Precision Navigation Sensors based on Atom Interferometry

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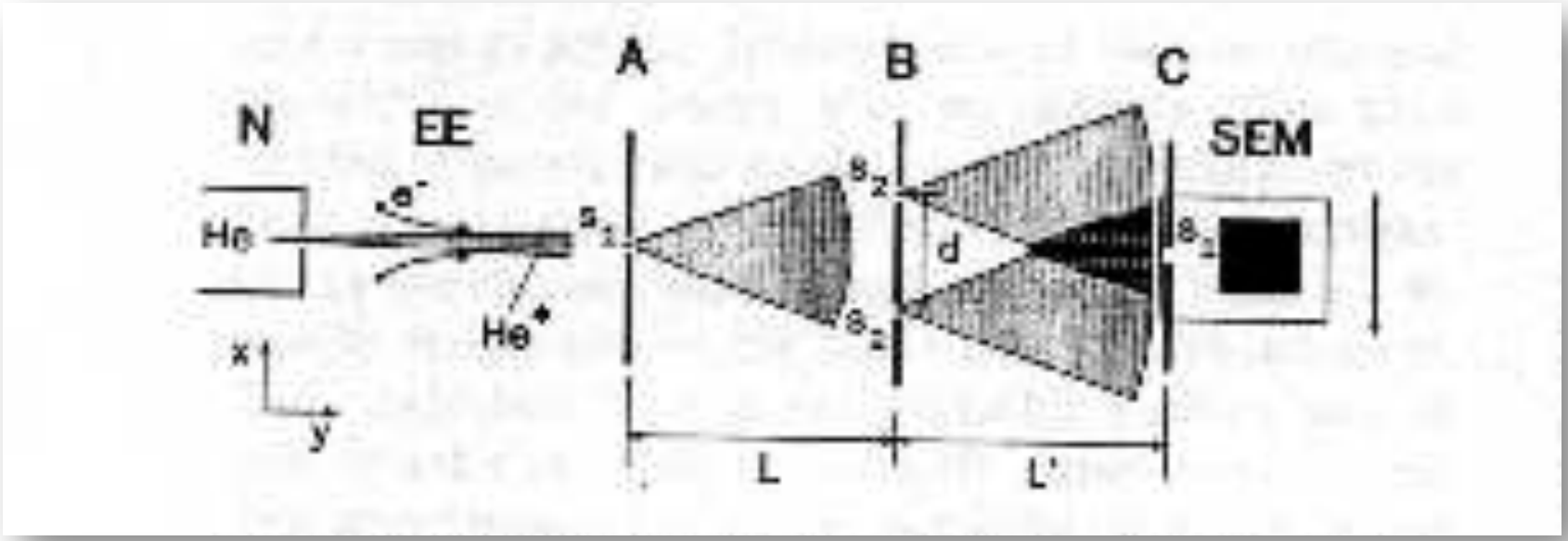
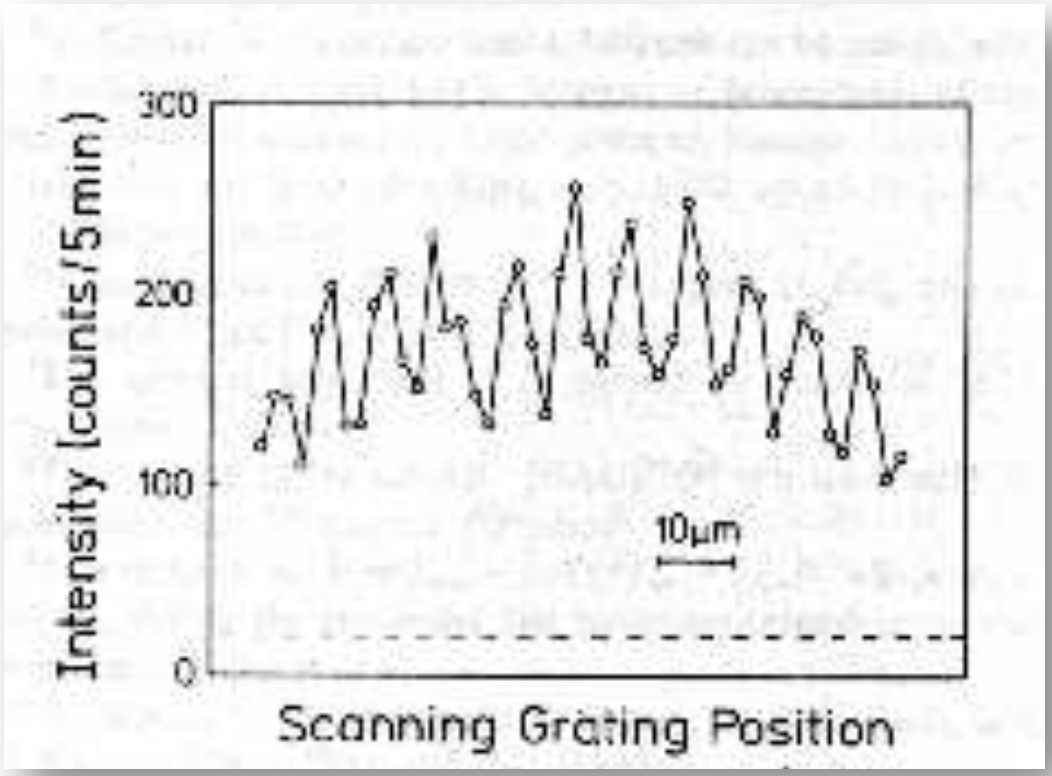
Young's double slit interferometer with atoms



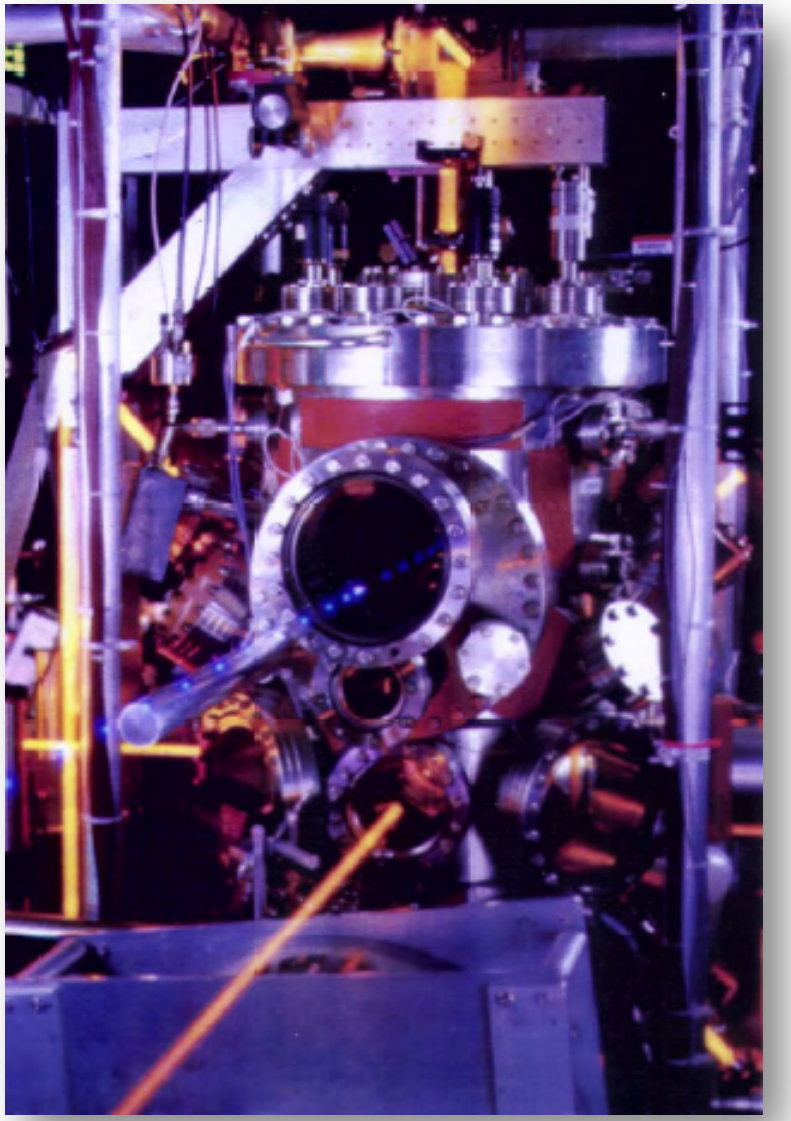
Mlynek, PRL, 1991

Young's double slit interference fringes

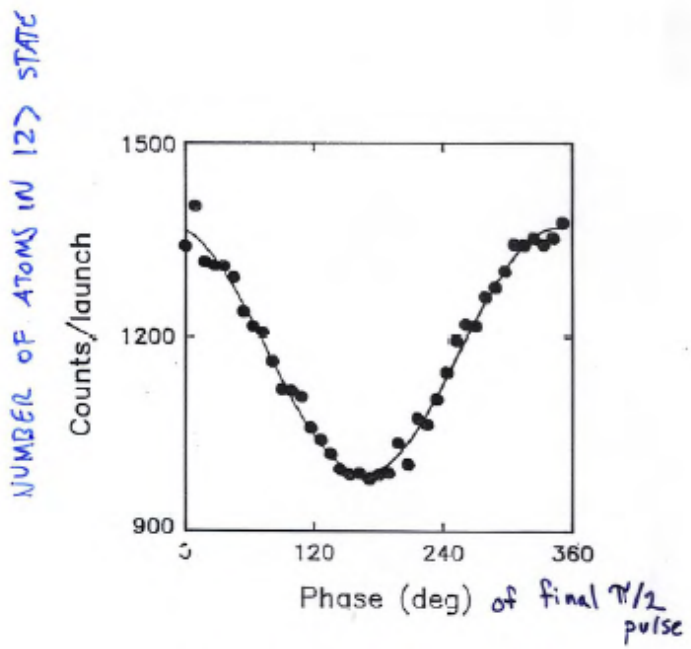


Mlynek, PRL, 1991

1991 Light-Pulse Atom Interferometer



ACCELEROMETER / GRAVIMETER: PROOF-OF-PRINCIPLE



50 msec between pulses

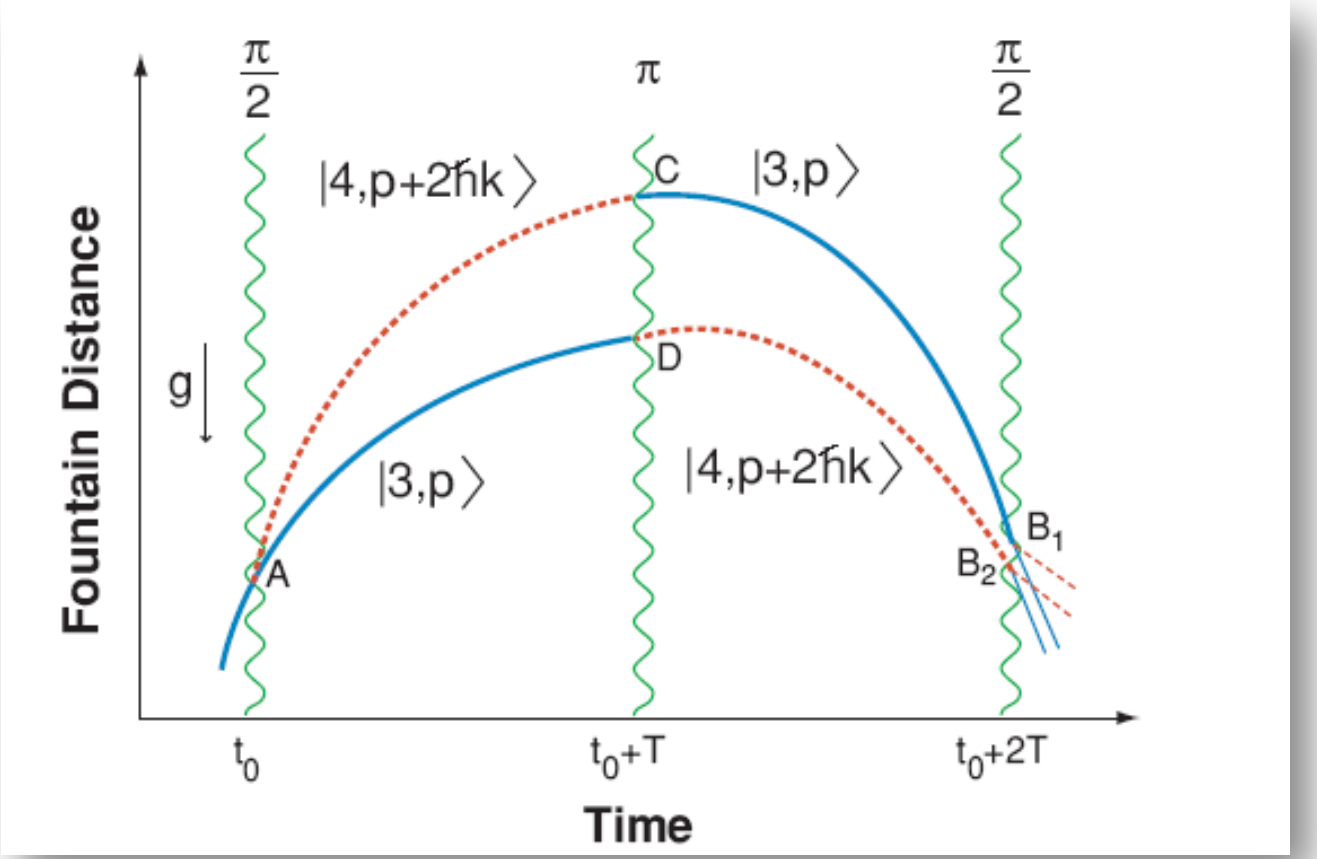
3 mm wavepacket separation

$\delta g/g = 3 \times 10^{-8}$

Kasevich and Chu, App. Phys B, 1992.

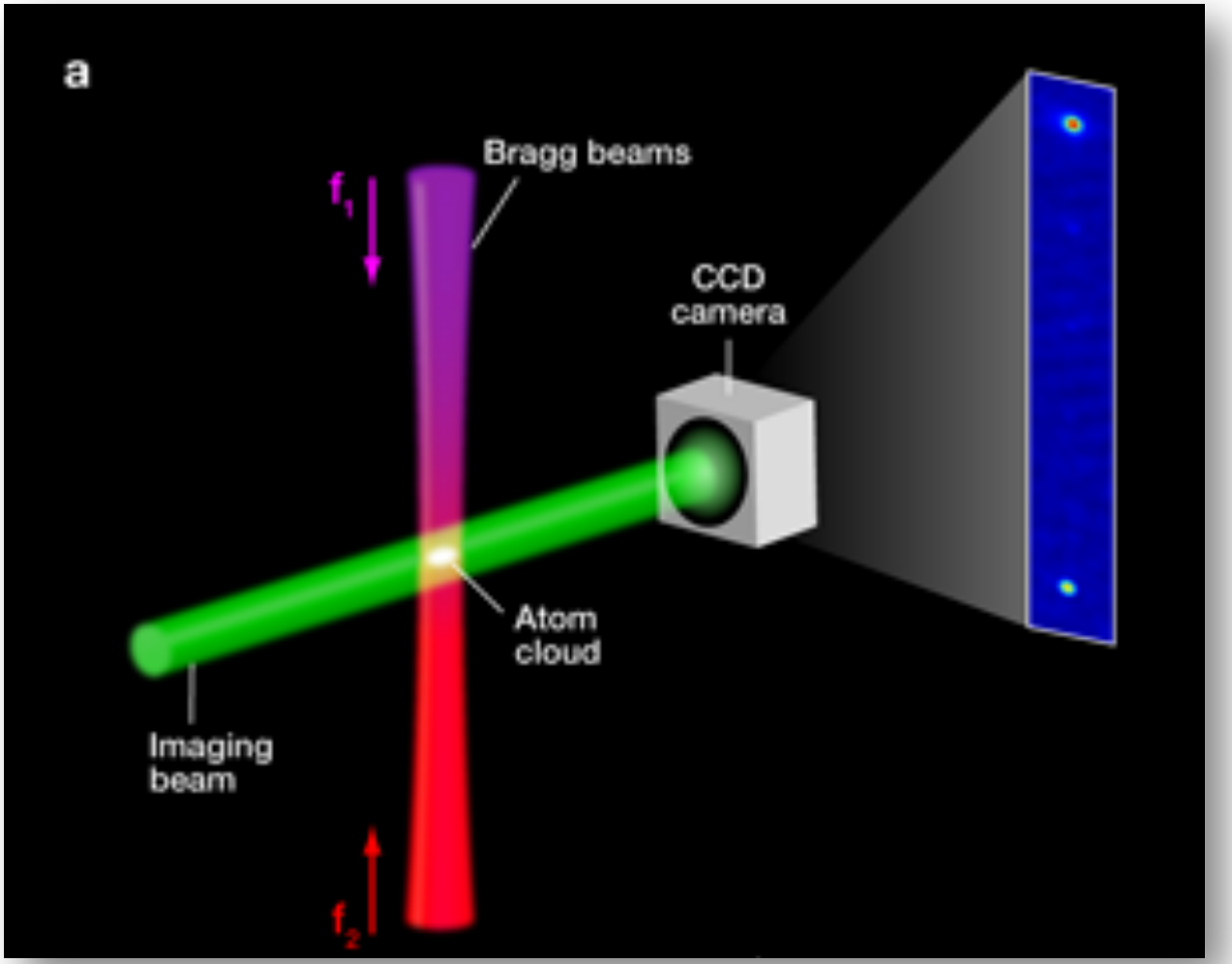
Light-pulse atom interferometry

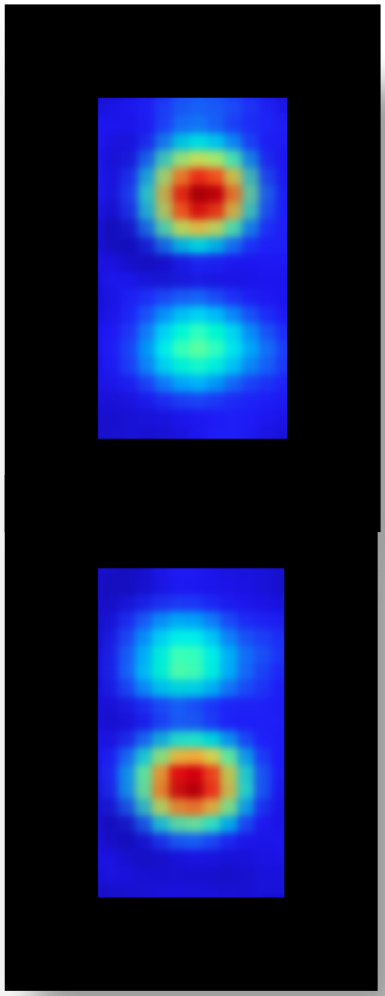
Pulses of light are used to coherently manipulate atom de Broglie waves:



Kasevich and Chu, PRL, 1991

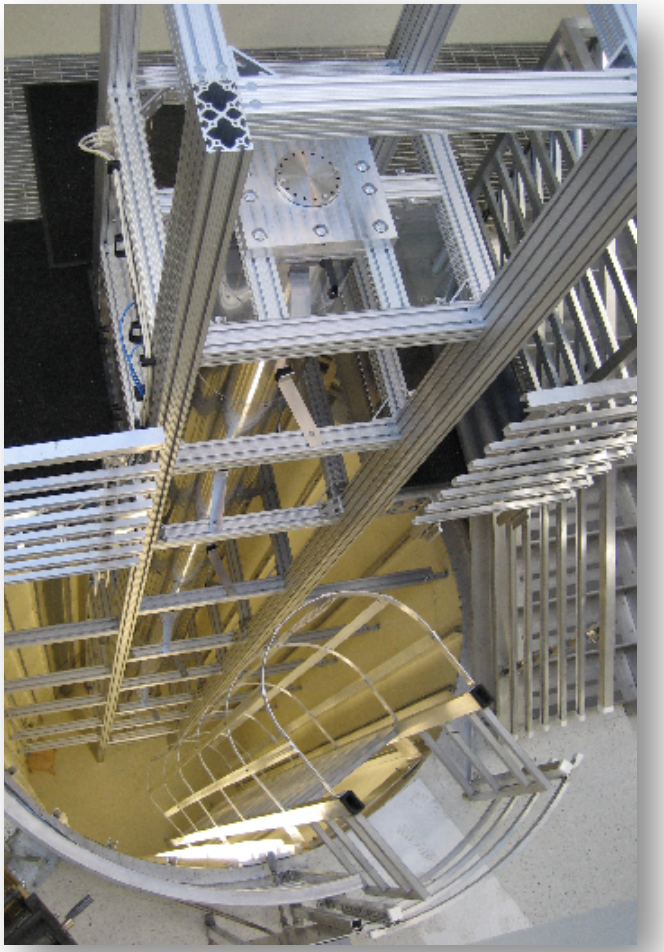
Images of atoms in interferometer



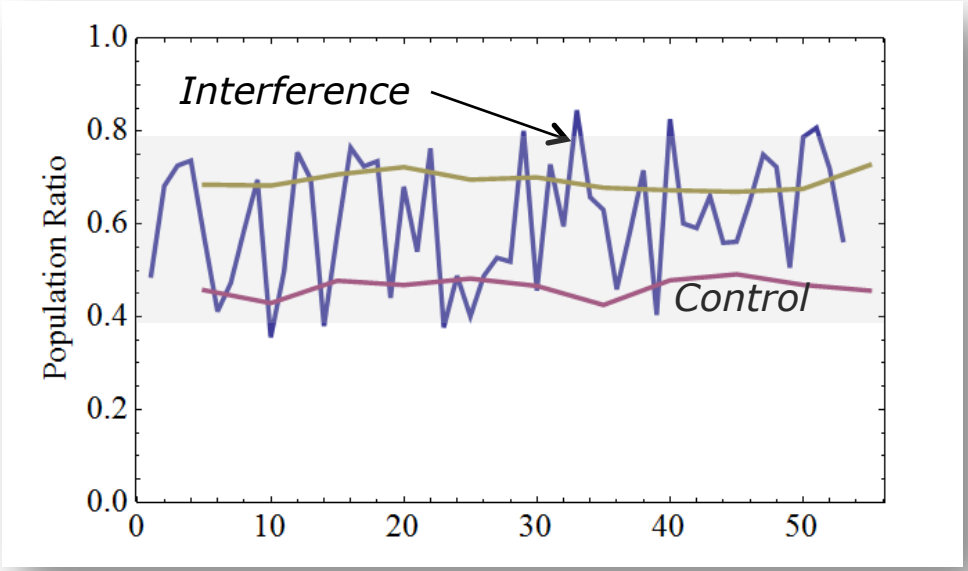


Chiow, PRL, 2011

1.4 cm wavepacket separation (!)



10 m atomic fountain apparatus

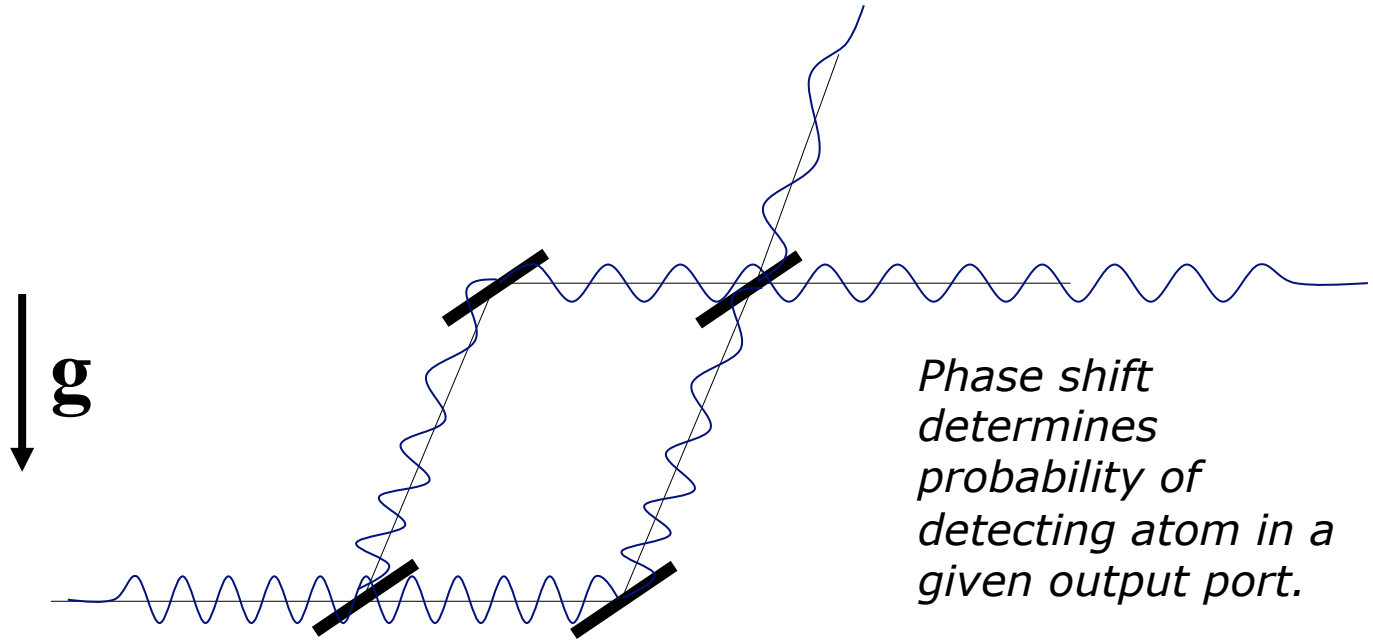


Interference contrast observed for 1.4 cm wavepacket separation.

Est. $\delta g < 1e\text{-}11$ g/shot accelerometer sensitivity.

Simple model for acceleration sensitivity

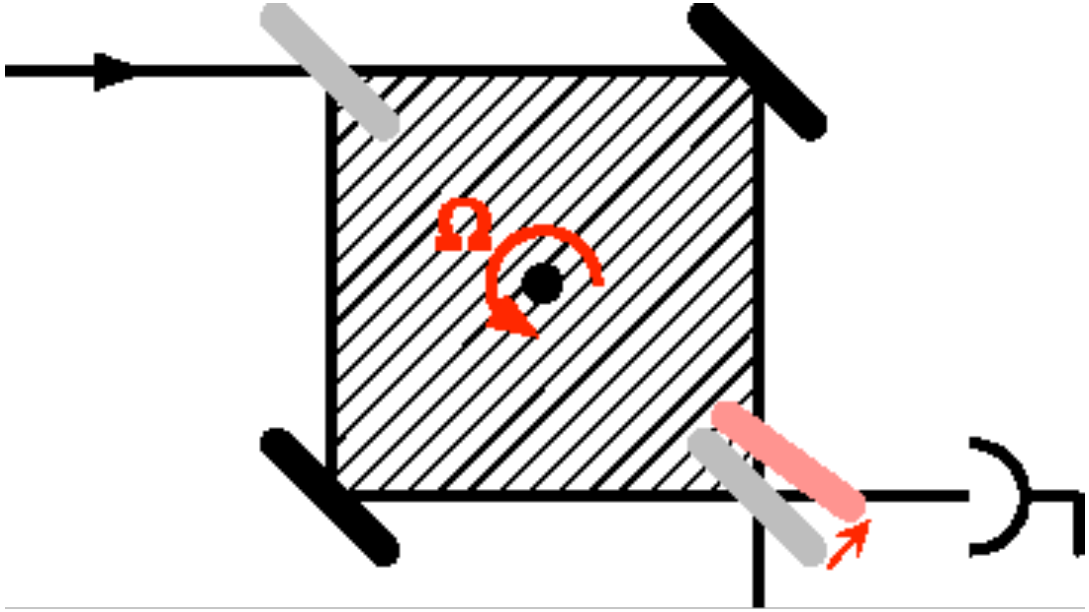
As atom climbs gravitational potential, velocity decreases and de Broglie wavelength increases ….



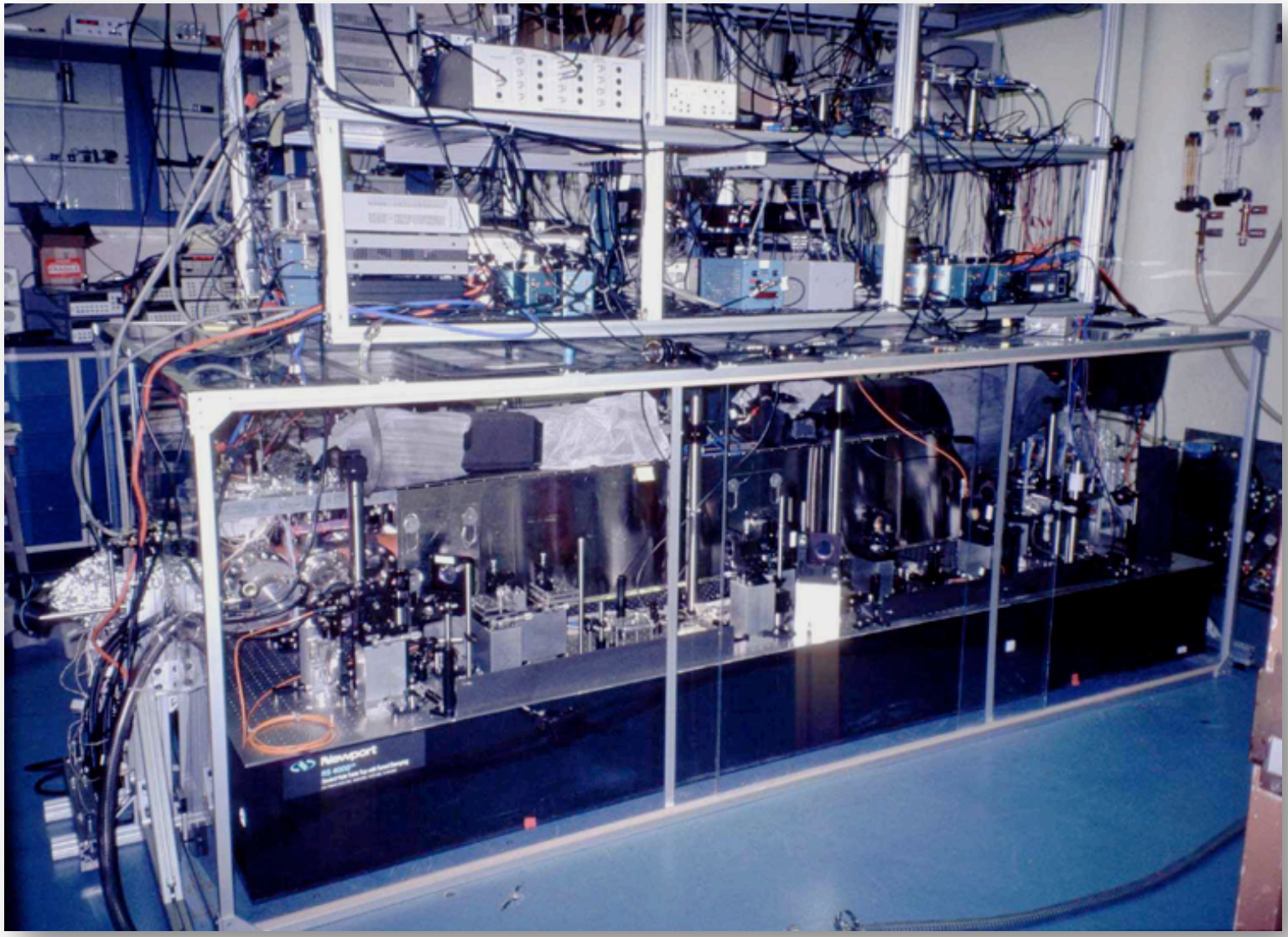
Phase shift determines probability of detecting atom in a given output port.

Simple model for rotation sensitivity

Sagnac effect for de Broglie waves ….

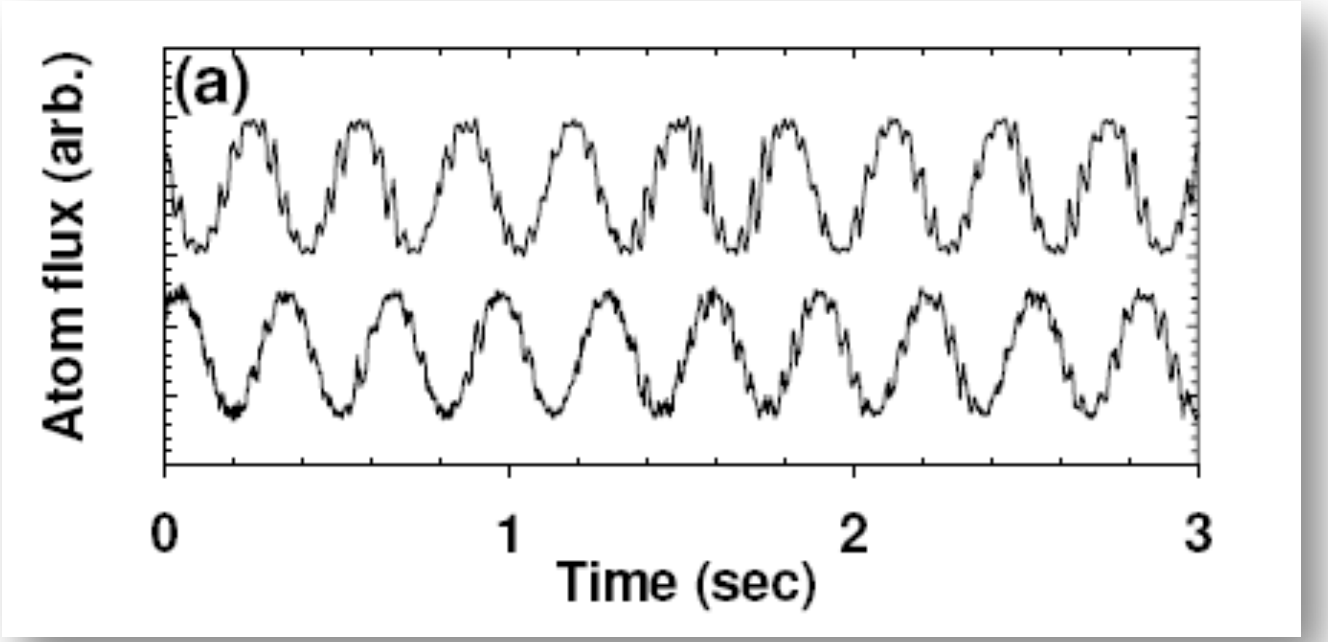


Gyroscope (1997)



Gustavson, PRL, 1997

Gyroscope interference fringes



Noise: 3 μdeg/hr$^{1/2}$

Bias stability: < 60 μdeg/hr

Scale factor: < 5 ppm

Gustavson, PRL, 1997
Durfee, PRL, 2006

Light-pulse AI Gyroscope Performance

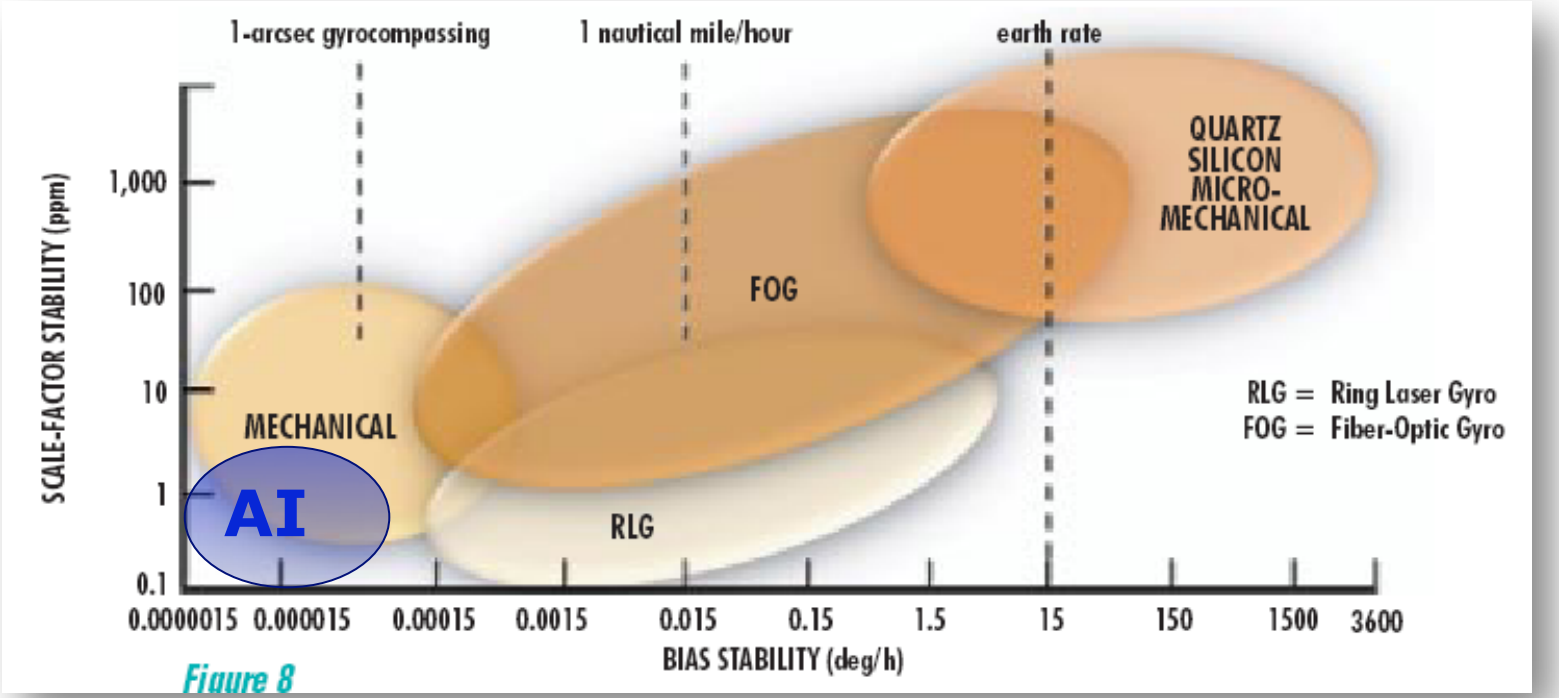
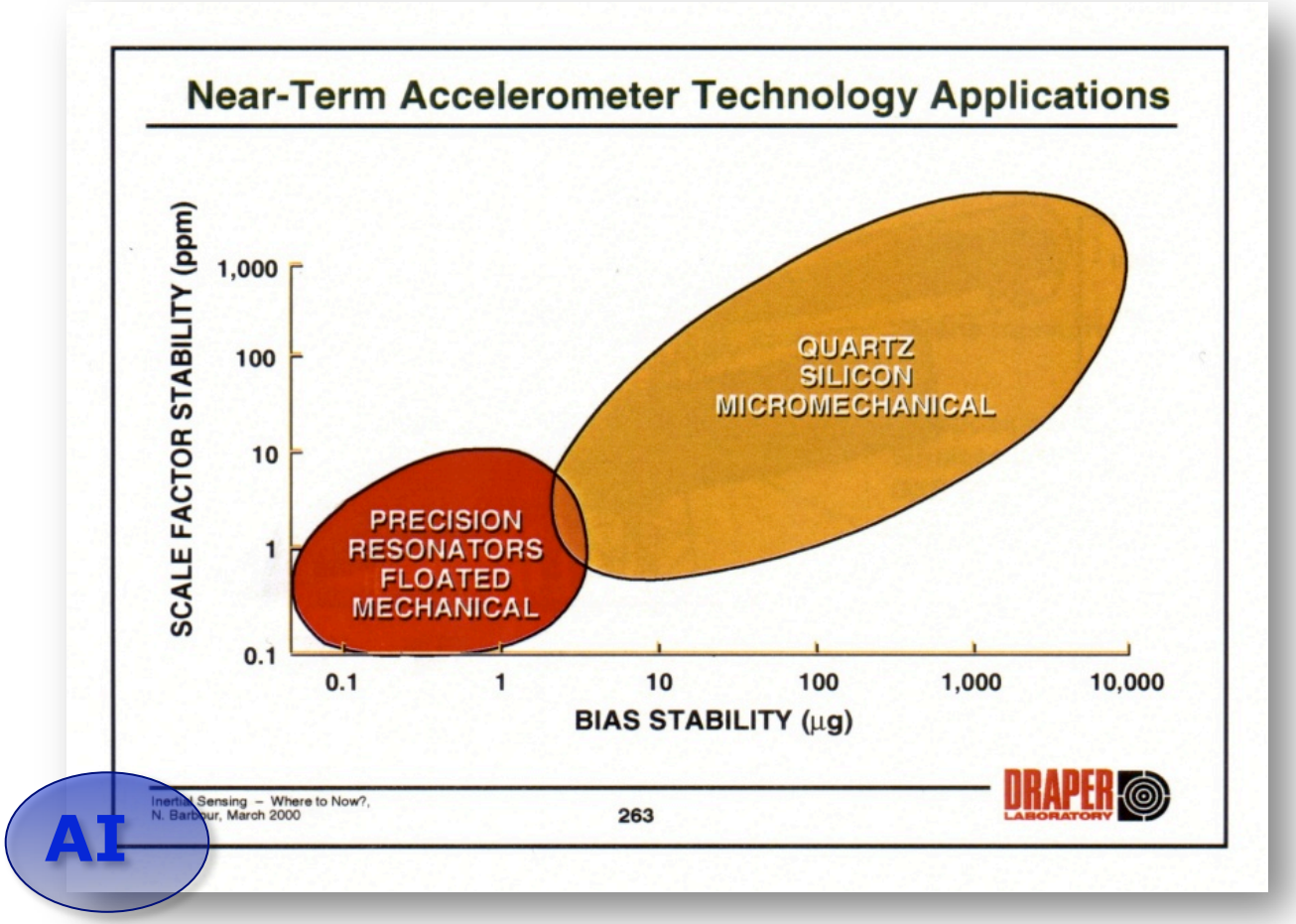


Figure 8

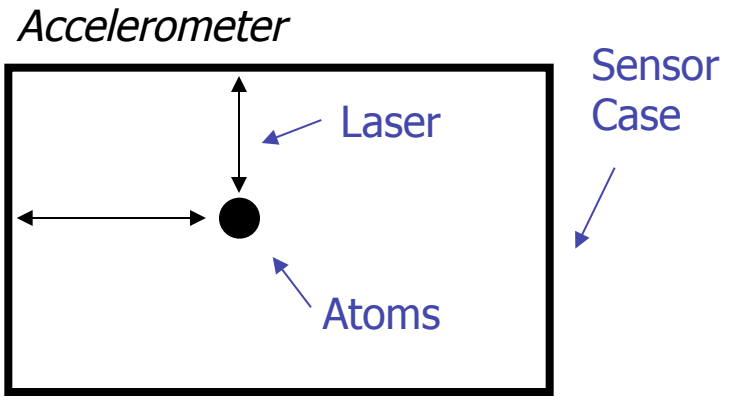
Source: Proc. IEEE/Workshop on Autonomous Underwater Vehicles

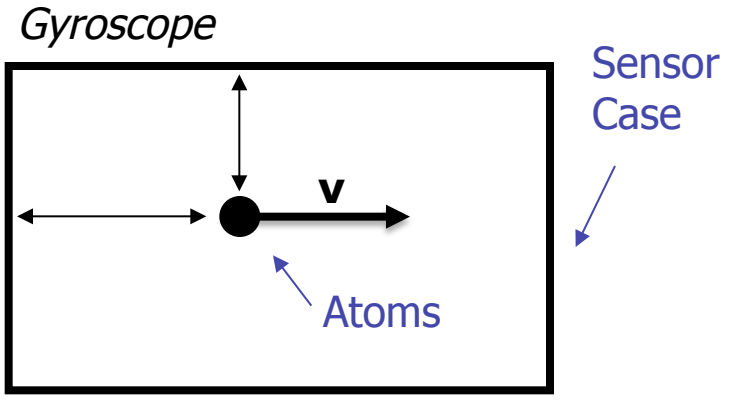
Light-pulse AI Accelerometer Performance



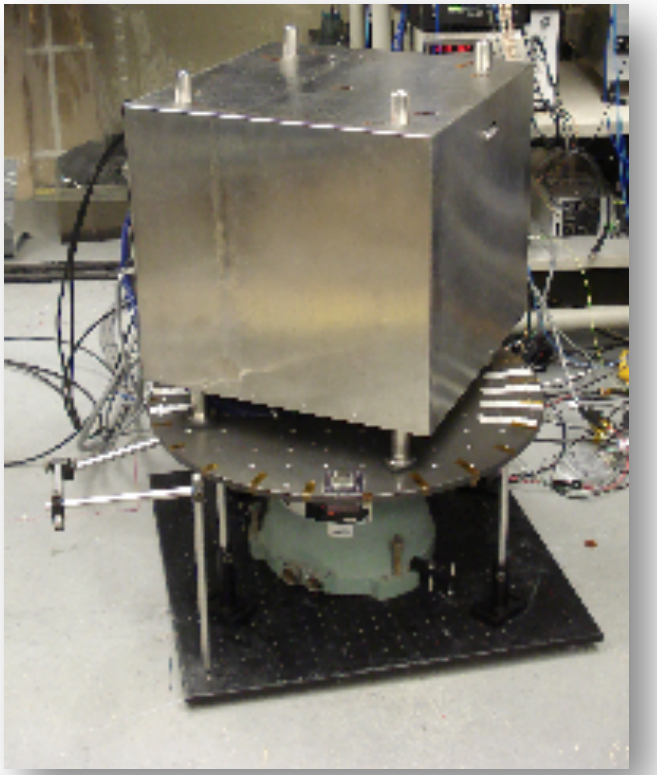
Why superb sensors?

- **Atom = near perfect inertial reference.**
- **Laser/atom interactions register relative motion between atom and sensor case.**
- **Sensor accuracy derives from the exceptional stability of optical wavefronts.**
- **Direct read-out of angular and linear displacements.**

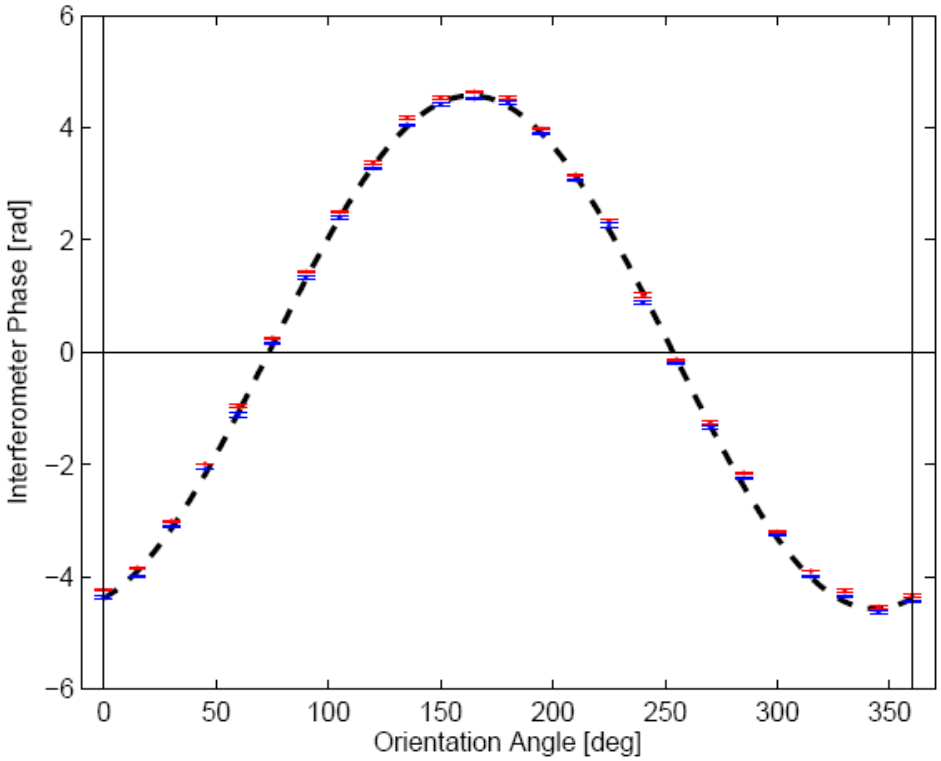




Hybrid sensor/Gyroscope mode



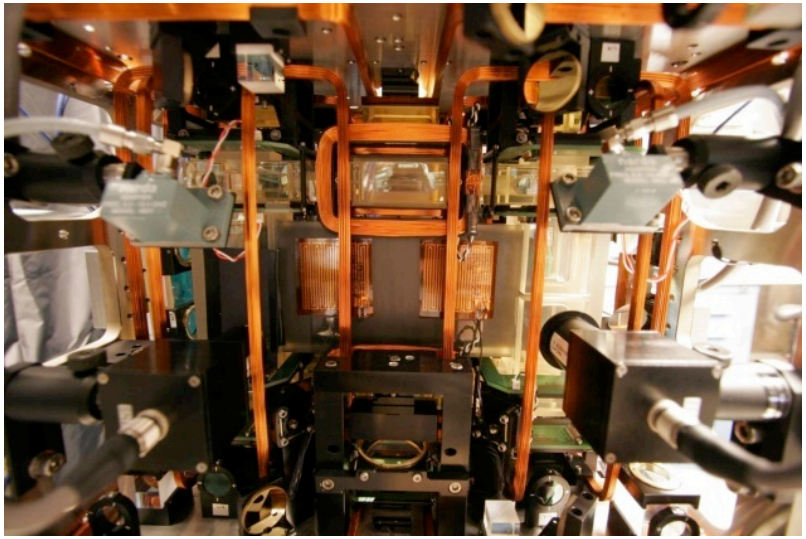
Measured gyroscope output vs.orientation:



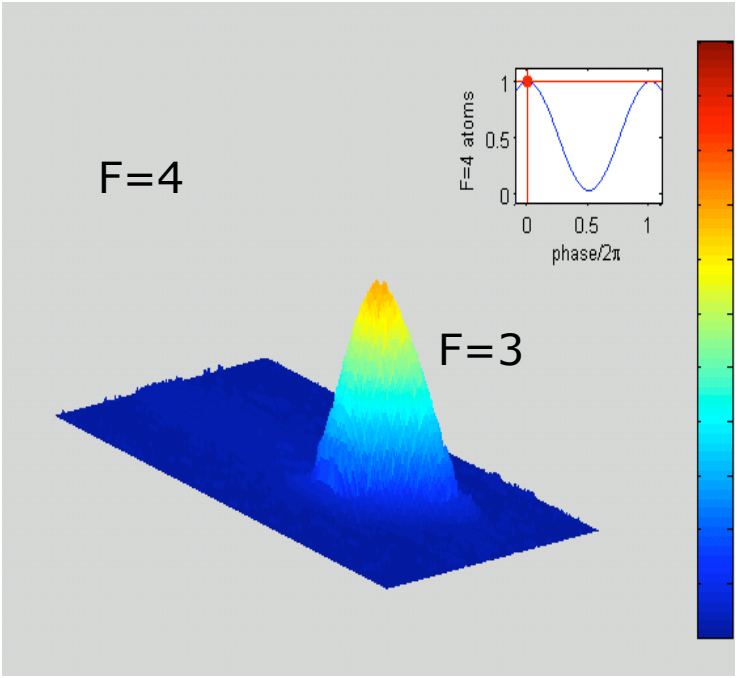
- Inferred ARW: < 100 μdeg/hr$^{1/2}$
- 10 deg/s max input
- <100 ppm absolute accuracy

Stockton, PRL, 2011

Hybrid sensor operation



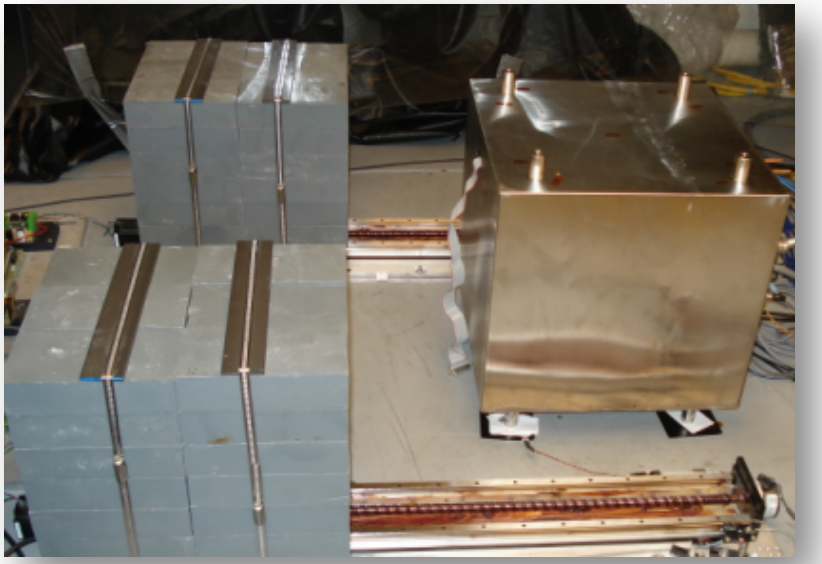
Interior view of sensor

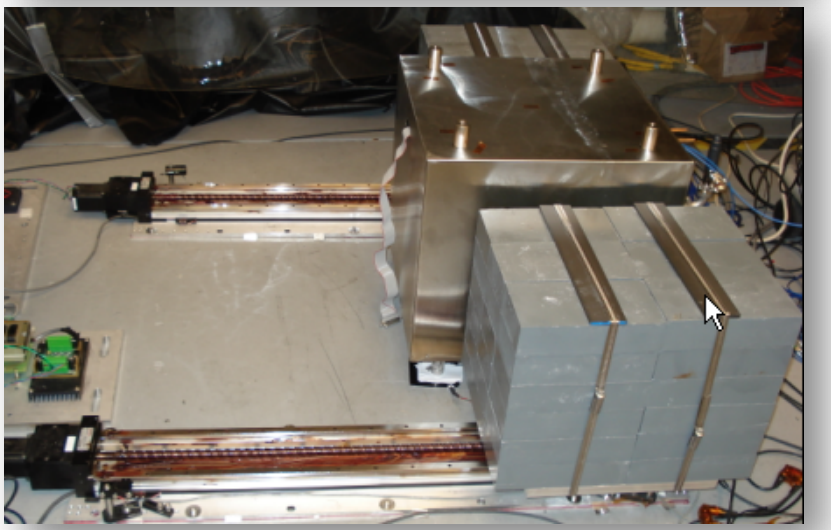


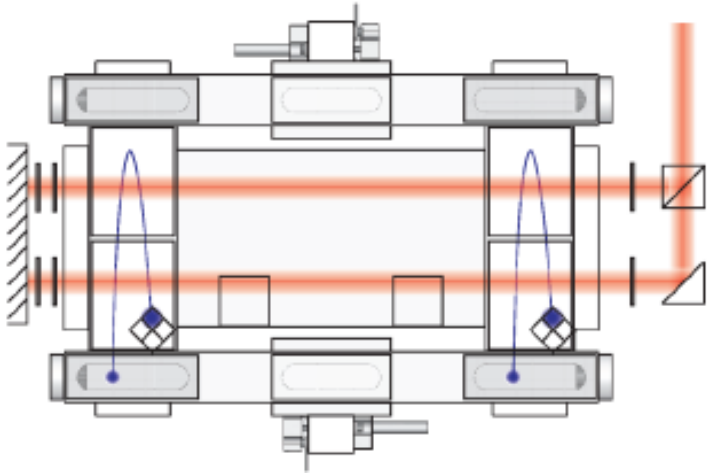
Interference fringes are recorded by measuring number of atoms in each quantum state.

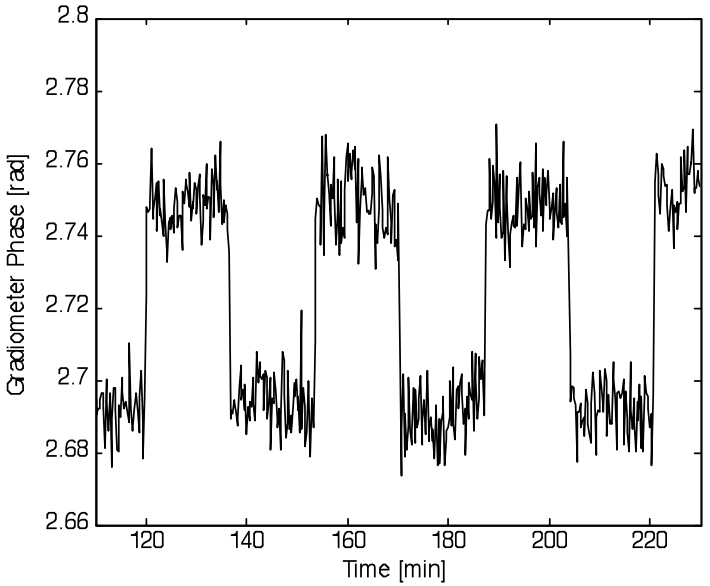
Fringes are scanned electro-optically.

Hybrid sensor/Gravity gradient mode

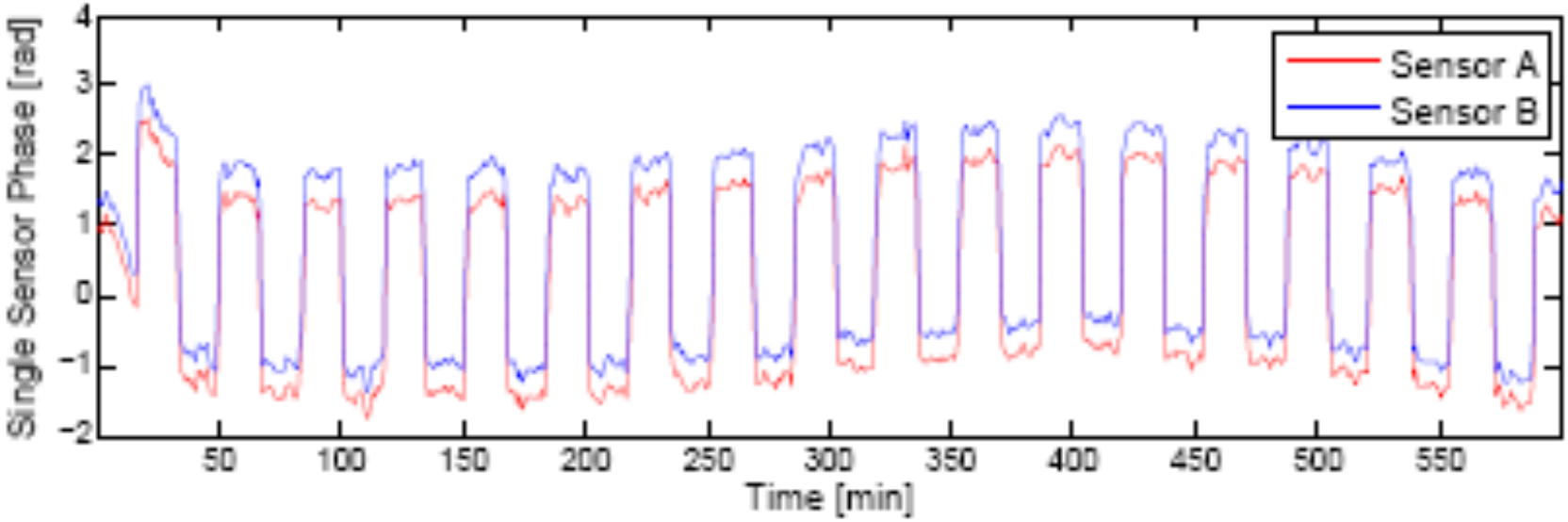






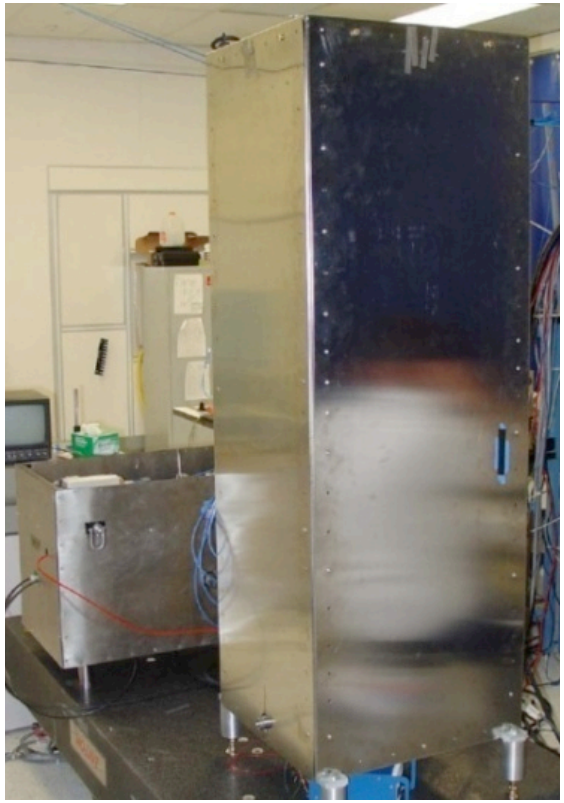


Hybrid sensor/Absolute accelerometer



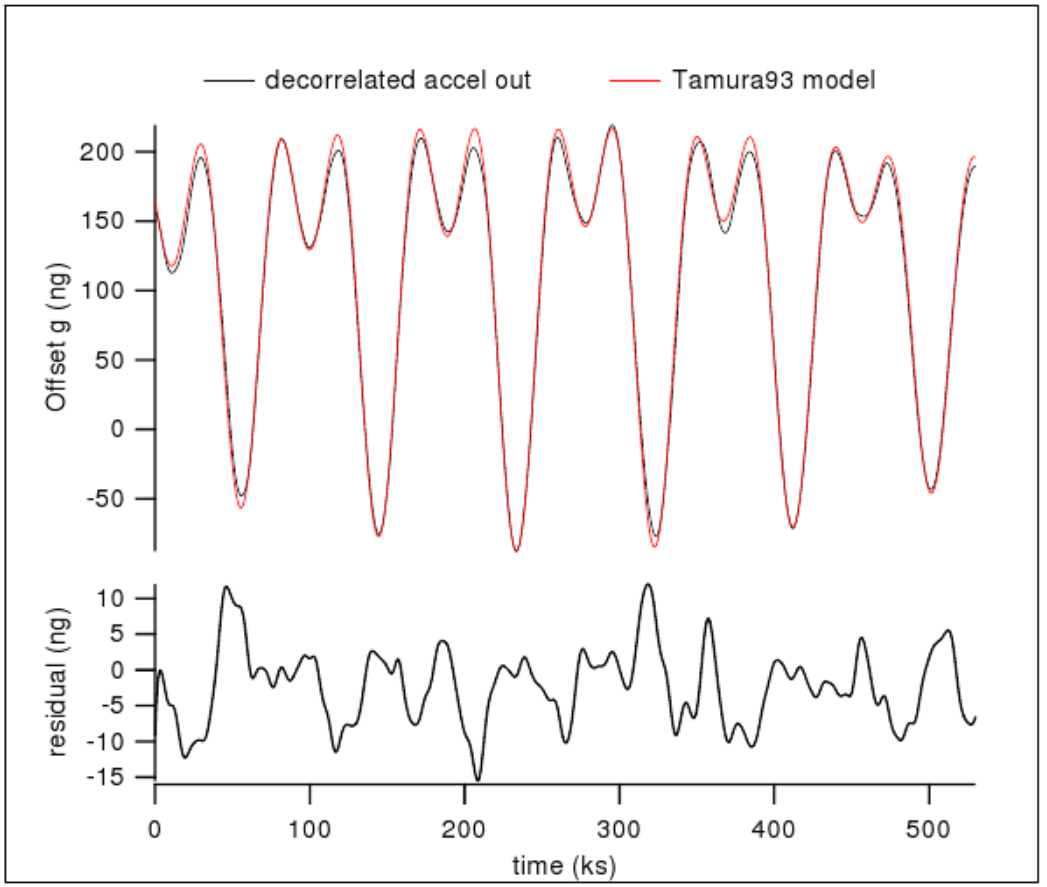
Horizontal input axis, microGal resolution.

Gravimeter, Measurement of g



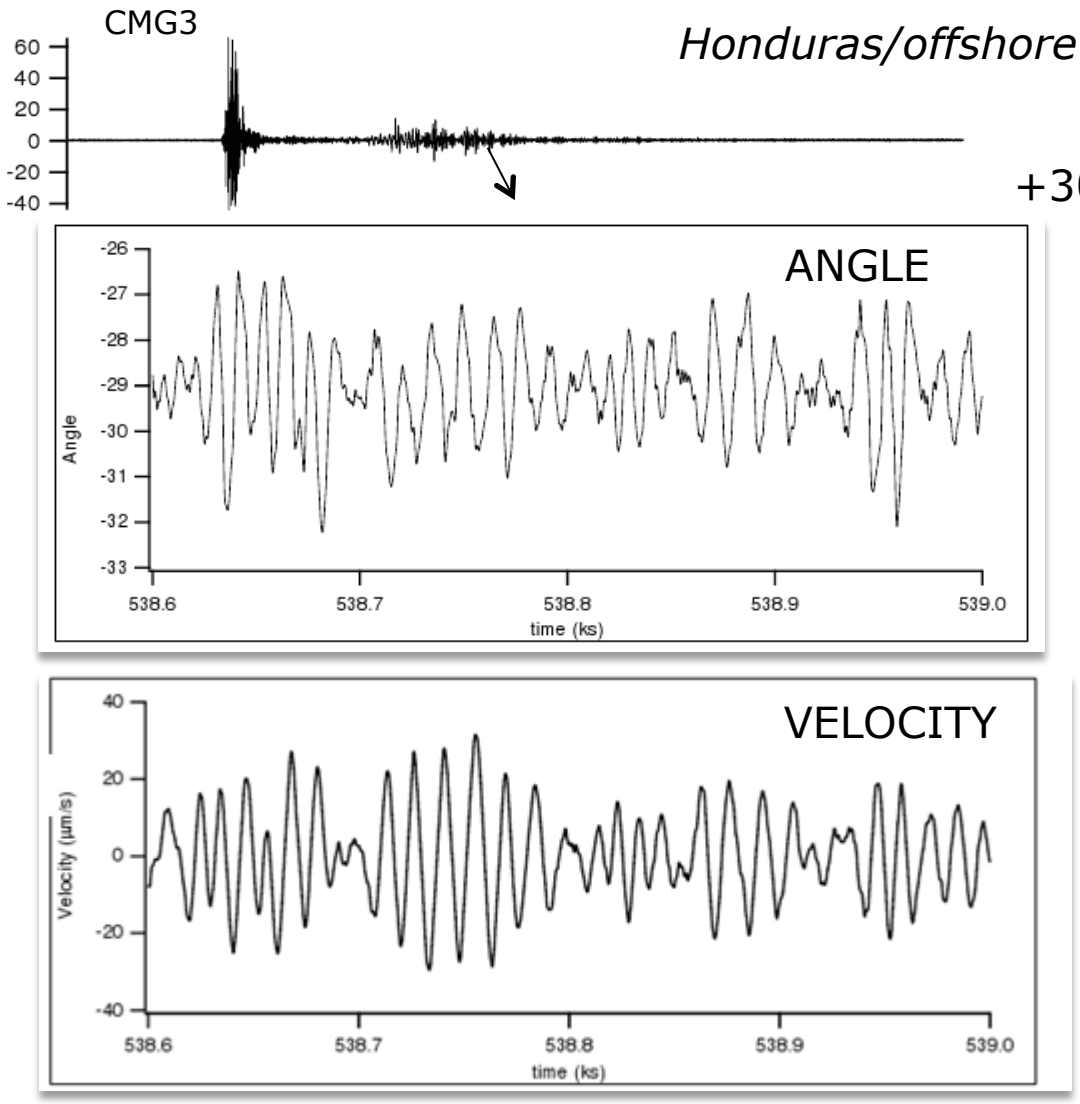
Fabricated and tested at AOSense, Inc., Sunnyvale, CA.

Sensors designed for precision navigation.

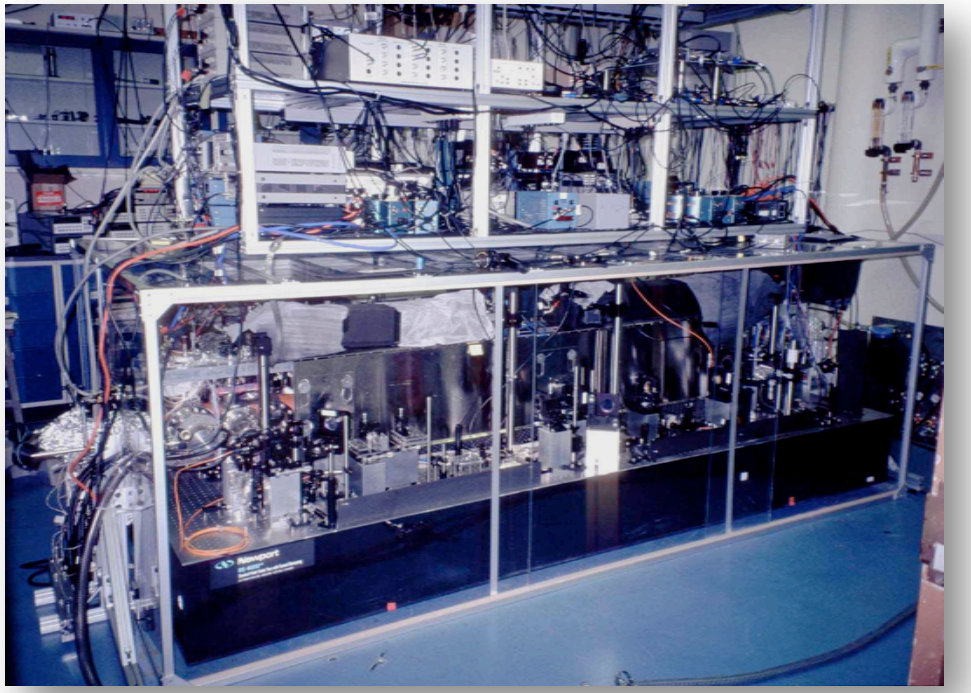


Gyroscope/Rotational Seismology

Gyroscope output necessary to disambiguate tilt from horizontal motion (navigation problem).

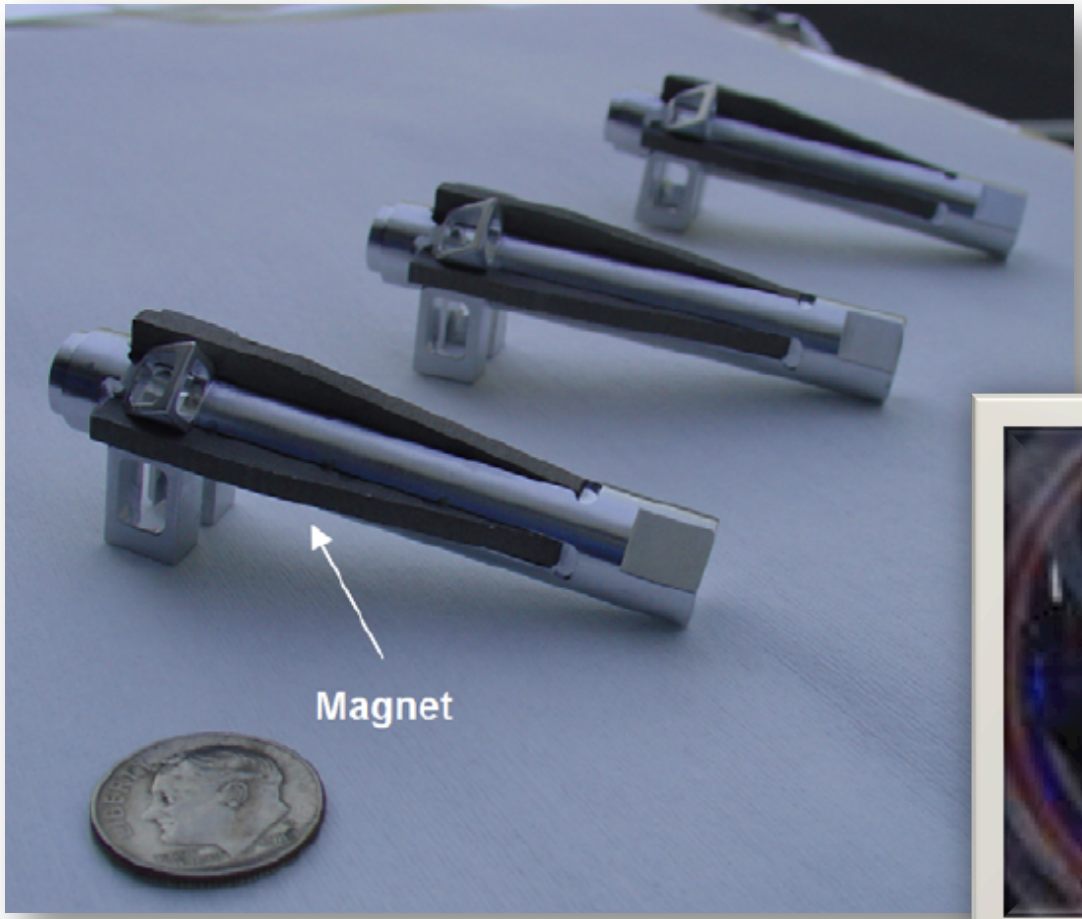


The challenge…



? how

Compact Zeeman slower



AOSense

408-735-9500
AOSense.com
Sunnyvale, CA

AOSense Commercial Compact Gravimeter

Commercial Cold Atom Gravimeter

- Noise < 1 μg/Hz$^{1/2}$
- Shipped 11/22/10
- First commercial atom optics sensor

AOSense

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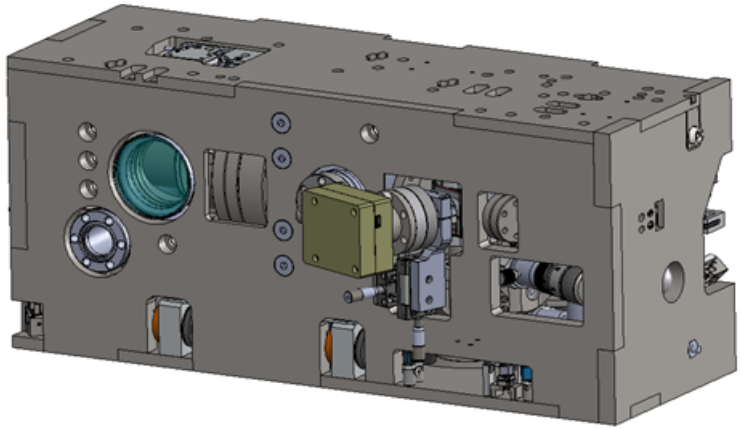
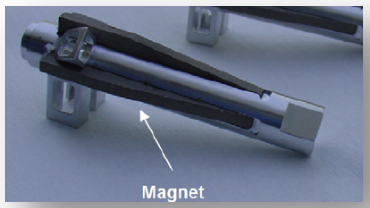
AOSense.com
Sunnyvale, CA

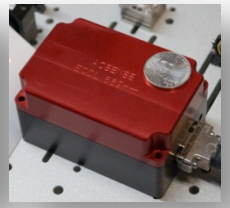
(Optical) Atomic Clock



6 L physics package. Includes all sub-systems except electronics.

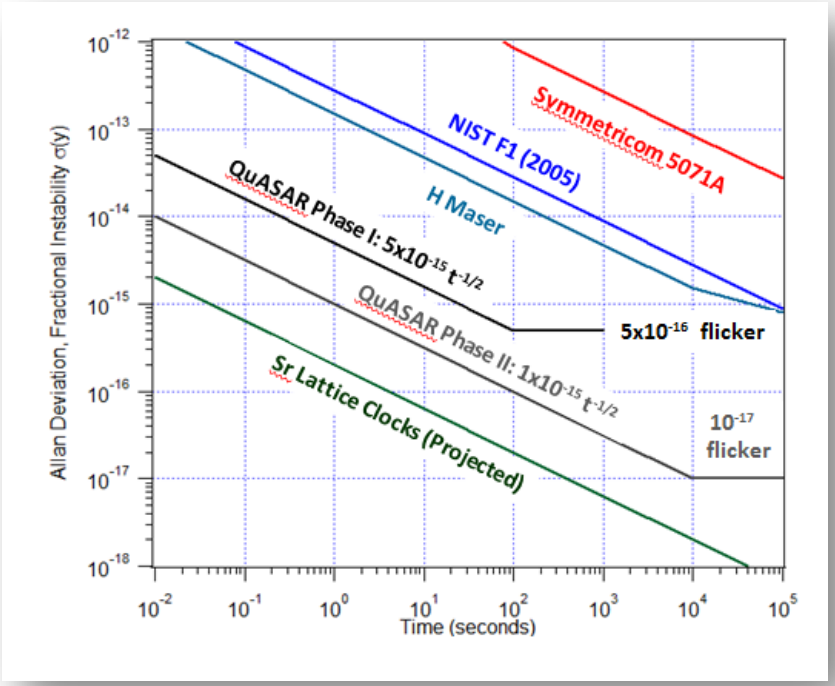


Zeeman slower



Sr clock laser

Sr oven, 3 W



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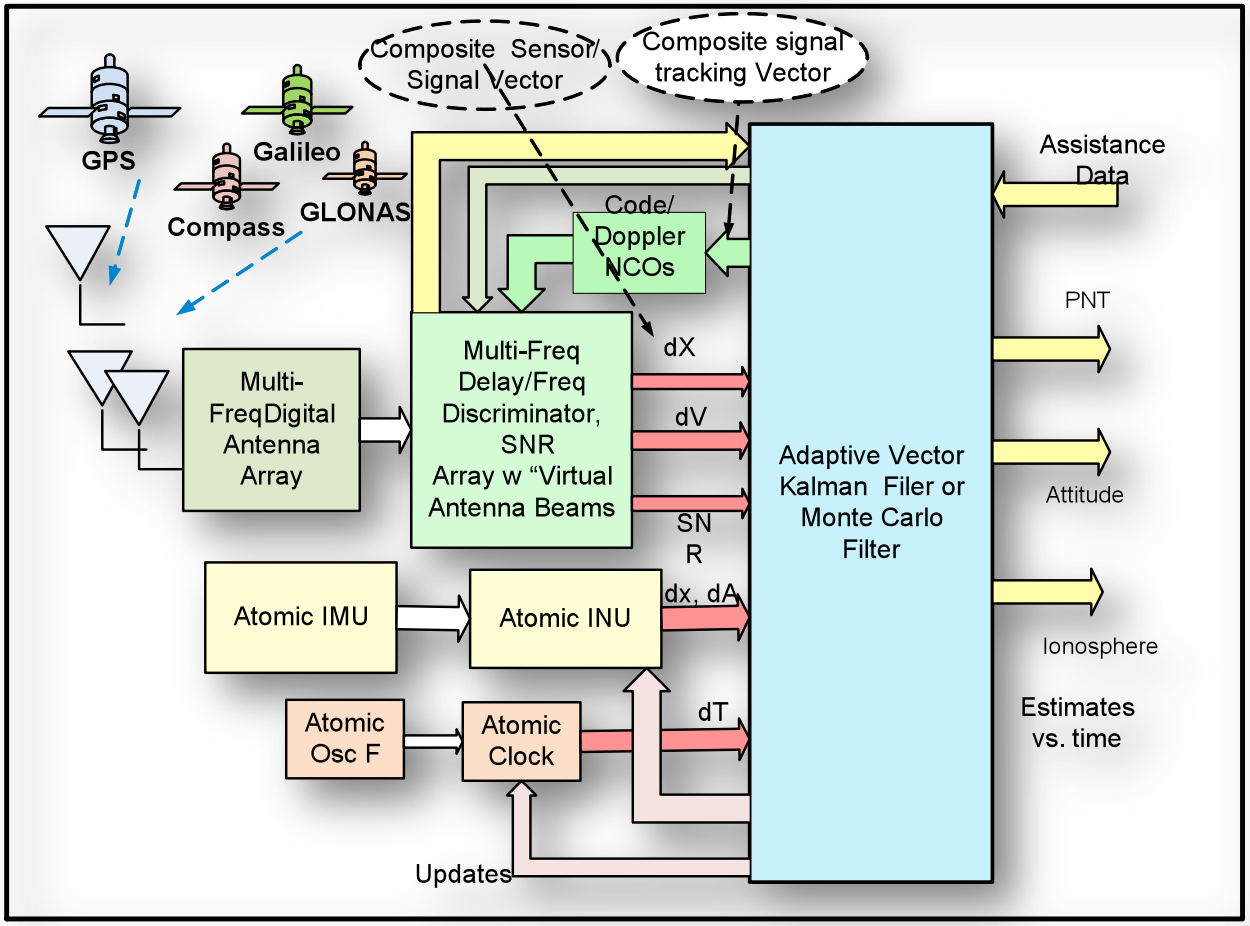
Sunnyvale, CA

System implementation



Space/time vector tracking with integrated atom inertial and clock (courtesy J. Spilker)

Technology Vision

- Inertial+ grade IMU
  - < 10 liters
  - < 10 m/hr drift
  - < 100 Watts
  - Gravity compensated
- Navigation grade IMU
  - < 0.1 liters
  - < 1 Watt
  - Low-cost ($1K ?)

408-735-9500
AOSense.com
Sunnyvale, CA