Space Quantum Science and Technology at JPL

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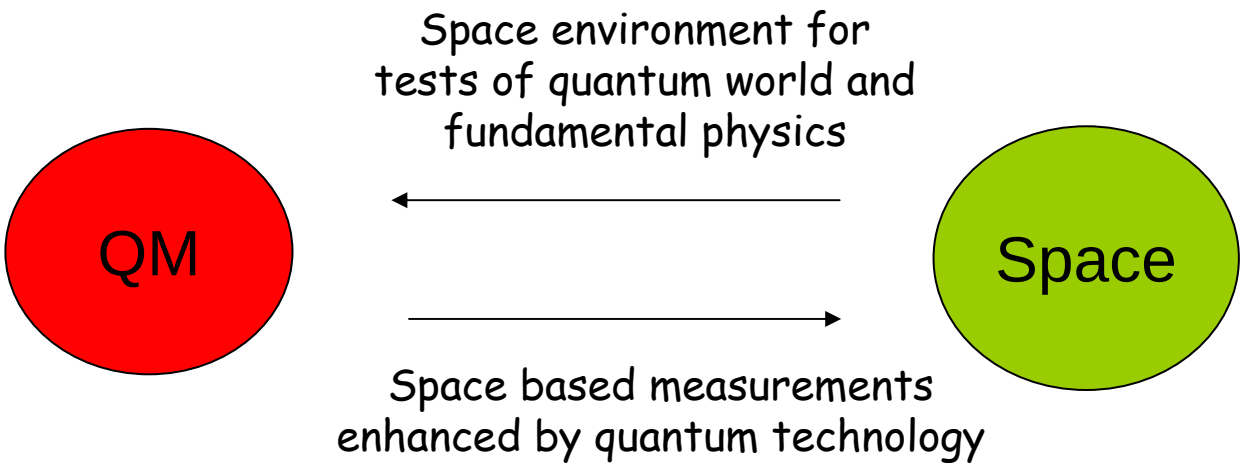
Quantum Mechanics and Space Space

Space exploration has a dual role:

– As a challenging endeavor, extremely sensitive instrumentation is required with features of performance, low power, low mass, and low cost.

– As a benign environment (low vibration, high isolation, space and time spans, etc.) it offers the opportunity to perform exacting tests of physics.



Space Has to Offer for Science

Examples of unique space environment:

- micro gravity
- Low vibration/low EMI
- Large spatial extend
- Large gravitational field variation
- Free from atmospheric interferences
- Inertial frame
- ....

- Tests of Relativity theories (PARCS, RACE, PHARAO/ACES, HYPER)
- Planck scale physics (SpaceTime, BEC, optical clocks)
- Equivalence Principle (Quite)
- Cosmology and Q decoherence (CLASS, HYPER, quantum degenarate gas)
- Quantum decoherence (HYPER, BEC, atom interferometers)
- Superposition and entanglement (atom interferometers, entangled photon communication)
- Earth and planetary science studies (gravity measurements)
- Fundamental symmetry (EDM)
- ....

Quantum Properties for Technology

- **The fundamentally quantum phenomena of wave-particle duality, superposition and entanglement, coherence and interference allow the realization of sensors with unprecedented capability**
- **Areas such as free cold atom based technology, are particularly suitable for space application**

- Ultra-stable clocks - timing keeping, navigation, fundamental physics tests
- Atom interferometer inertial sensors - gravity mapping for Earth science, gravity survey for planetary science, autonomous inertial navigation, tests of fundamental physics, drag-free control, pointing and guidance control
- BEC and quantum degenerate gas - enhancement for cold atom interferometers, tests for fundamental physics, quantum system modeling
- Entangled photon - quantum communication, secure communication, tests of quantum measurements and correlations
- EIT magnetometer - planetary magnetic field mapping
- ….

JPL's Quantum Sciences and Technology Projects

1. CLOCKS:
   - testing variation of fundamental constants and the validity of string theory
   - testing Einstein relativity theories (NIST/Yale collaborations)
   - deep-space telecommunication and navigation
2. ATOM INTERFEROMETERS
   - testing equivalence principle (Stanford Collaboration)
   - gravity mapping
   - inertial navigation and drag-free control
   - atom chips
3. BEC
   - exploring quantum gas/fluid in absence of gravity (NIST collaboration)
   - studying matter wave coherence and decoherence
   - accessing Planck scale physics and the structure of space-time
   - atom interferometer enhancement
4. EIT
   - sensor for magnetic field measurement

SpaceTime Mission Summary

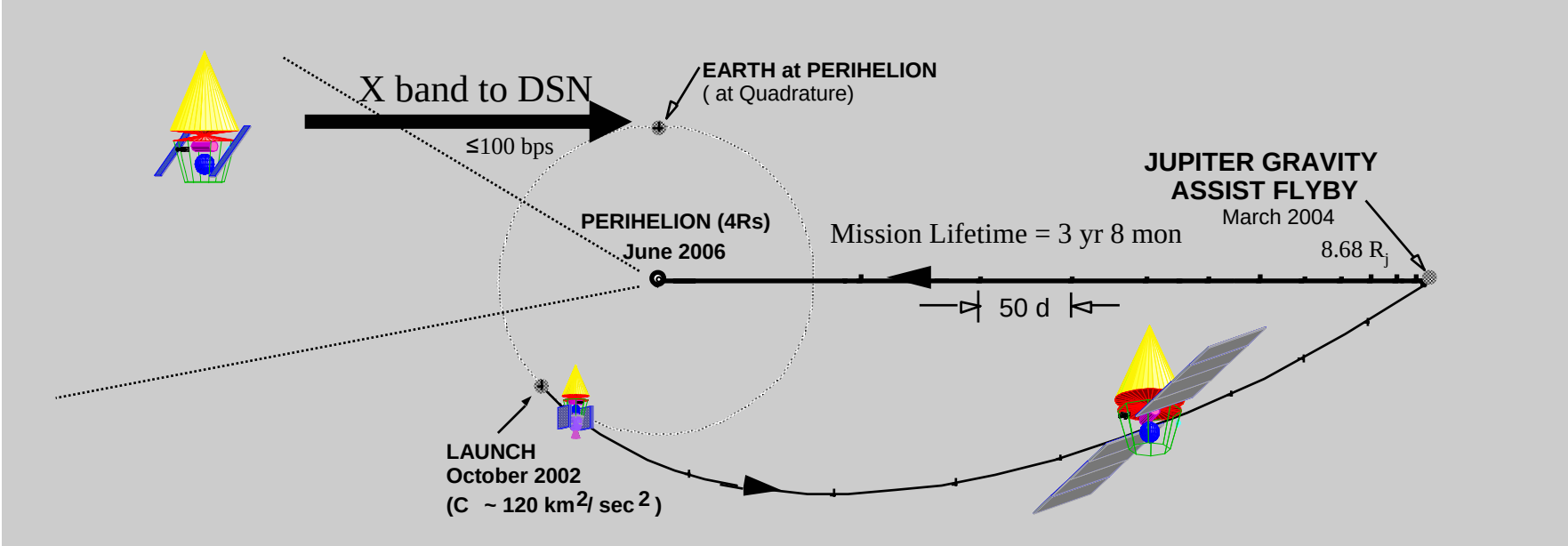
PI: Lute Maleki (JPL)
Co-I/collaborators: J. W. Armstrong (JPL), K. J. Johnson (USNO), K. L. Nordtvedt (NW Analysis), and J. Prestage (JPL)

Science Objectives:

Test the influence of proximity to Sun on α

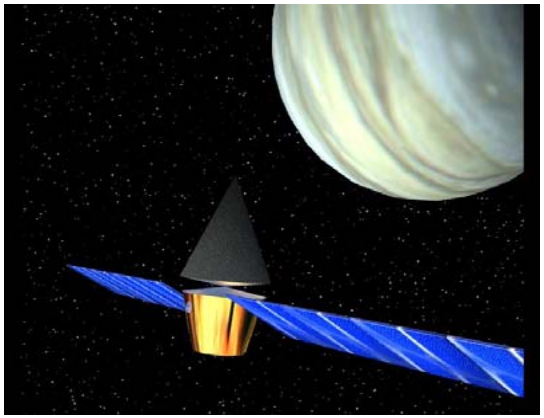
– Measure differential drift of three clocks with different atomic numbers, from 10 to 6 Solar Radii

- Direct, "clean" measurement
- Six orders of magnitude improved sensitivity over GPA, in differential mode



α Dependence of HF Transition

Hyperfine Transitions



For alkali atoms and alkali-like ions:

$$A_s = \frac{8}{3}\alpha^2 g_I Z \frac{z^2}{n^{*3}}\left(1-\frac{d\Delta_n}{dn}\right)F_{rel}(\alpha Z)(1-\delta)(1-\varepsilon)\frac{m_e}{m_p}R_{\infty c}$$

With f as the frequency of transition:

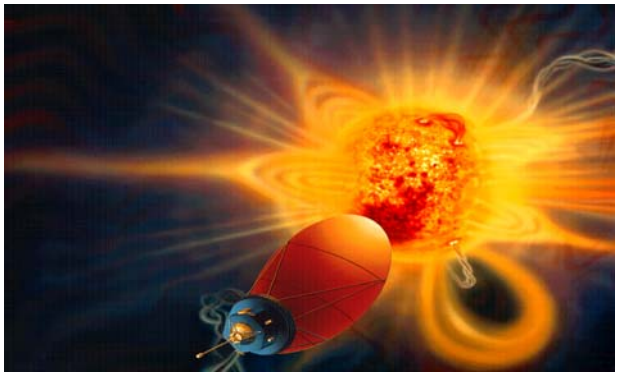
$$f = \alpha^4 \frac{m}{M}\frac{mc^2}{h}F(\alpha Z)$$

	H	Rb	Cs	Hg+
H	0	0.3	0.74	2.2
Rb	-0.3	0	0.45	1.9
Cs	-0.74	-0.45	0	1.4
Hg+	-2.2	-1.9	-1.4	0

α time dependence to location dependence in scalar field

$\dot{\alpha}/\alpha < 10^{-14}$/yr by comparing Hg+ with H
Prestage, Tjoelker, Maleki
PRL, 74, 3511(1995)

Tri-clock Approach



Instrument:

A tri- clock based on trapped ions, Hg^+ , Yb^+, and Cd^+, in the same environment, based on JPL's LITS design

- –Mass: 20 Kg for tri-clock
- –Power: 30 W for tri-clock
- –Data Rate: < 100 bps

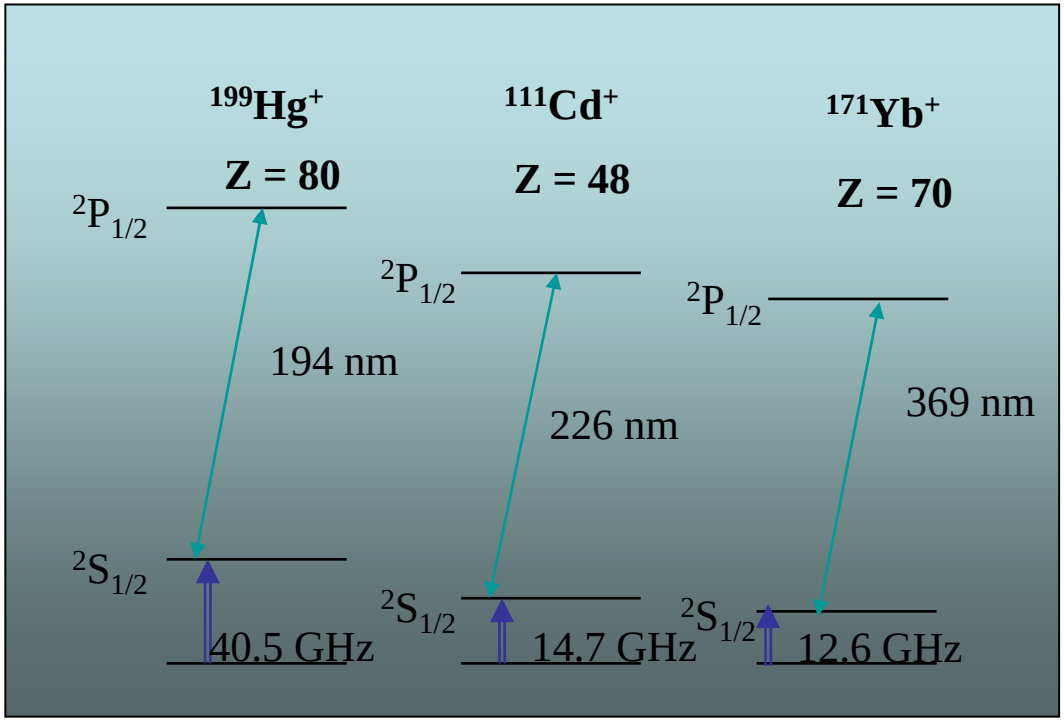
- Three ion traps in same environment:
  - Common vacuum system, thermal environment, magnetic environment
    - Allows elimination or minimization of environmental perturbations
  - Common LO
    - Allows use of high performance quartz, and still achieve 10^{-16} stability
- Most electronic components and circuits are common
- Mass and power requirements compatible with limitations
- Provides needed stability (10^{-16}) at 40,000 s
- Comparison made onboard, only results are beamed back

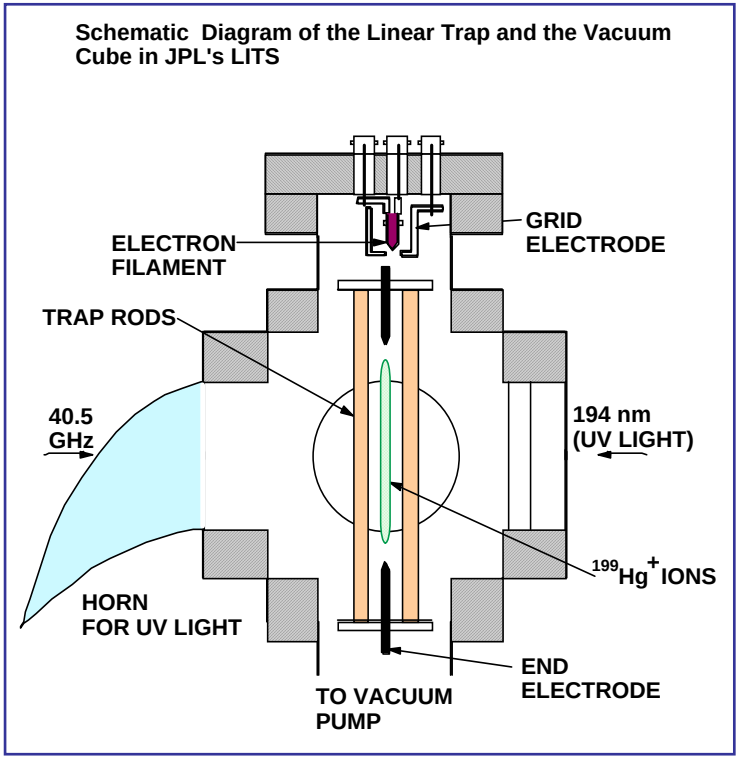
The Linear Trapped Ion Standard (LITS)

Developed at JPL for NASA's Deep Space Network.

-- Operates with lamp and buffer gas cooling.

-- Currently three units operating in the DSN. A flight unit, as a prototype for GPS, is under development.





Gravity Mapping for Earth and Planetary Sciences

- **Earth and Planetary Interiors**
  - Lithospheric thickness, composition
  - Lateral mantle density heterogeneity
  - Deep interior studies
  - Translational oscillation between core and mantle
  - Volcanology and seismology

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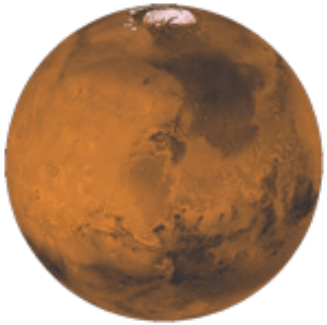
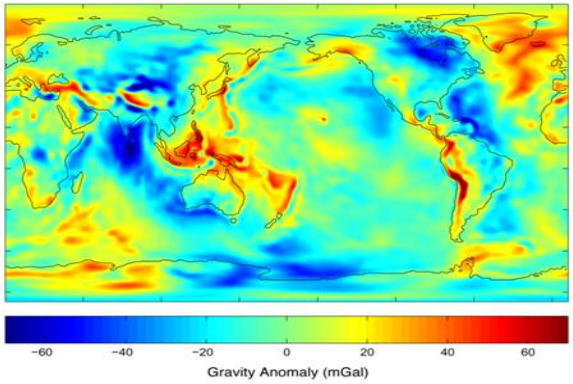


Simulation of compressible mantle convection (Tackley and Stevenson *Caltech)*

Mars gravity field mapping, Supporting Mars exploration.

- **Earth and Planetary Climate Effects**
  - Ice mass variations and ground water storage
  - Oceanic circulation
  - Tectonic and glacial movements
  - Tidal variations

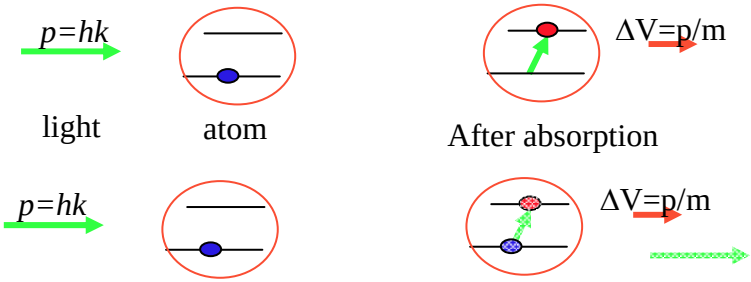


Gravity anomalies from 111 days of GRACE data

Atom Interferometer as Accelerometer

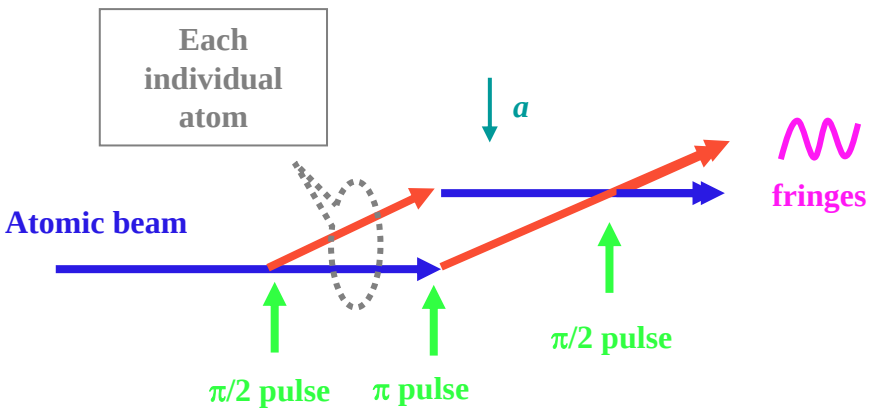
Atom interferometer accelerometer using light pulses*

Photon absorption process
(π pulse)



Superposition state
(π/2 pulse)

* M. Kasevich and S. Chu *Phys. Rev. Lett.* vol. 67, p.181, 1991
[1] A. Peters, K. Y. Chung, and S. Chu, Metrologia 38 , 25 (2001).
And



The phase difference of two atomic beam paths at the end of 2nd π/2 pulse:

$$\Delta\Phi = 2\,k\,a\,T^2$$

where k is the laser wavenumber and T is the interaction time.

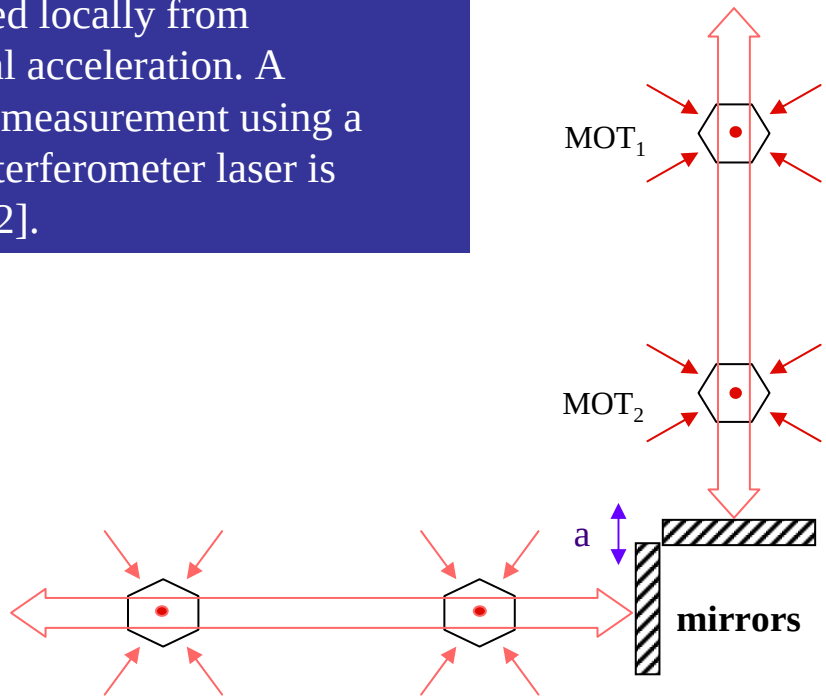
Terrestrial laboratory measurements:
- with over 10^6 atoms, the shot-noise limited SNR ~ 1000, per launch sensitivity: $10^{-11}/T^2$ g.
- demonstrated resolution: 10^{-11} g [1].

Under microgravity in space:
Better than 10^{-13} g $Hz^{-1/2}$ possible with >10 s interrogation time.

Atom Interferometer Gravity Gradiometer in Space

Einstein's Equivalence Principle: the frame acceleration can not be distinguished locally from gravitational acceleration. A differential measurement using a common interferometer laser is employed [2].

gravity gradient = $(g_1 - g_2)/L = \Delta\Phi_{12}/2kLT^2$



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

$\Delta\Phi = 2k\,(g_1-g_2)\,T^2$

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

The common reference acceleration is cancelled out,[1] which allows the gradiometer to be used on moving platforms such as spacecraft.

(1) M. J. Snadden et al. PRL **81**, 971 (1998).

Single satellite: *(L=10m) 5×10^{-4} E/Hz$^{1/2}$*

Long baseline: *(100 m) 5×10^{-5} E/Hz$^{1/2}$*

Satellite formation: *(200km): 3×10^{-8} E/Hz$^{1/2}$*

Advanced Gravity Missions

GPS-CHAMP high-low satellite-to-satellite and ground based laser tracking

CHAMP

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are needed to see this picture.

Low-low satellite-to-satellite microwave tracking and ranging (for long wavelength i.e. 500 km and time variation)

GRACE

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GOCE

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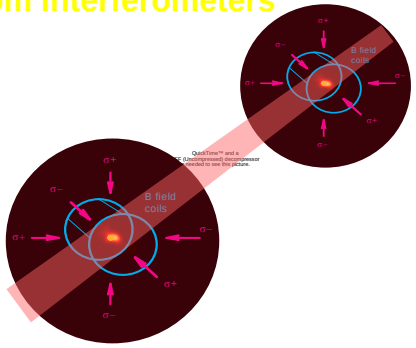
GOCE satellite gradiometry using 3-axis accelerometers (for high resolution ,i.e. 100 km)

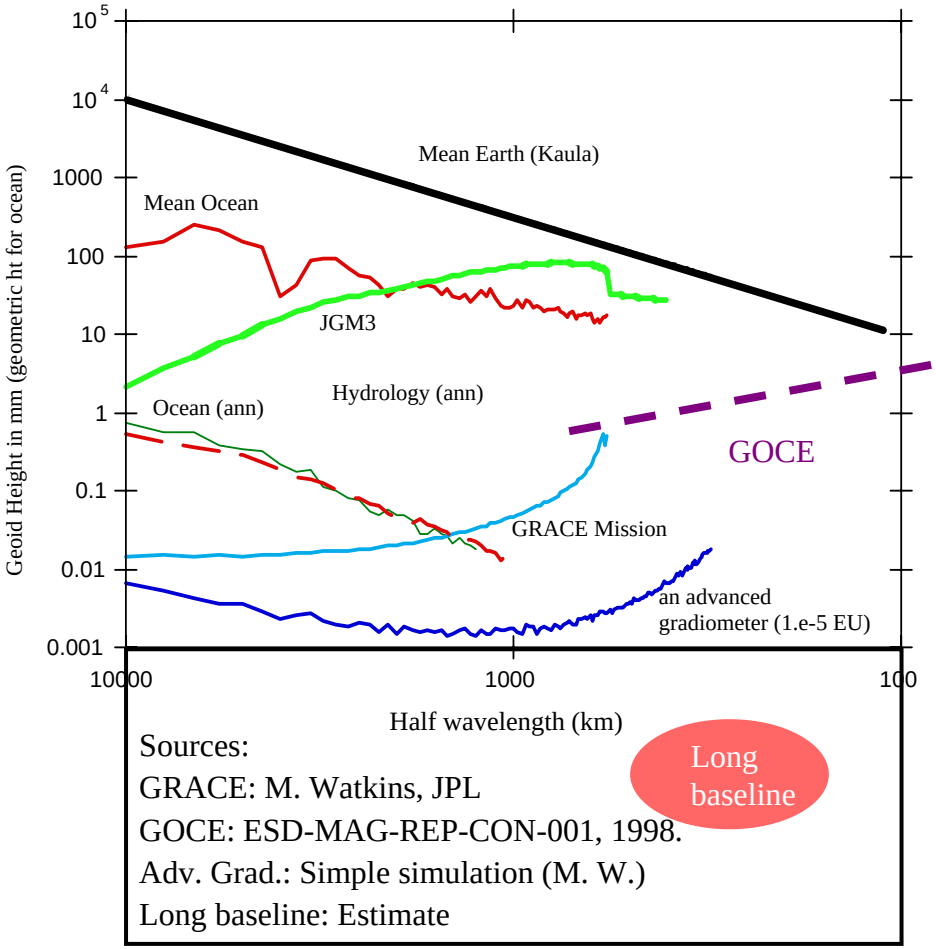
Atom Interferometers



Quantum gravity gradiometer using cold atoms as truly drag-free test masses (high spatial resolution + high stability for time variation)

Potential for Gravity Missions

Potential for Science Missions

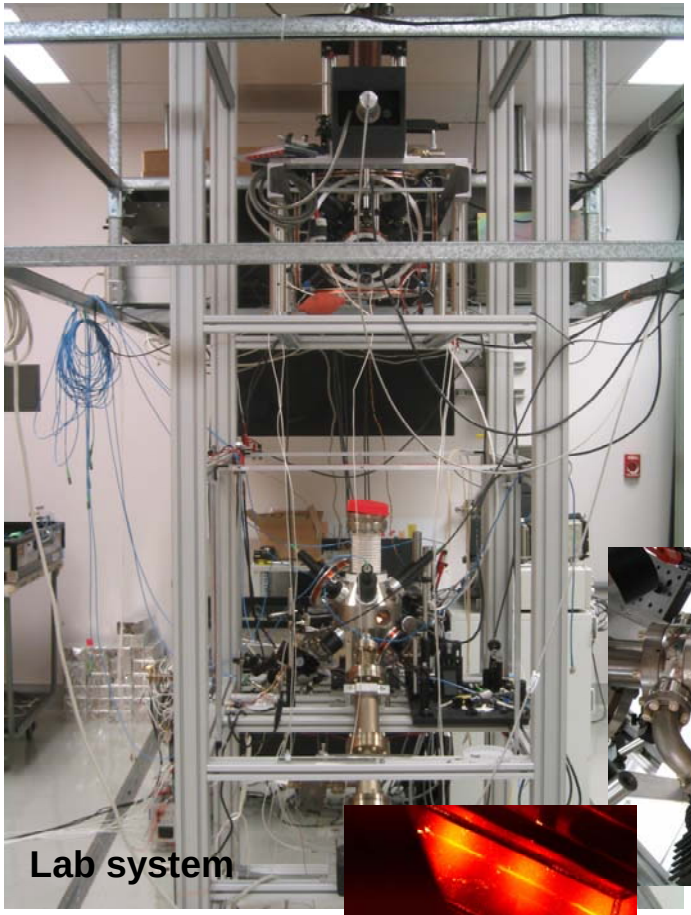


Advantages with Atom Interferometer Gravity Gradiometer

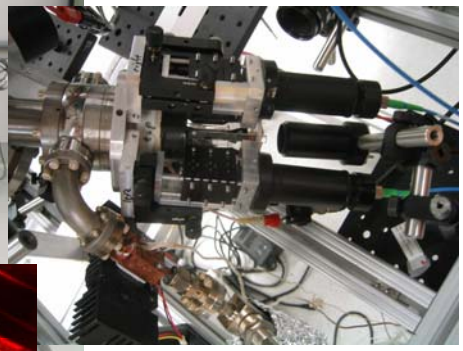
- ✓ Great sensitivity for inertial sensing
- ✓ Identical atomic test mass - no fabrication tolerance issue
- ✓ Free atoms in vacuum - true drag-free
- ✓ Laser cooled test mass - no cryogenics needed
- ✓ All laser manipulation - minimal mechanical moving parts
- ✓ Inherent self calibration - excellent long term stability
- ✓ Single spacecraft mission

JPL Laboratory Gradiometer Development

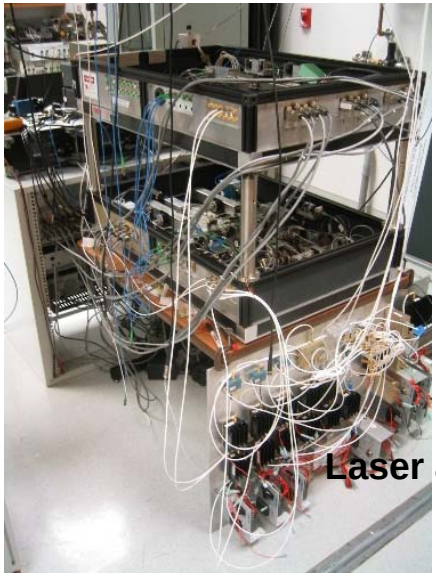
Work done by Nan Yu, James Kohel, James Kellogg

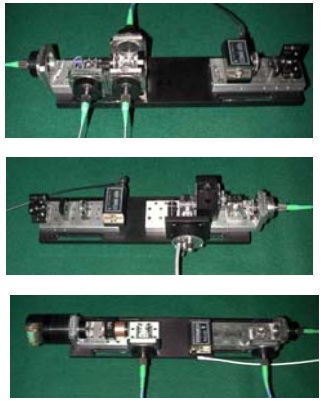


Lab system

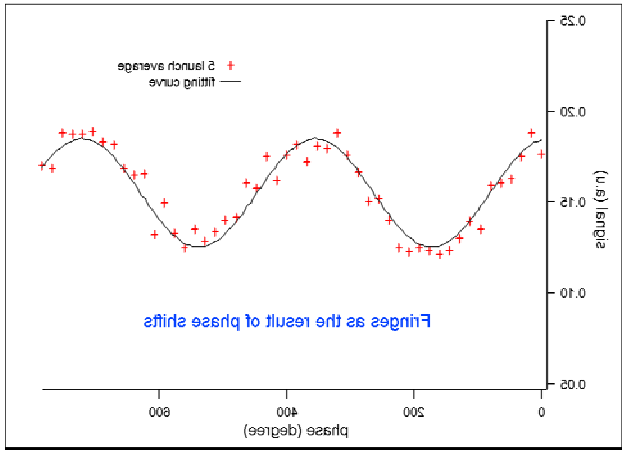


Compact source





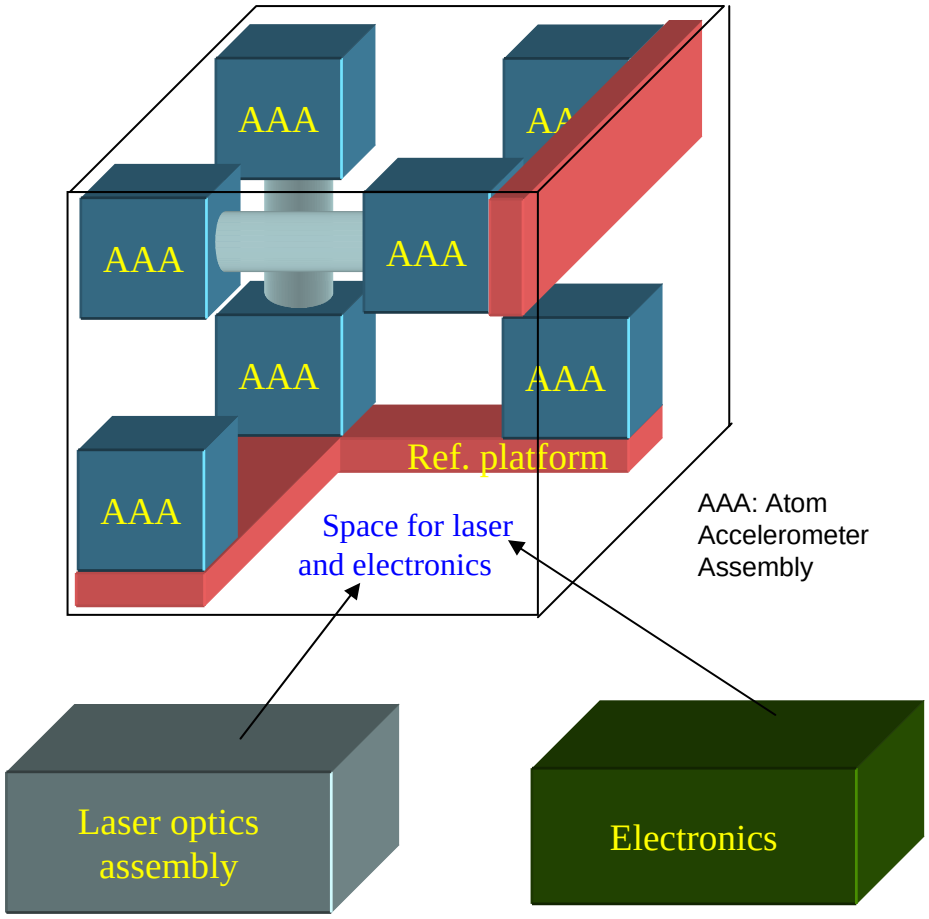
Laser and optics system



Interference fringes

Other Applications Under Study

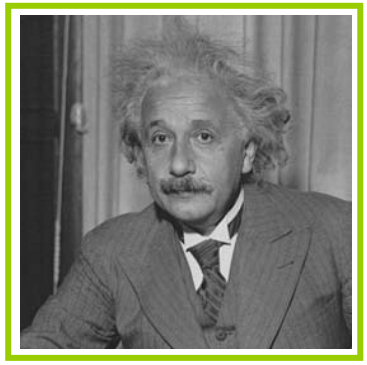
- Grace like mission (on board accelerometers)
- Application in LISA-like missions (drag-free control)
- Inertial navigations
- Near surface gravity survey instrument



Compact gradiometer design illustration

Testing EEP (QuITE) Mission Concept

QuITE - Quantum Interferometer Test of Equivalence Principle

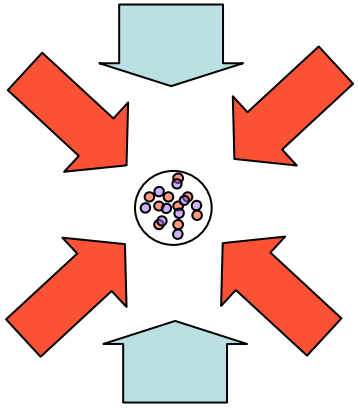


PI: Mark A. Kasevich, Yale University
Co-I: Lute Maleki, Jet Propulsion Laboratory
(2002)

Science Objective:
Seeking a violation of Einstein's Equivalence Principle (EEP) by improving the test limit by three orders of magnitude.

$\Delta g = g_A - g_B = ?$

Two species differential accelerometer



Technology Goal:

Differential Accelerometer Attribute	Existing Laboratory Gravity Gradiometer	Proposed Ground	Space-Borne
Sensitivity	1×10^{-9} g/Hz$^{1/2}$	1×10^{-11} g/Hz$^{1/2}$	1×10^{-13} g/Hz$^{1/2}$
Accuracy for 6 months of data collection	NA	3×10^{-15} g	$< 1\times10^{-16}$ g

CLASS Mission Summary

CLASS - Bose Einstein Condensation Laboratory aborad the Space Station

Principal Investigator: W.D. Phillips (NIST-Gaithersburg)
Co-Investigators: K. Helmerson P. D. Lett, S. Rolston (NIST-Gaithersburg)
R.J. Thompson, L. Maleki (Jet Propulsion Lab)

A technology demonstration experiment

- BEC for Scientific Investigations
- Bose Condensation in Microgravity
- Picokelvin atoms in space
- An Atom Laser in Space
- Proposed Flight Experiments
- Experiments involving Reflection from Optical Potentials
- A Single-Mode Fabry-Perot Cavity
- Quantum Reflection
- Quantum Collapse and Revivals
- Three-dimensional Matter-Wave Holograms
- Future Flight Experiments
- Quantum Fluids
- Spin-Gravity measurements
- Atom Interferometry

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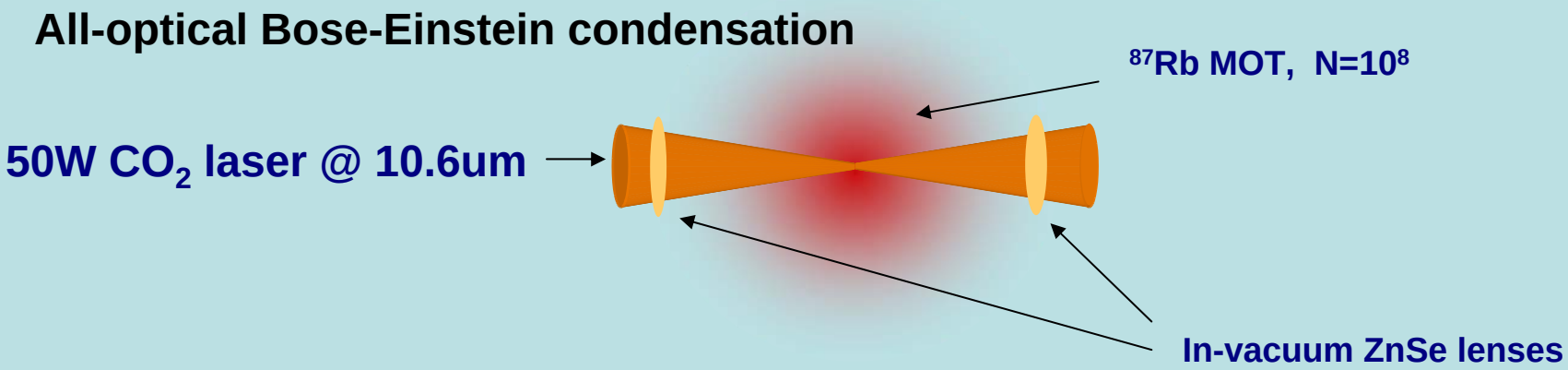
JPL BEC Status

Work done by Nathan Lundblad (student member of the group) , Robert Thompson , David Aveline

All-optical Bose-Einstein condensation



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- BEC achieved through evaporatively cooling ^{87}Rb in a dipole-force optical trap
- BEC of N>20,000 formed in spinor of $m_f = \{0,\pm1\}$ or pure $m_f = 0$
- Initial trap frequencies: {4kHz, 4kHz, 300Hz}
- T_c typically 100-150nK

PARCS and RACE Missions

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Co-Principal Investigators:
Don Sullivan and Bill Phillips (NIST)
Neil Ashby (University of Colorado)

JPL is responsible for flight hardware development.

Principal Investigators:

Kurt Gibble (Penn State)

JPL is responsible for flight hardware development.

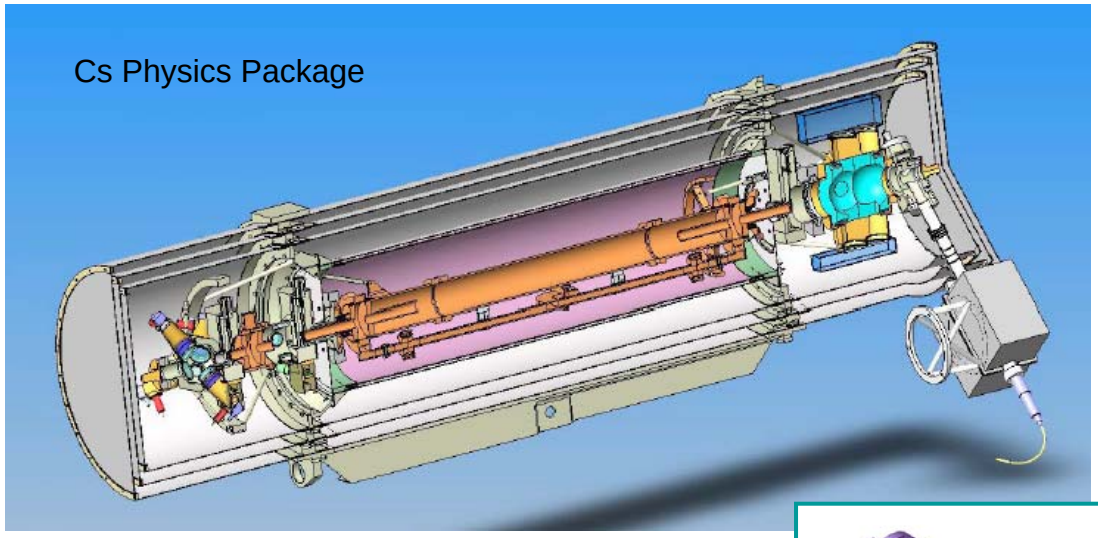
PARCS mission objectives:

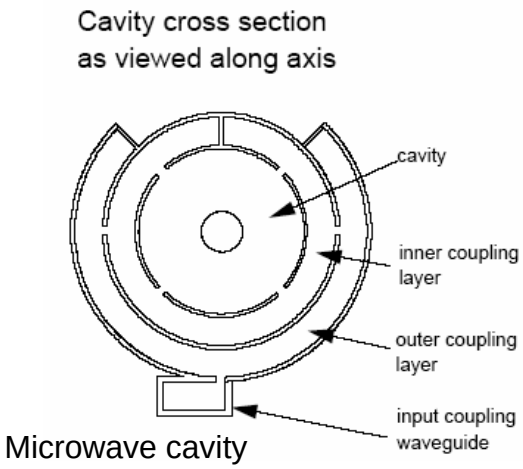
- Test gravitational theory
- Study laser-cooled atoms in microgravity
- Improve the accuracy of timekeeping on earth

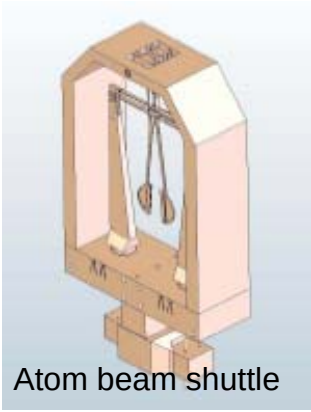
RACE mission objectives:

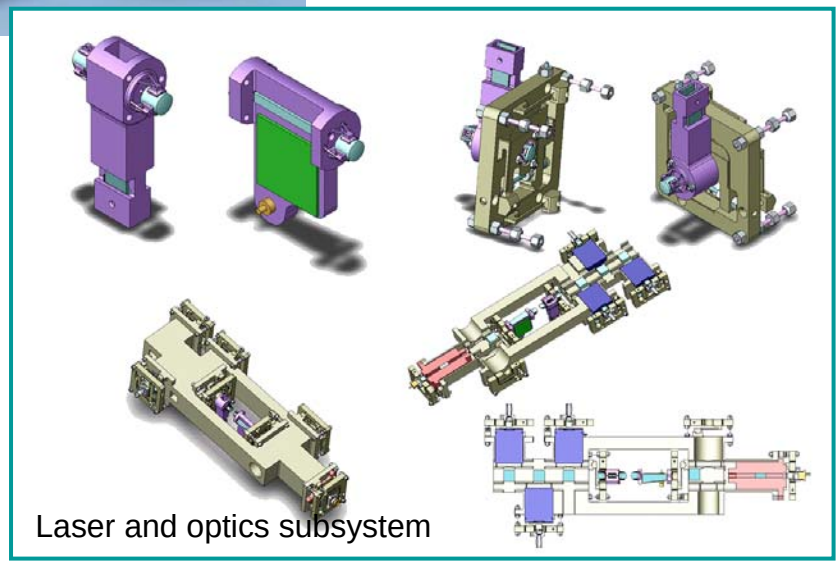
- Advance atomic clock science and techniques to enable measurements with accuracies of 1 part in 10^{-17}.
- Significantly improve the classic clock tests of general relativity.
- Distribute the highest achievable time and frequency stability accuracy from the ISS.

PARCS Fight System Development



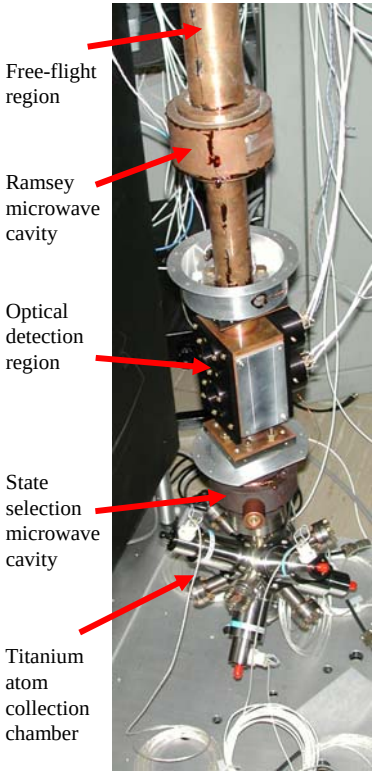


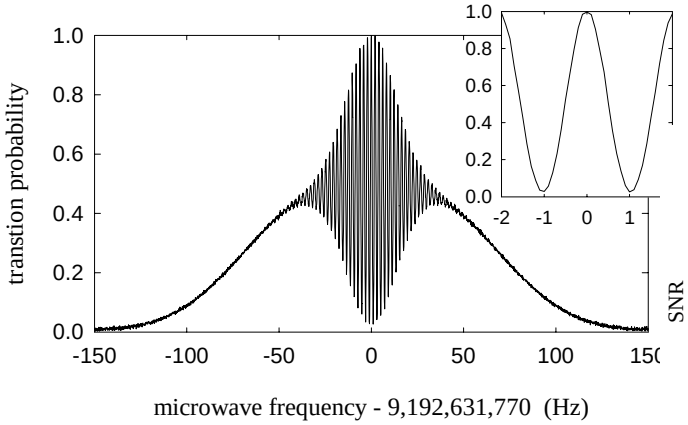


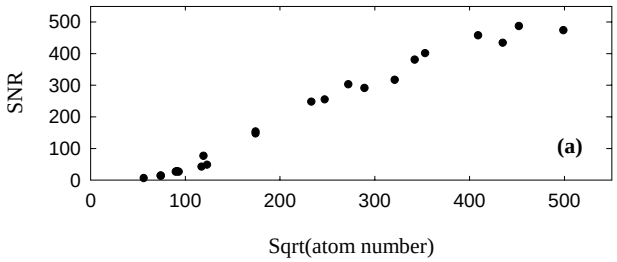


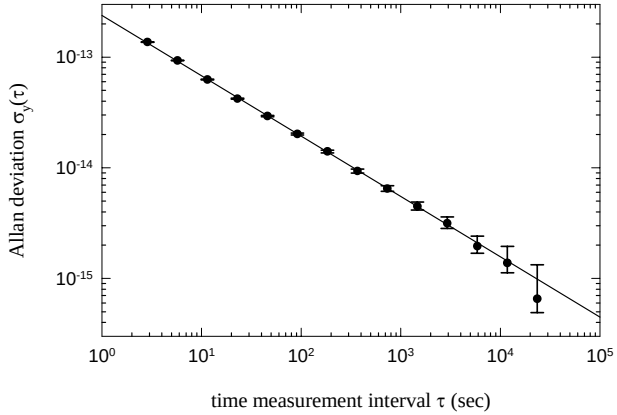
PARCS Ground Testbed Status

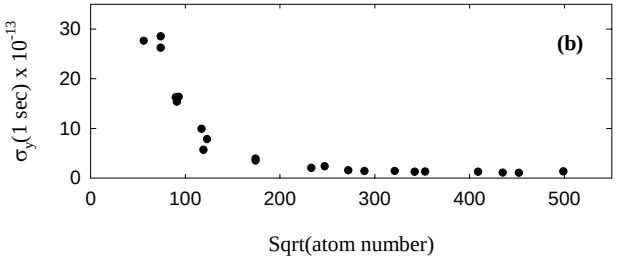
Work done by D. G. Enzer and W. M. Klipstein of JPL







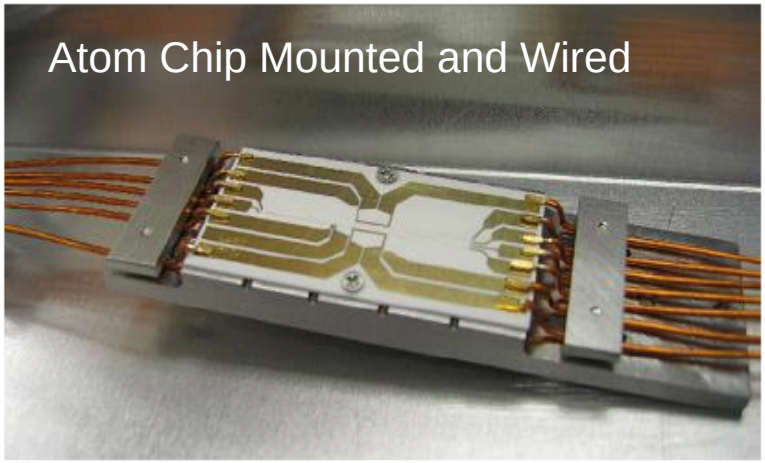




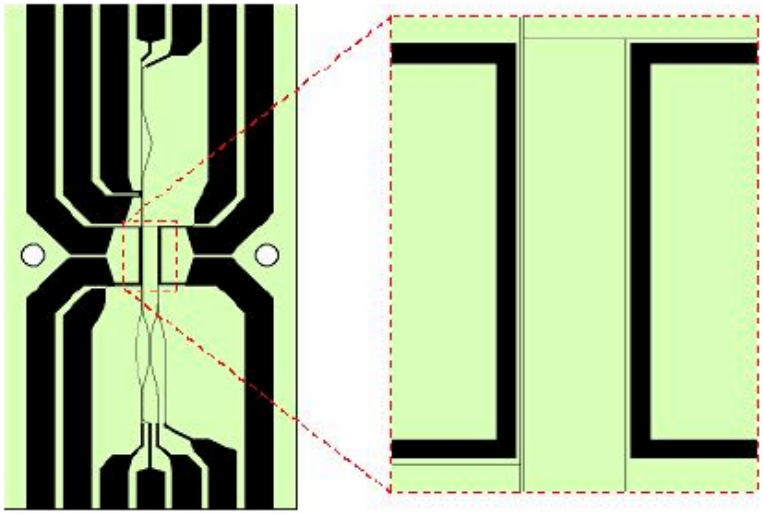
D. G. Enzer and W. M. Klipstein. *Proc. 2004 IEEE Int. Freq. Contr. Symp. and Exposition*, Montreal, 2004, pp. 775-780.

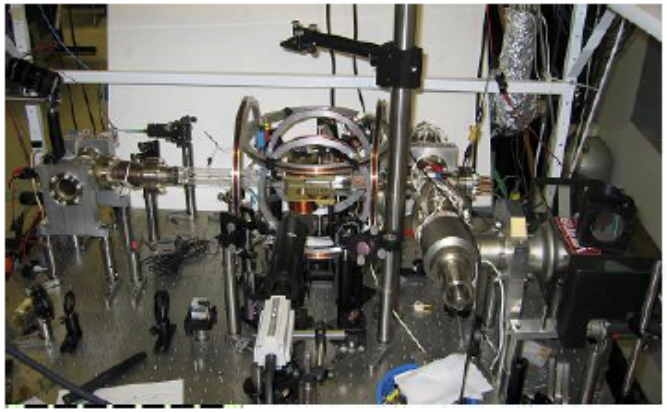
Atom Chip Experiment

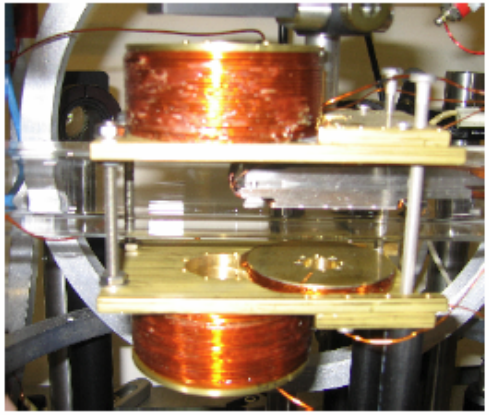
Work done by David Aveline, Nanthan Lundblad Robert Thompson. James Kohel, and Nan Yu

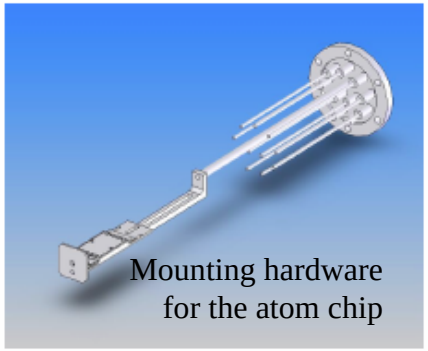


Layout of Atom Chip Magnetic Waveguide

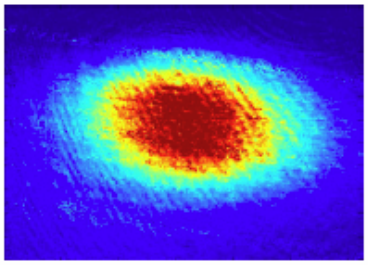




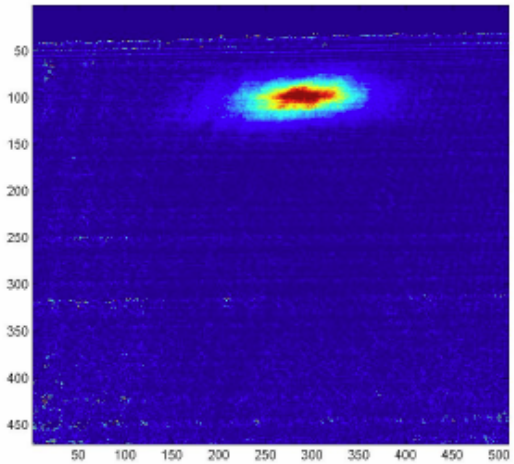


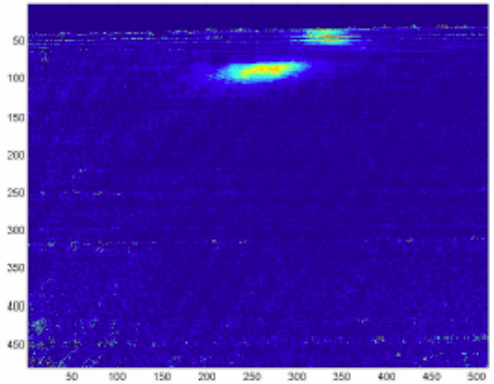


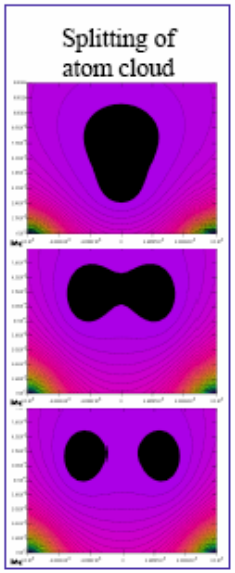
Atom Loading to Atom Chip Guide

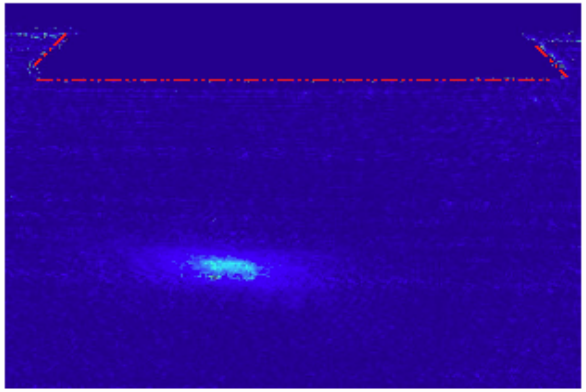


Cold atom in 3D MOT

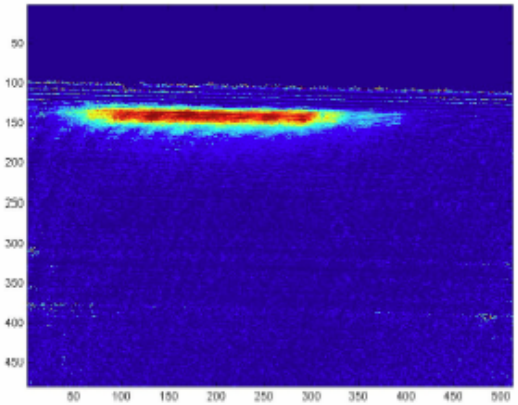








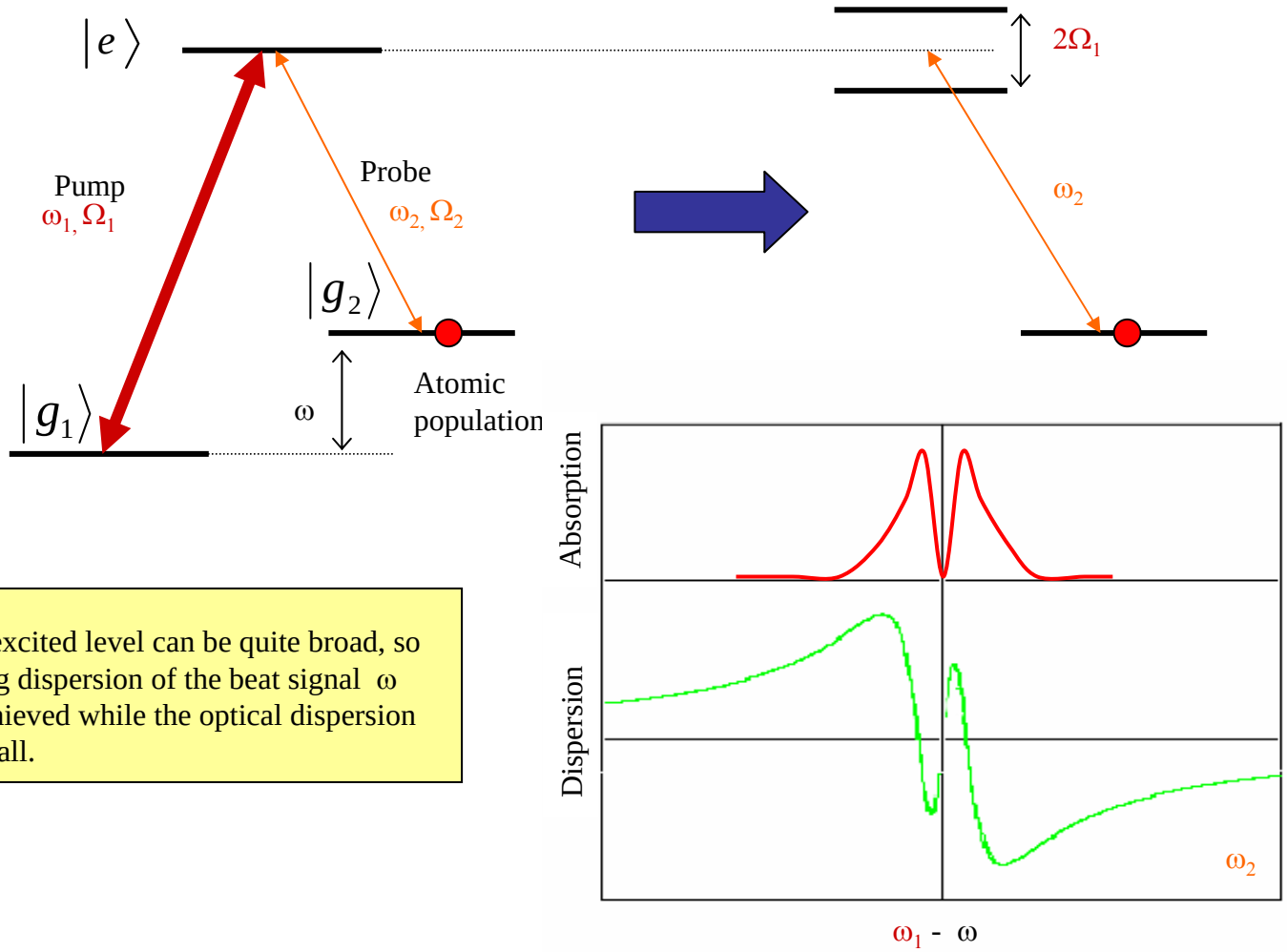
~ 1mm



Atom cloud after being held in U-wire trap

Electromagnetically Induced Transparency (EIT)

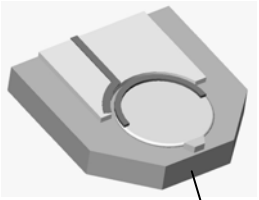
Electromagnetically induced transparency



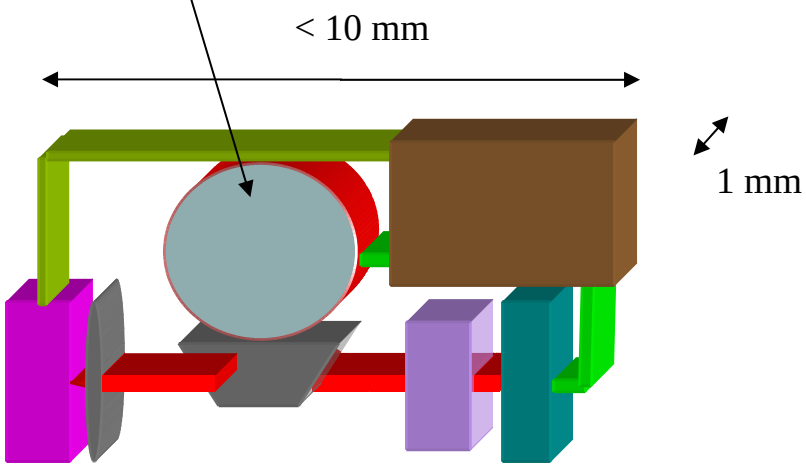
The excited level can be quite broad, so strong dispersion of the beat signal ω is achieved while the optical dispersion is small.

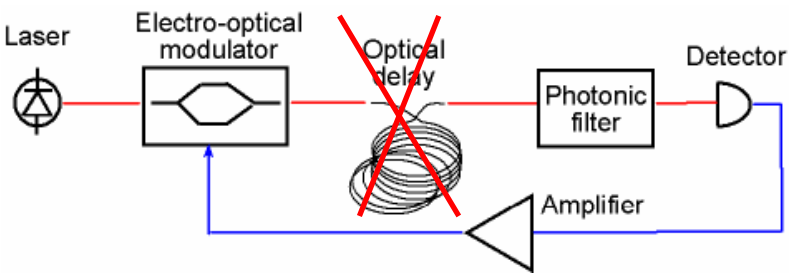
EIT Devices (Magnetometer, Clock)

Work done by Dmitry Strekalov, Anatoliy Savchenko, Andrey Matsko, Nan Yu



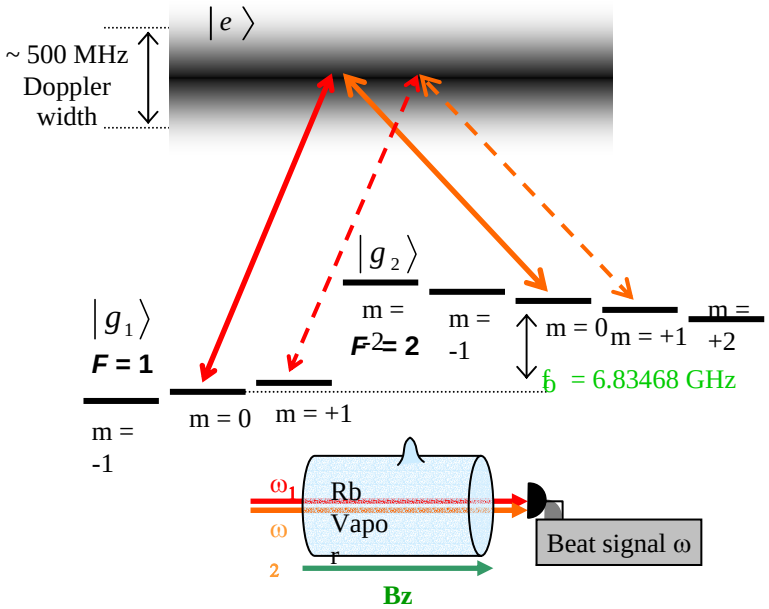
High efficiency resonance modulator



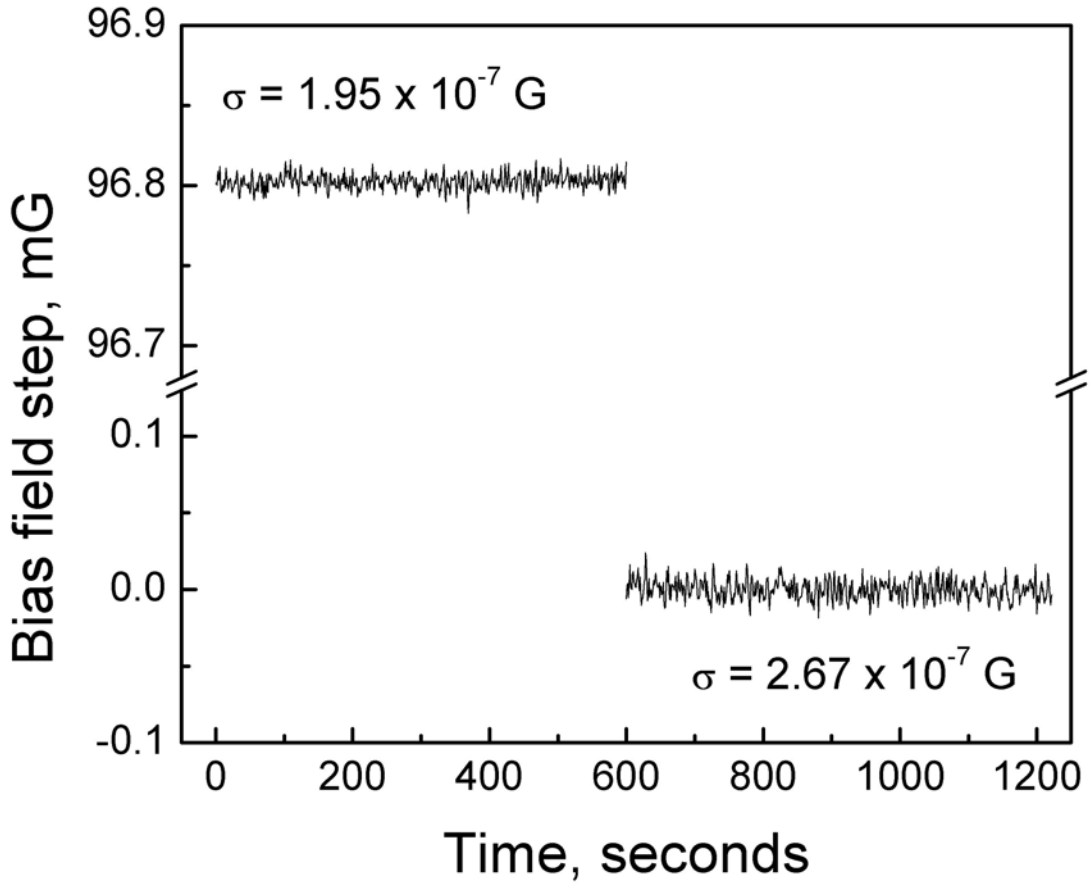


Opto-electronic oscillator with EIT transmission filter

^{87}Rb D_1-line ($5^2S_{1/2} \rightarrow 5^2P_{1/2}$),
$F = 2 \rightarrow F' = 1$



EIT-OEO Magnetometer Results



Conclusion Remarks

- Properties of quantum mechanics can be utilized to implement and enhance sensors of unprecedented performance.
- Space-based measurements for both science and application often require extraordinary sensitivity which is afforded by quantum devices.
- Space environment is also ideal and often necessary for tests of fundamental physics and quantum physics itself.
- Near-term quantum applications in space will include ultra-precise clocks for test of special and general relativity and navigation; atom interferometers for tests of General Relativity and EEP; and gravity gradiometer for gravity mapping.
- Atomic clocks and atom-wave inertial sensors will play important roles in space applications for gravity and magnetic filed measurements, navigations, pointing and guidance, inertial-fame referencing and drag-free control.
- JPL is developing a number of key quantum technologies (specially clocks and gravity measurement devices) in support of NASA missions, including Earth Science, Space and Planetary Sciences, as well as Mars explorations.