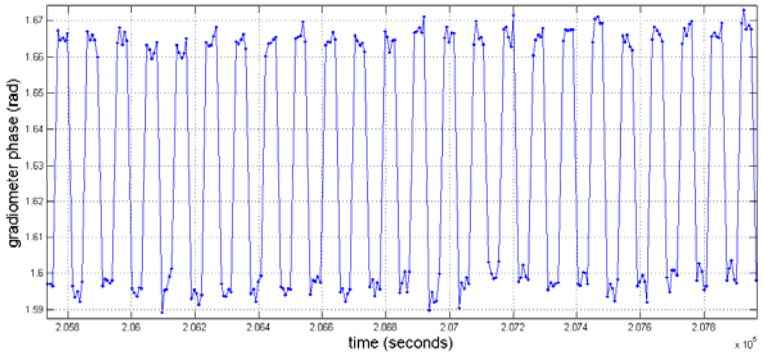
$\delta G/G$ ~ 0.3%

Fixler, et al., Science, 2007

New instrument (2007)

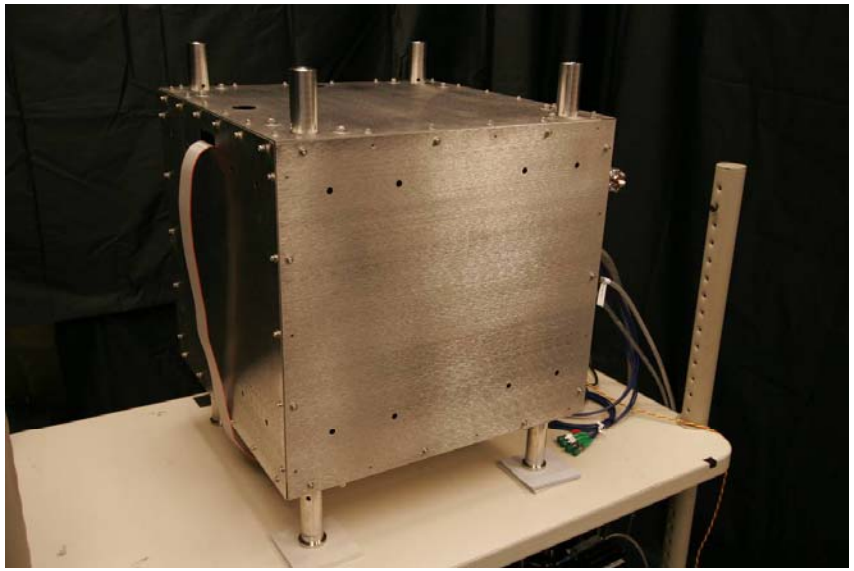




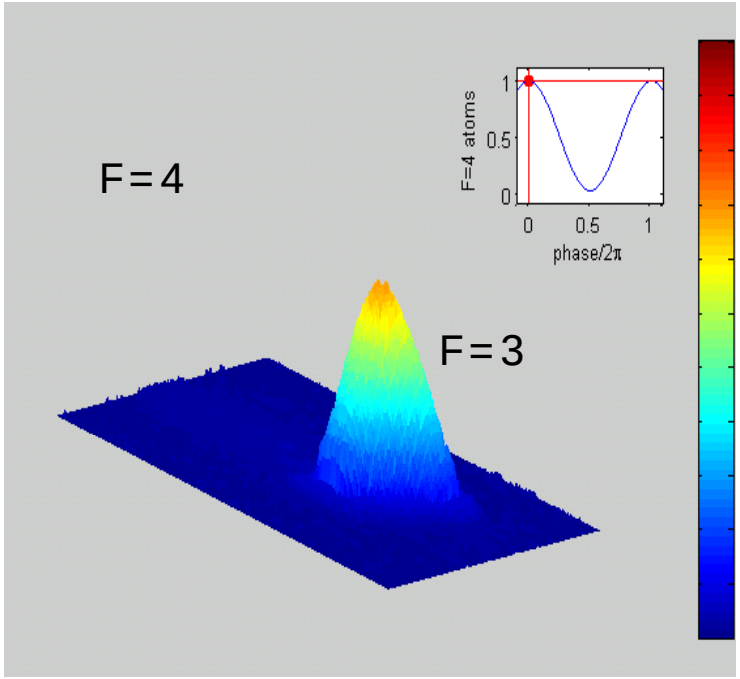


Currently achieved statistical sensitivity at ~2×10^{-4} G (10^{-12} g acceleration resolution).

Compact gravity gradiometer (2007)

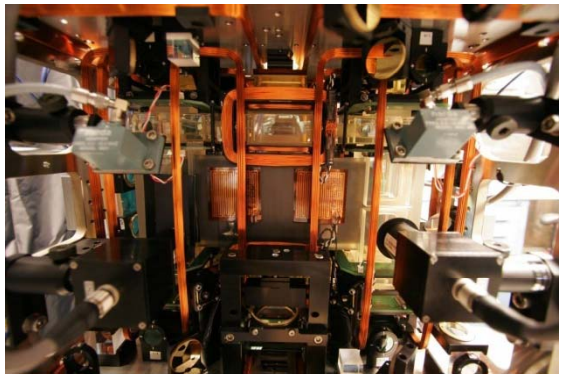


Multi-function sensor measures rotations and linear accelerations along a single input axis.



Interference fringes are recorded by measuring number of atoms in each quantum state

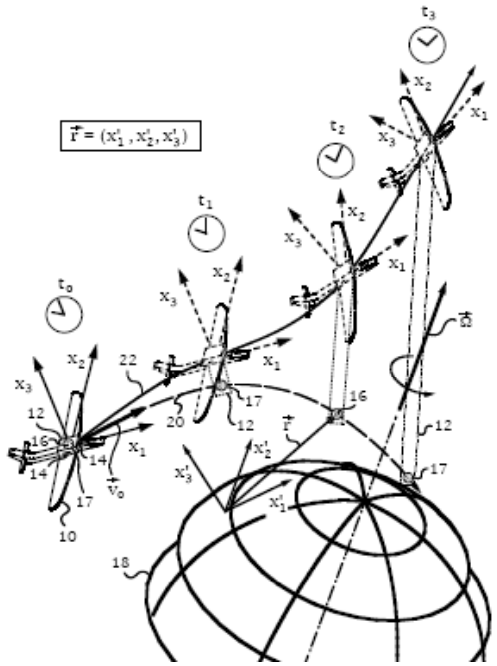
Interior view

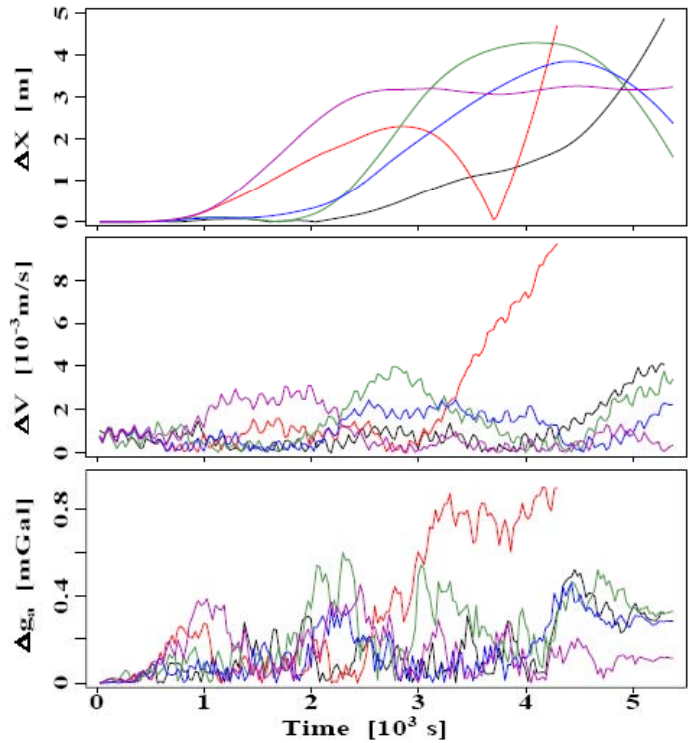


Navigation performance

Determine geo-located platform path.

Necessarily involves geodetic inputs



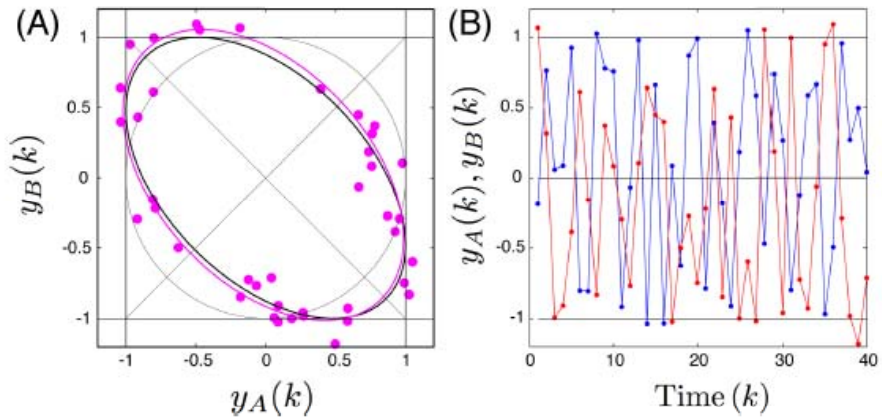


Simulated navigation solutions.
5 m/hr system drift demonstrated.

Optimal phase retrieval

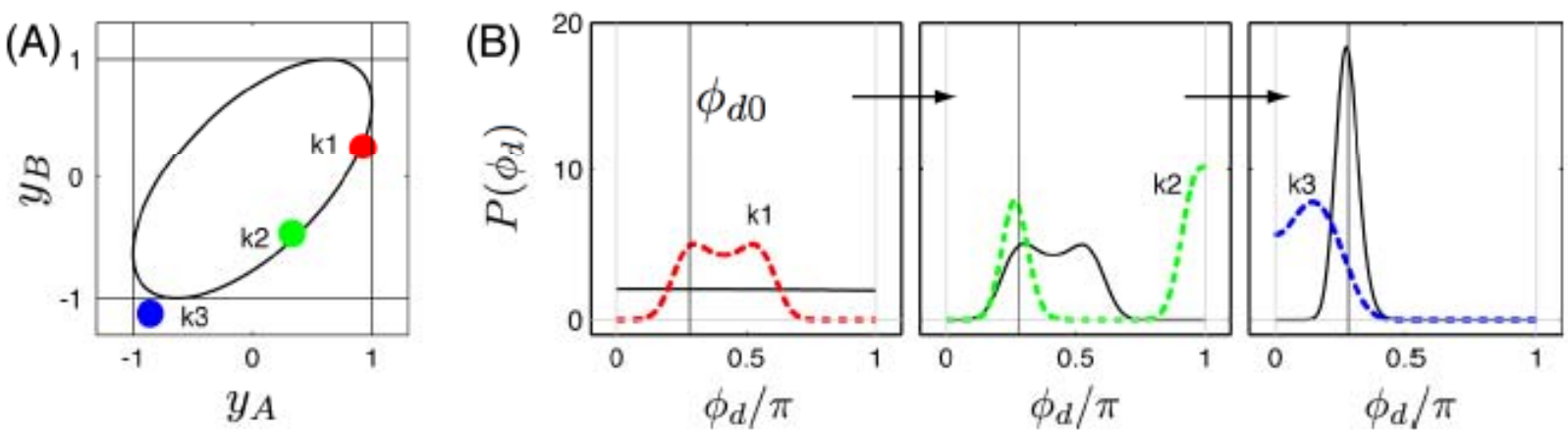
Interferometer outputs and noise model:

$$y_A(k) = c_{1,A}(k) + (1 + c_{2,A}(k))\sin(\phi_d + \phi_c(k) + c_{3,A}(k))$$
$$y_B(k) = c_{1,B}(k) + (1 + c_{2,B}(k))\sin(\phi_c(k)).$$



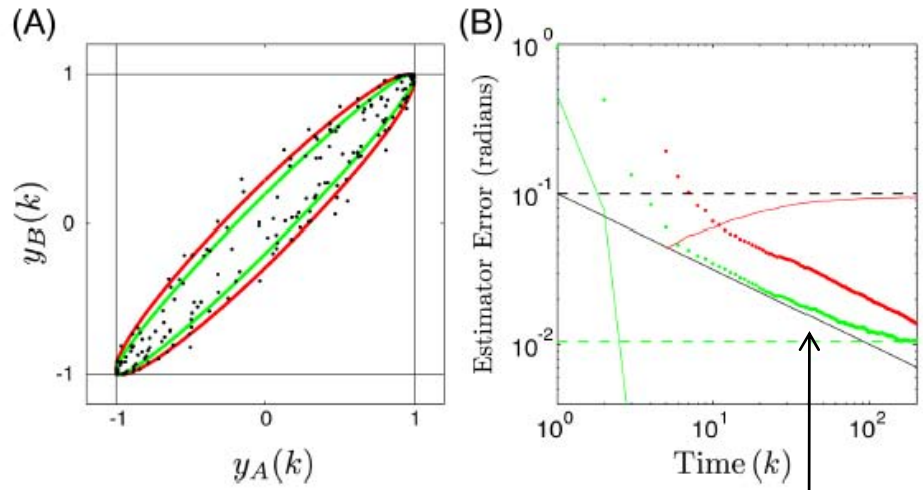
Previous: Outputs parametrically describe an ellipse. Use non-optimal ellipse specific fitting to extract relative phase (McGuirk, Opt. Lett., 2001).

New: Use Bayesian estimation to optimally determine relative phase (Stockton, submitted).

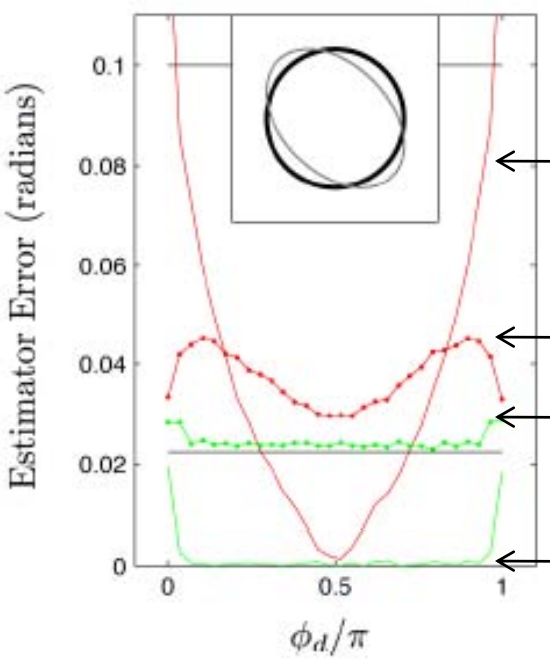


Optimal Bayesian Phase Estimation vs. Ellipse Fitting

Numerical simulation to compare performance of Bayesian vs. ellipse specific methods for white, non-common, phase noise.



Bayesian method integrates as $t^{-1/2}$ without systematic error offset



Ellipse error

Ellipse noise

Bayesian noise

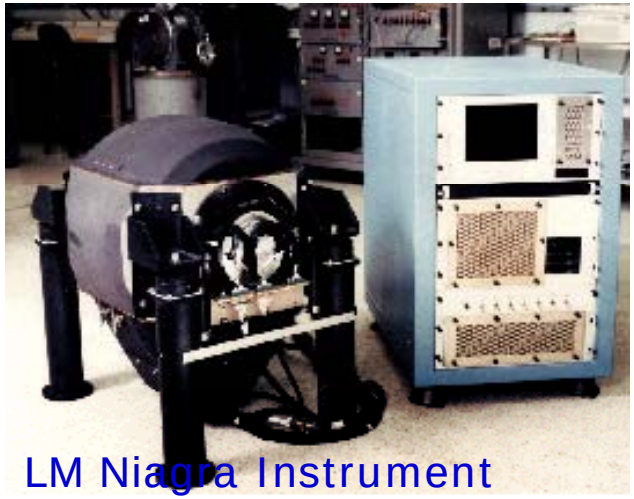
Bayesian error

Currently investigating computationally efficient implementations.

Suppresses systematic offsets in phase determination

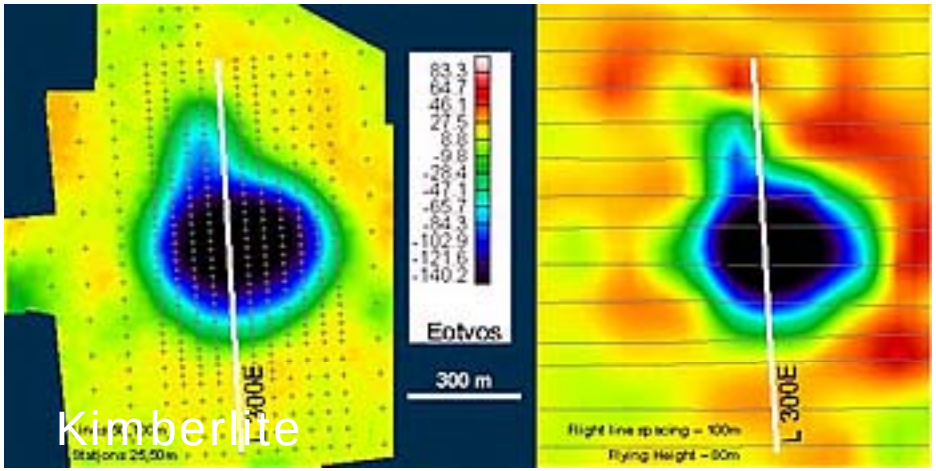
Airborne Gravity Gradiometer: BHP FALCON Program

Existing technology



Land: 3 wks.

Air: 3 min.



AI sensors potentially offer 10 x – 100 x improvement in detection sensitivity at reduced instrument costs.

Equivalence Principle

Co-falling ^{85}Rb and ^{87}Rb ensembles

Evaporatively cool to < 1 μK to enforce tight control over kinematic degrees of freedom

Statistical sensitivity

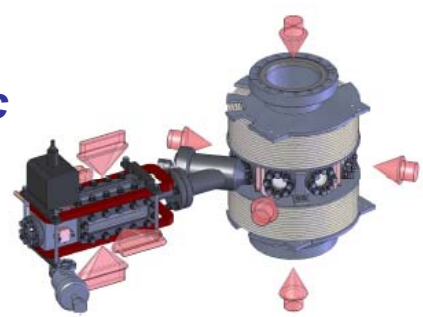
$\delta g \sim 10^{-15}$ with 1 month data collection

Systematic uncertainty

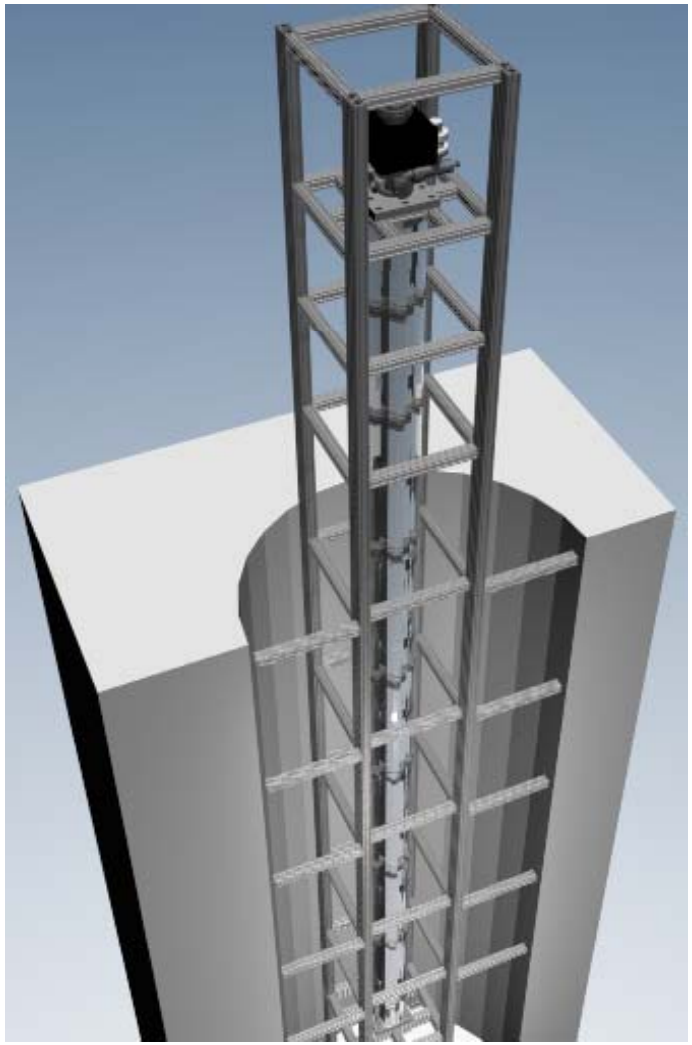
$\delta g \sim 10^{-16}$ limited by magnetic field inhomogeneities and gravity anomalies.

Also, new tests of General Relativity

Atomic source

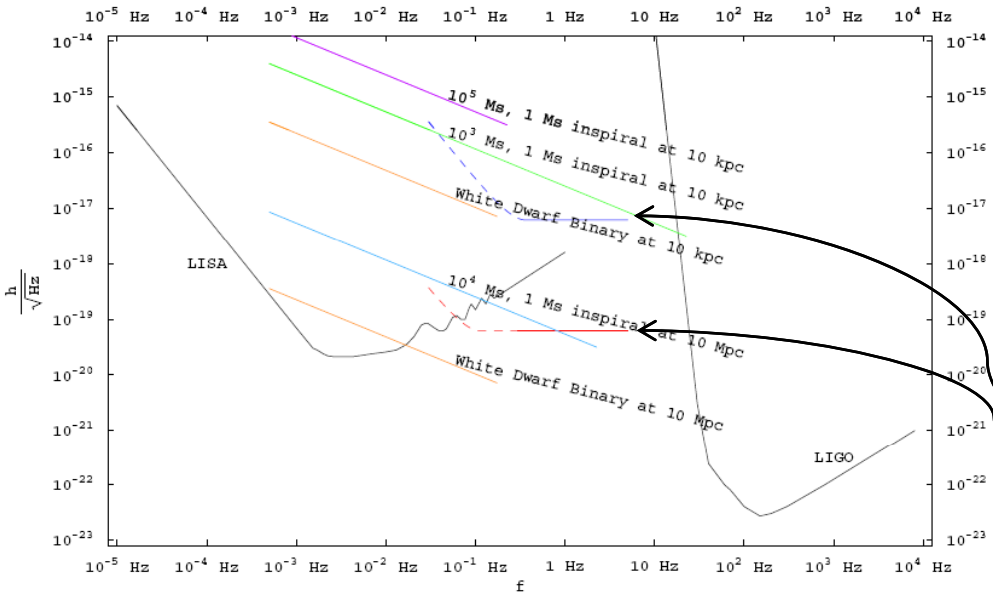


10 m atom drop tower



Equivalence Principle Installation

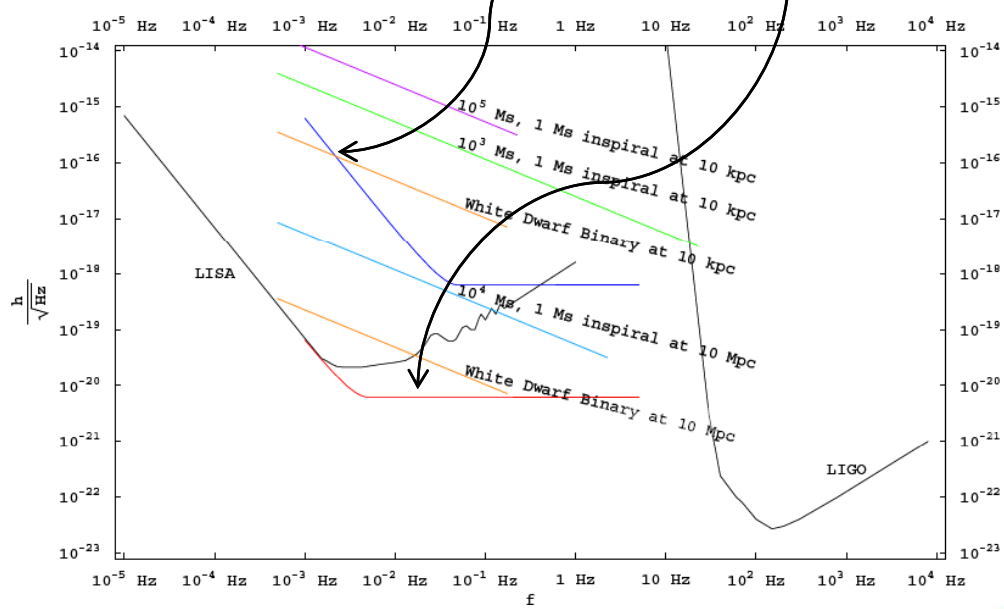
Gravity-wave detection



Earth-based detectors (blue and red indicate two AI geometries)

Atom interferometer detectors

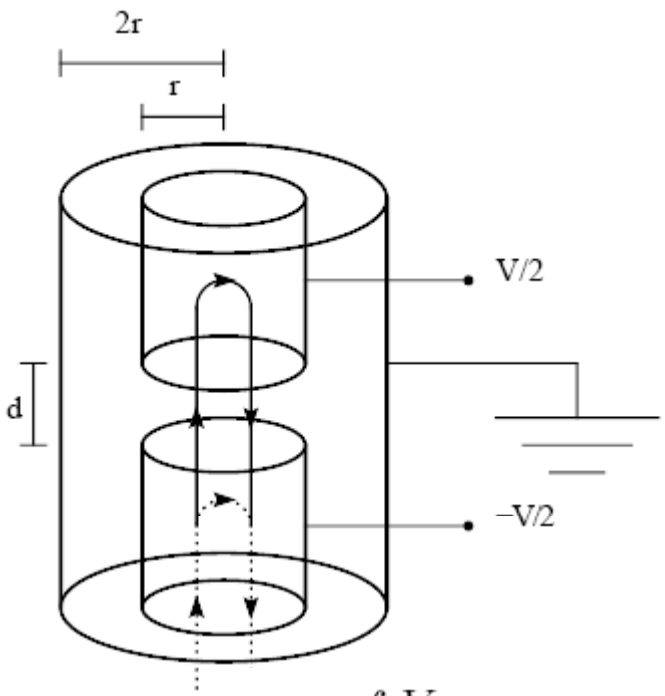
Space-based detectors (blue and red indicate two AI geometries)



Theory collaborators:
S. Dimopoulos, P. Graham, S. Rajendran.

Electron-proton charge balance

- Apparatus will support >1 m wavepacket separation
- Enable ultra-sensitive search for charge electron/proton charge.



Phase shift: $\epsilon e \int \frac{V}{\hbar} dt$

$\varepsilon \equiv \delta e/e \sim 10^{-30}$

Current limit: $\delta e/e \sim 10^{-22}$ (Unnikrishnan e*t al*., Metrologia **41**, 2004)

Impact of an observed imbalance currently under investigation.

Theory collaborators:
A. Arvanitaki, S. Dimopoulos, A. Geraci

Future technology: Quantum Metrology

Atom shot-noise limits sensor performance.

Recently evolving ideas in quantum information science have provided a road-map to exploit exotic quantum states to significantly enhance sensor performance.

- Sensor noise scales as 1/N where N is the number of particles
- "Heisenberg" limit
- Shot-noise ~ $1/N^{1/2}$ limits existing sensors

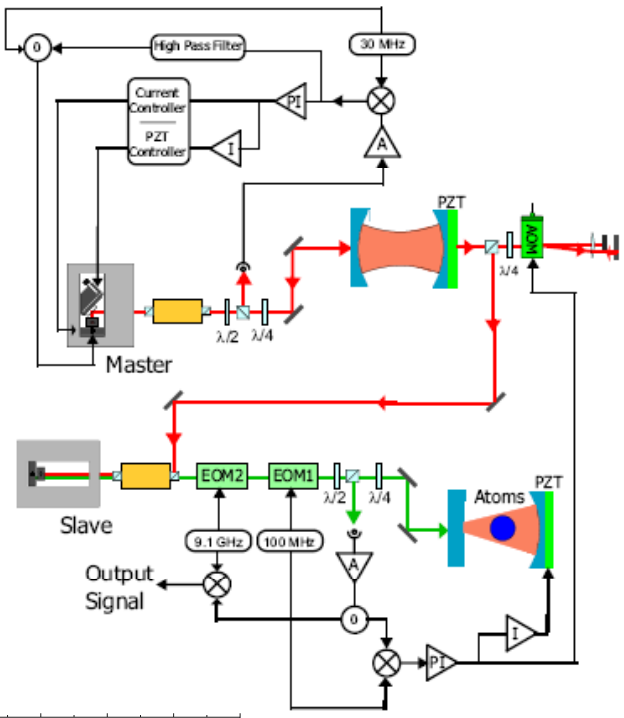
Challenges:

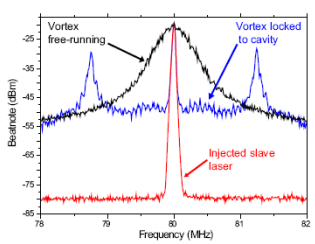
- Demonstrate basic methods in laboratory
- Begin to address engineering tasks for realistic sensors

Impact of successful implementation for practical position/time sensors could be substantial.

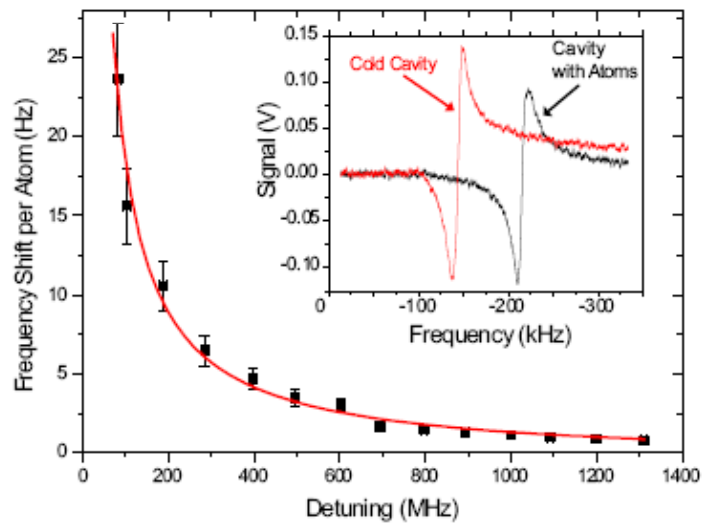
Enables crucial trades for sensitivity, size and bandwidth.

Quantum non-demolition atom detection

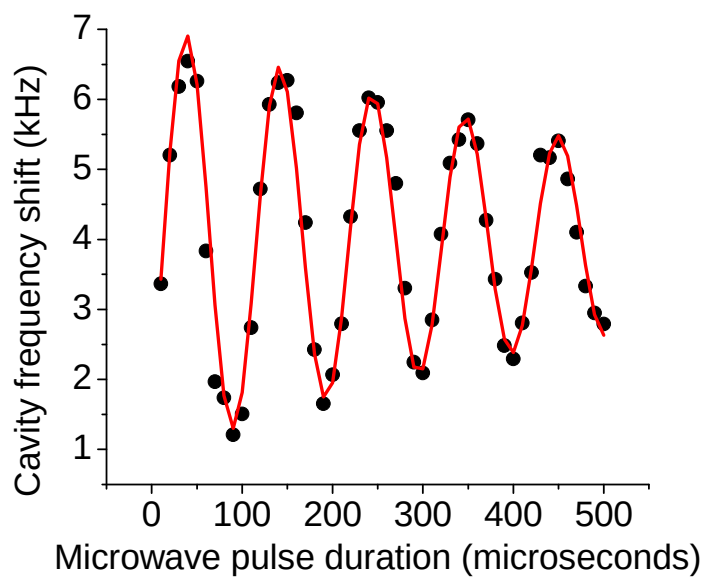




(Tuchman, et al. PRA, 2006, Long, Opt. Lett)



Dispersive cavity shift



Rabi oscillations detected via cavity shift

Thanks

Current team:

- Boris Dubetsky, Research Scientist
- Igor Teper, Post-doctoral Fellow, Physics
- Ken Takase, Graduate student, Physics
- Grant Biedermann, Graduate student, Physics
- Xinan Wu, Graduate student, Applied Physics
- Jongmin Lee, Graduate student, Electrical engineering
- Chetan Mahadeswaraswamy, Graduate student, Mechanical Engineering
- David Johnson, Graduate student, Physics
- Geert Vrijsen, Graduate student, Applied physics
- Jason Hogan, Graduate student, Physics
- John Stockton, Post-doctoral fellow, Physics
- Sean Roy, Graduate student, Physics
- Louis Deslauriers, Post-doctoral fellow, Physics
- Tom Langenstein,PM