Opportunities and Development of Atomic Systems and Quantum Devices in Space

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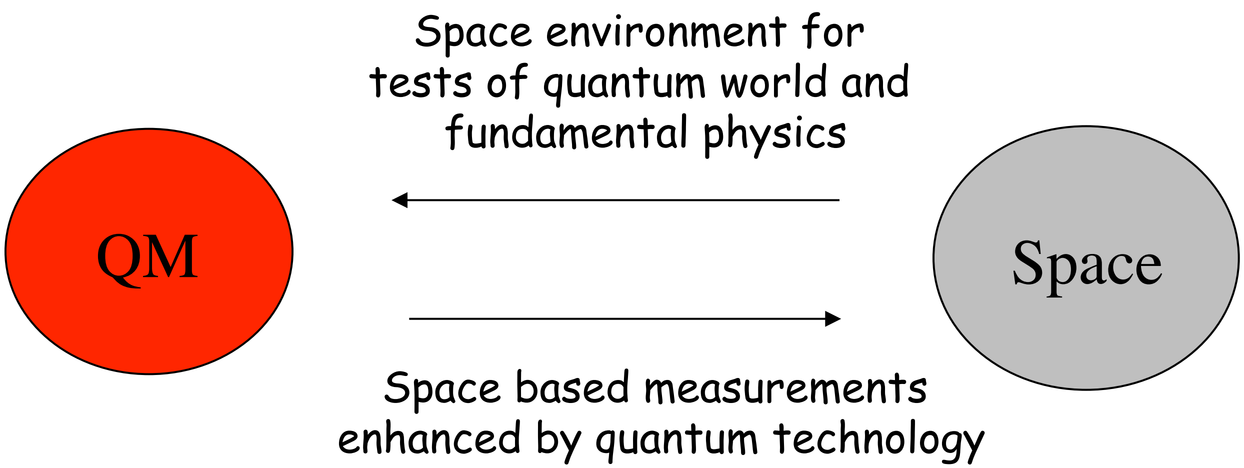
Quantum Mechanics and Space

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 (micro gravity, low vibration, high isolation, space and time spans, etc.) it offers the opportunity to perform exacting tests of physics.



Quantum Properties for Technology

- **The fundamentally quantum phenomena of quantum coherence and interferences, wave-particle duality, entanglement, quantum photon statistics 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 - timekeeping, 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 source and correlation properties - quantum communication, secure communication, imaging and computation

Space for Fundamental Physics and Applications

Precision Measurement Technology

- Laser cooling and atom trapping
- Atom optics
- Ultra-stable lasers
- Self-referenced optical frequency comb
- Atomic clocks
- Atomic sensors

Unique space environment

- Global access
- Free from atmospheric interference
- Microgravity
- Low vibration
- Large spatial extent
- Large gravitational field variation
- Inertial frame

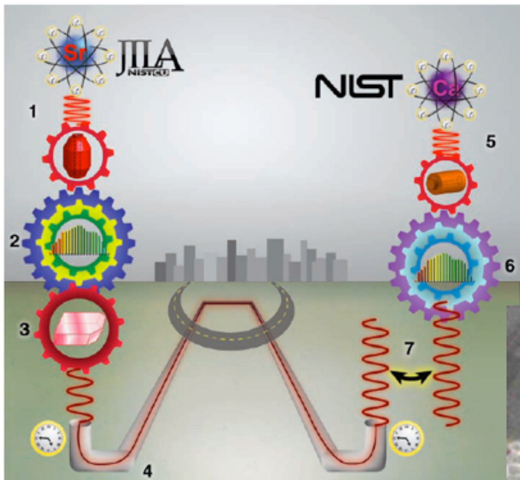
Fundamental Physics and Applications

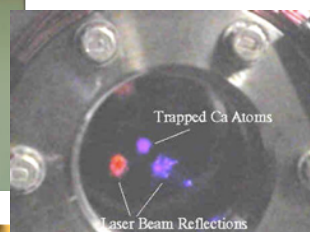
- Relativity theories
- Standard Model
- Equivalence Principle
- Gravity physics
- Cosmology and quantum decoherence
- Gravitational wave detection
- Earth and planetary gravity measurements
- Astrophysics observations
- Communication
- Navigation
- Geodesy
- Global timekeeping

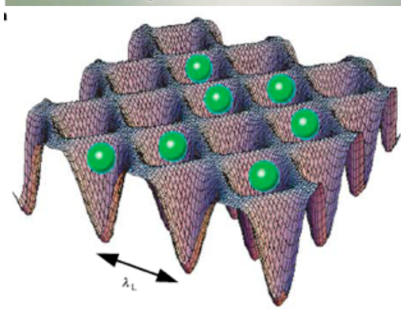
Optical Clocks – Next Generation High Accuracy Clocks of Cold Atoms

Science AAAS

Sr Lattice Clock at 1 x 10 16 Fractional Uncertainty by Remote Optical Evaluation with a Ca Clock
A. D. Ludlow, *et al.*
Science **319**, 1805 (2008);
DOI: 10.1126/science.1153341

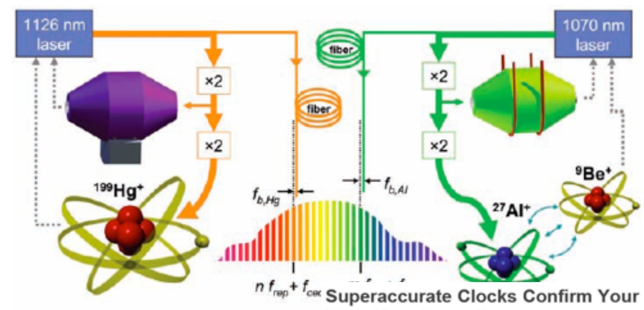






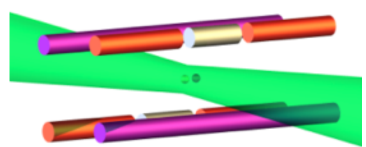
Frequency Ratio of Al^+ and Hg^+ Single-Ion Optical Clocks; Metrology at the 17th Decimal Place

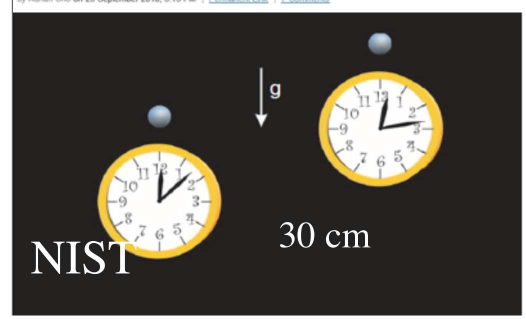
T. Rosenband,* D. B. Hume, P. O. Schmidt,† C. W. Chou, A. Brusch, L. Lorini,‡ W. H. Oskay,§ R. E. Drullinger, T. M. Fortier, J. E. Stalnaker,‖ S. A. Diddams, W. C. Swann, N. R. Newbury, W. M. Itano, D. J. Wineland, J. C. Bergquist



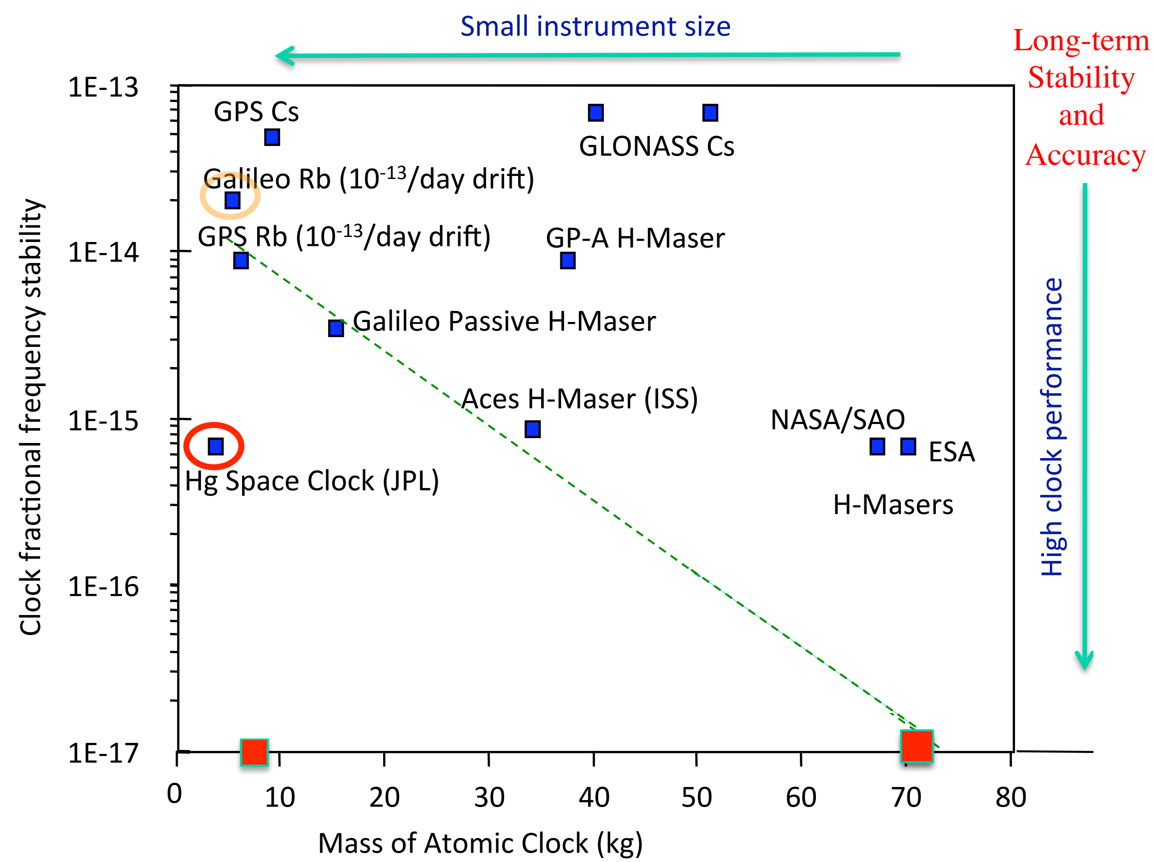
Superaccurate Clocks Confirm Your Hair Is Aging Faster Than Your Toenails

by Adrian Cho on 23 September 2010, 5:13 PM | Permanent Link | 7 Comments





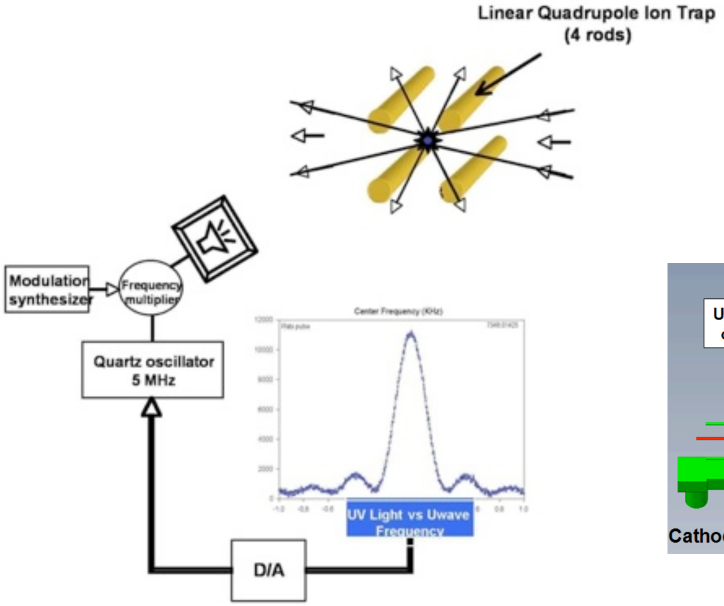
Space clock size vs. performance

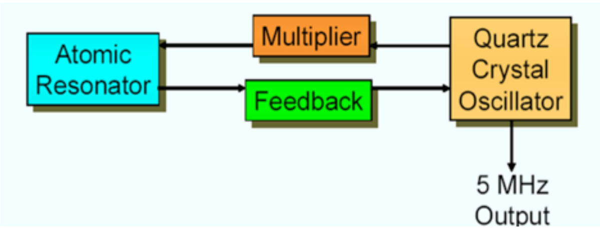


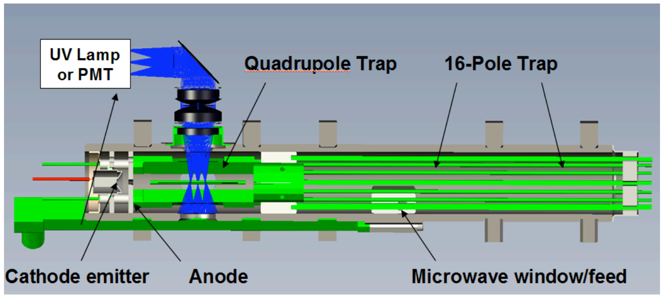
(Based on chart from J. Prestage)

JPL linear ion trap clock development

LITS clock technology





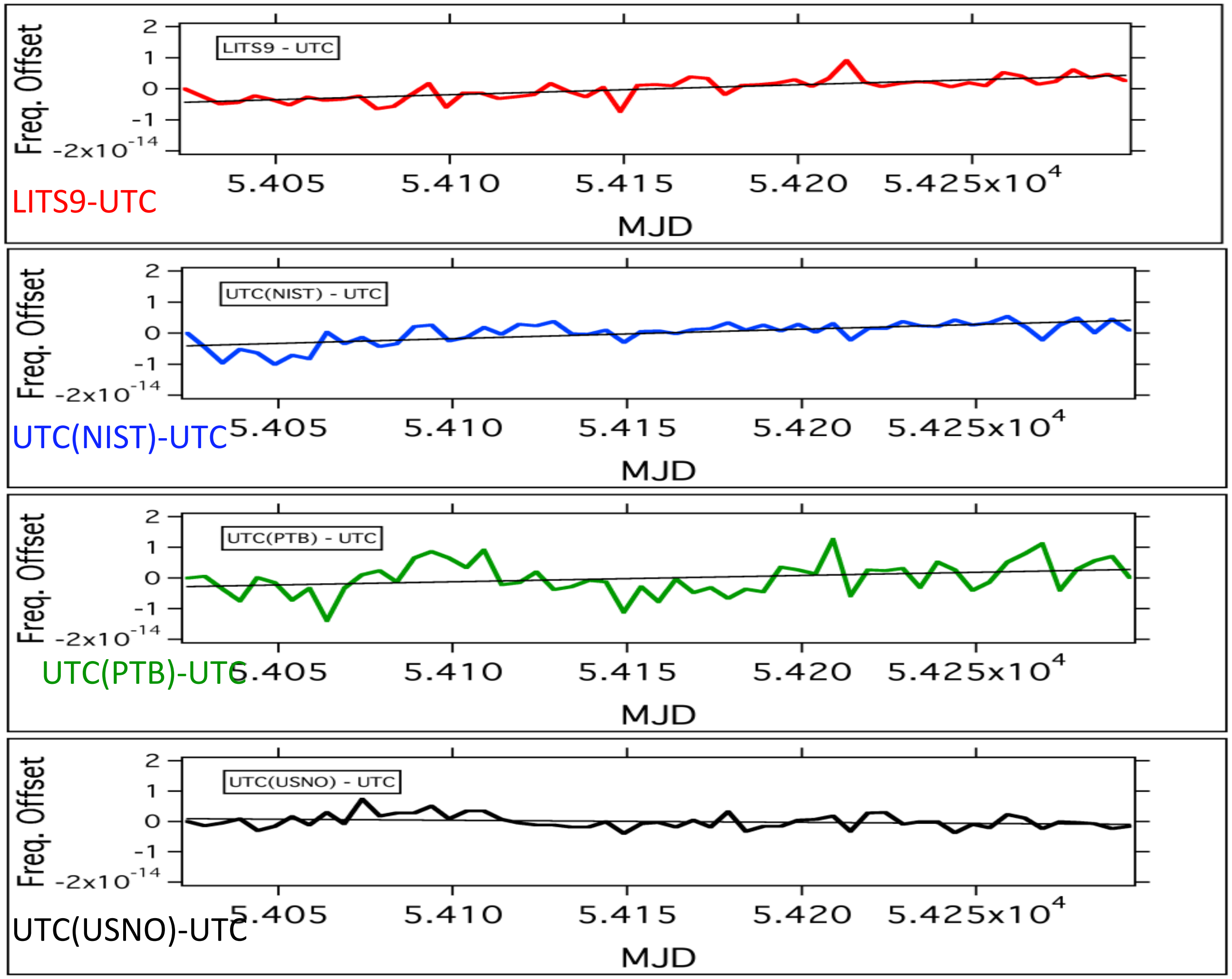


J. Prestage et al.

Ground LITS clock

Tjoelker et al.

Long-term stability of linear ion trap clock



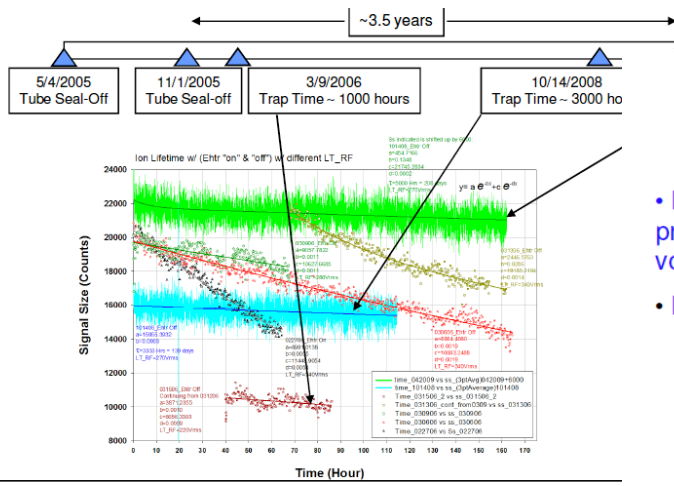
- 9 month comparison: MJD 54023 to MJD 54296
  - LITS-9 operating continuously - no intervention
- Relative drift (to primary standards & TTBIPM)

(Robert Tjoelker and Eric Burt)

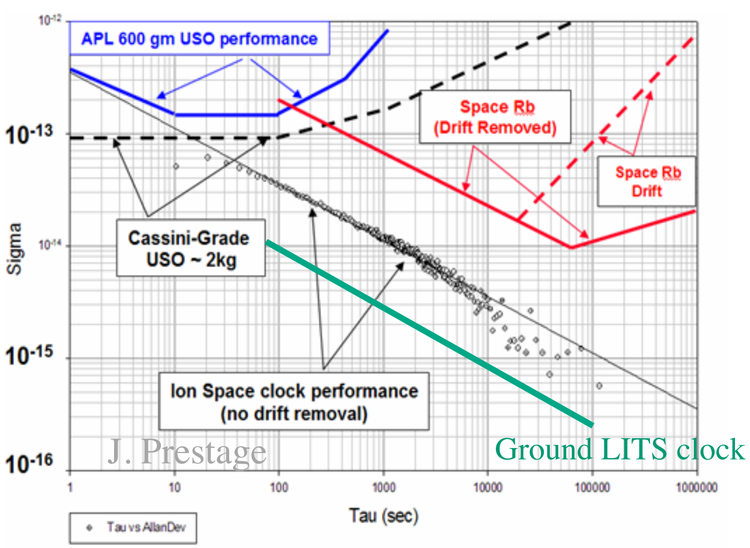
$+2.7(0.4)\mathrm{x}10^{-17}$/day

Jet Propulsion Laboratory
California Institute of Technology
National Aeronautics and Space Administration

Miniaturization of linear trapped ion clocks



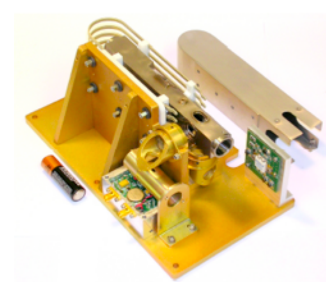
Sealed Tube Method has demonstrated adequately long life
-- Eliminates moving parts
-- Converts technology to No Consumables (No gas-flow)
-- Hg Oven not turned on for years
-- Reduce Hg within tube by >> 1000-fold
Comparison: Original ground clocks with mechanical pumps have ~ 1 hr hold time



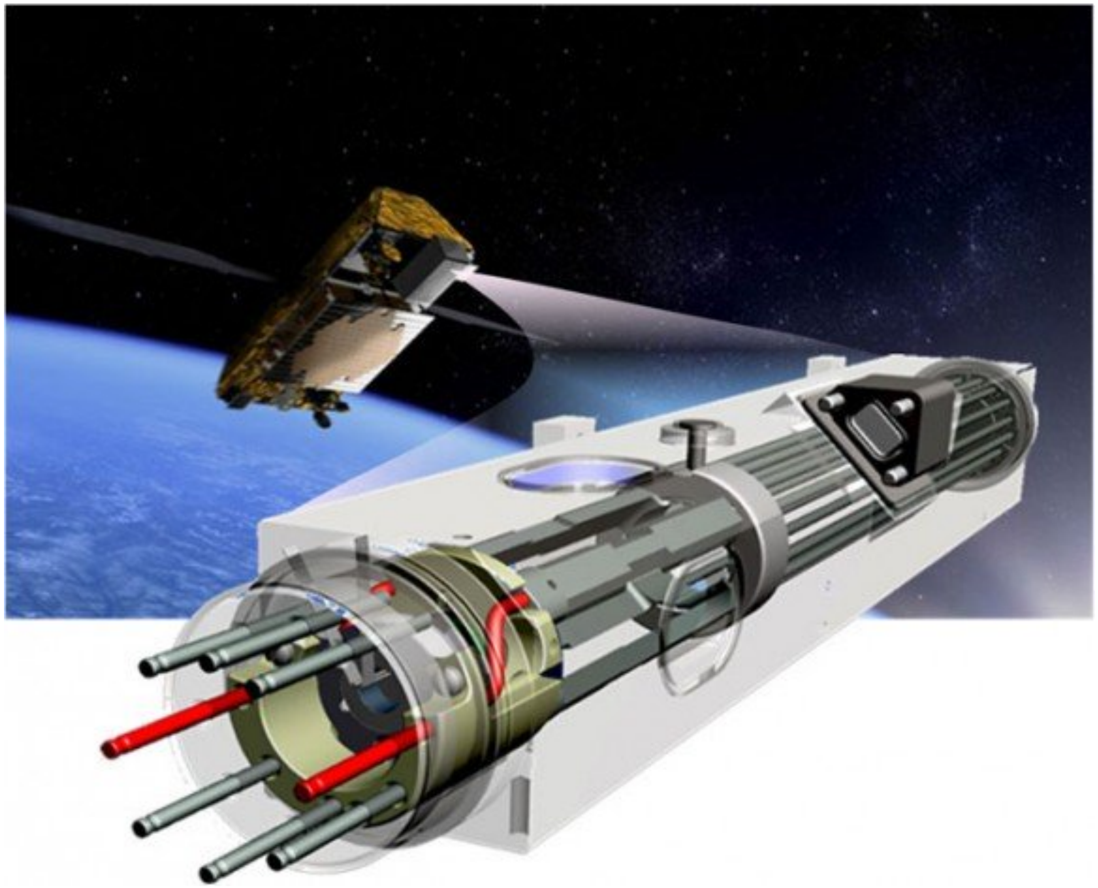
Technology Challenges: Miniaturize Ion Clock Technology to 1kg

- Eliminate moving parts, ovens, vacuum pumps, pressure gauges, buffer gas flow w/ heaters, ~1000x volume reduction.
- Employ vacuum methods of space TWTA Tube devices.
  - Tube materials, UV windows seals must withstand 400 C vacuum bake-out. (Sapphire/Alumina and Titanium)
  - Bulk chemical Getters pump residual gases.
  - ~10^{-5} Torr Neon Buffer gas sealed within tube.
  - Ultra-clean/low vacuum pressure is essential for clock stability and lifetime.

Ground Based Ion Clock Technology at JPL and USNO (1998-2002)



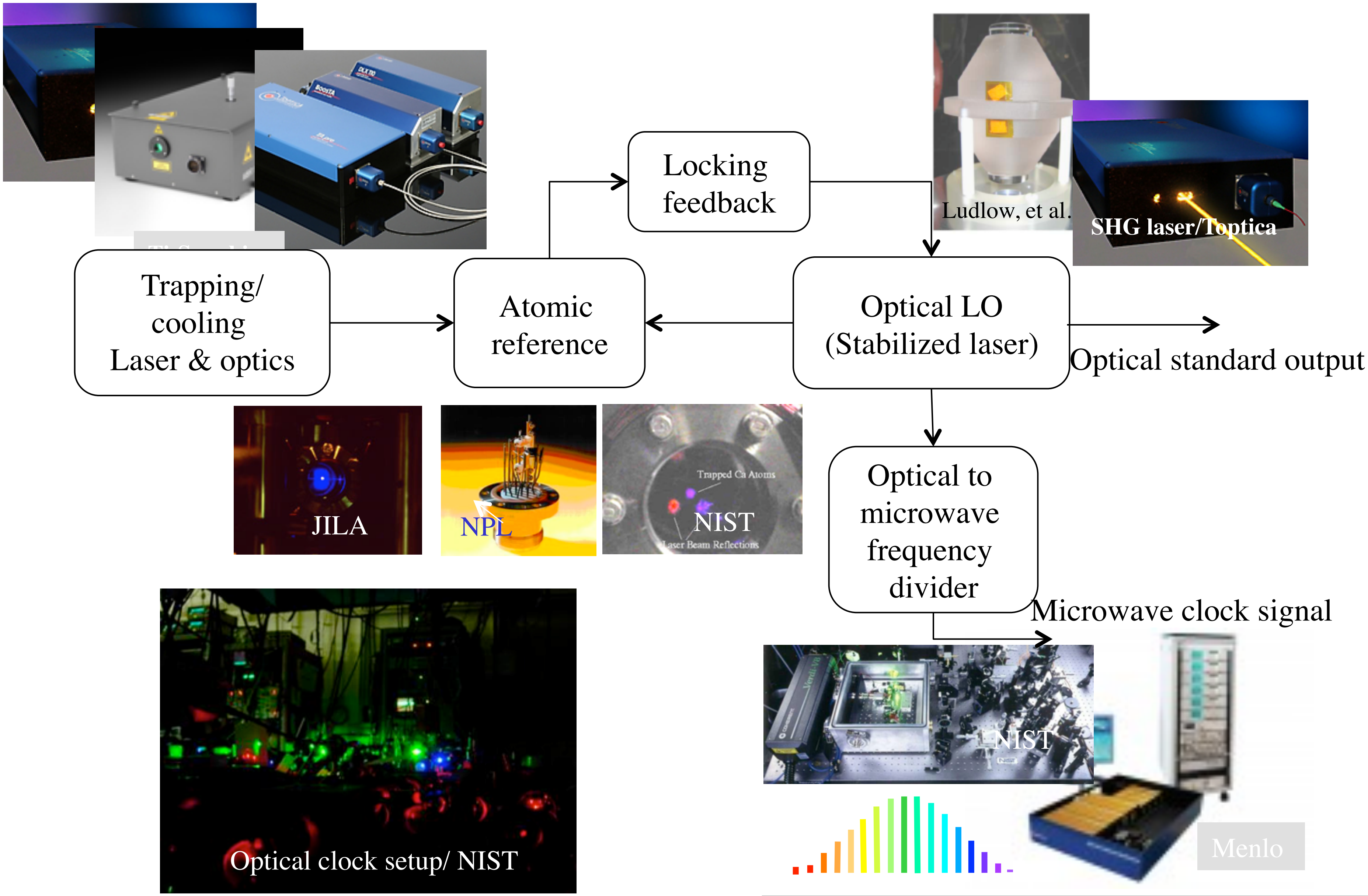
Deep Space Atomic Clock – Technology Demo



Artist's rendering of a vacuum tube, one of the main components of an atomic clock that will undergo a technology flight demonstration. Image Credit: NASA

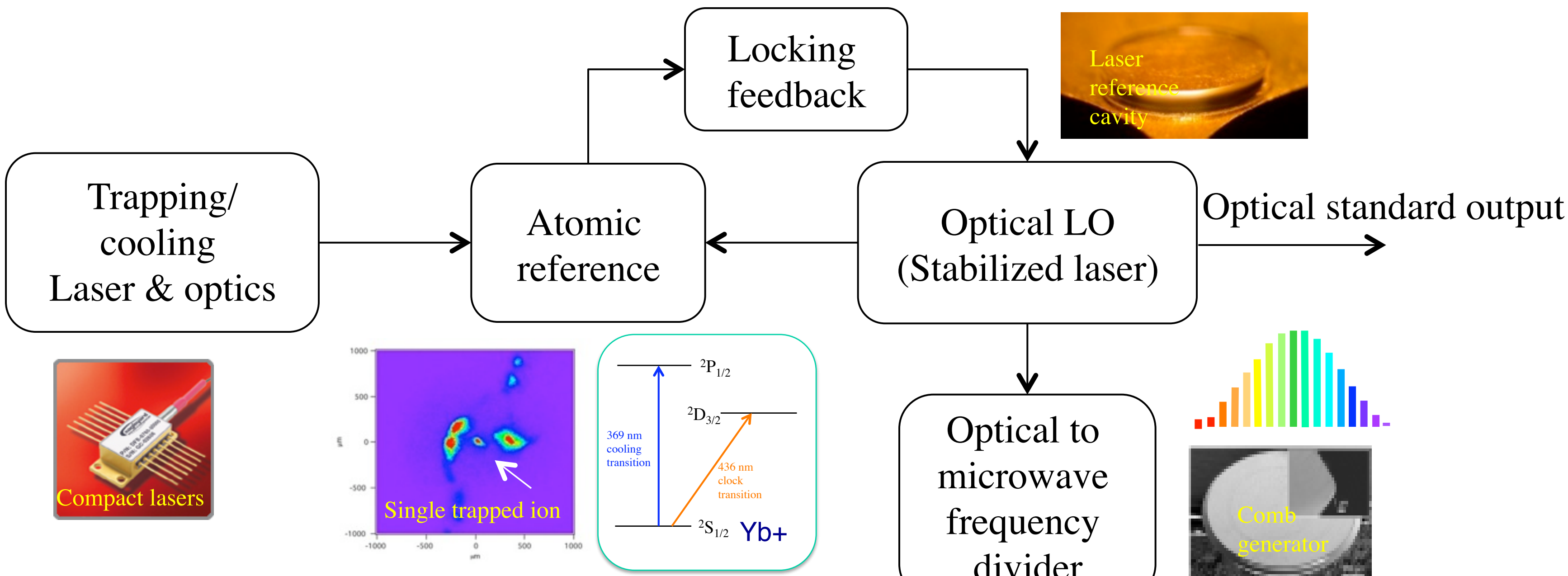
The Deep Space Atomic Clock demonstration mission will fly and validate a miniaturized mercury-ion atomic clock that is 10-times more accurate than today's systems. This project will demonstrate ultra-precision timing in space and its benefits for one-way radio navigation. The investigation will fly as a hosted payload on an Iridium spacecraft and make use of GPS signals to demonstrate precision orbit determination and confirm the clock's performance. Precision timing and navigation is critical to the performance of a wide range of deep space exploration missions.

Optical clock system overview



Towards an ultra-compact optical clock

Can one envision to package everything into liter-sized device, < 10 kg, <20 W, and > x10 improvement over microwave clocks of similar size?

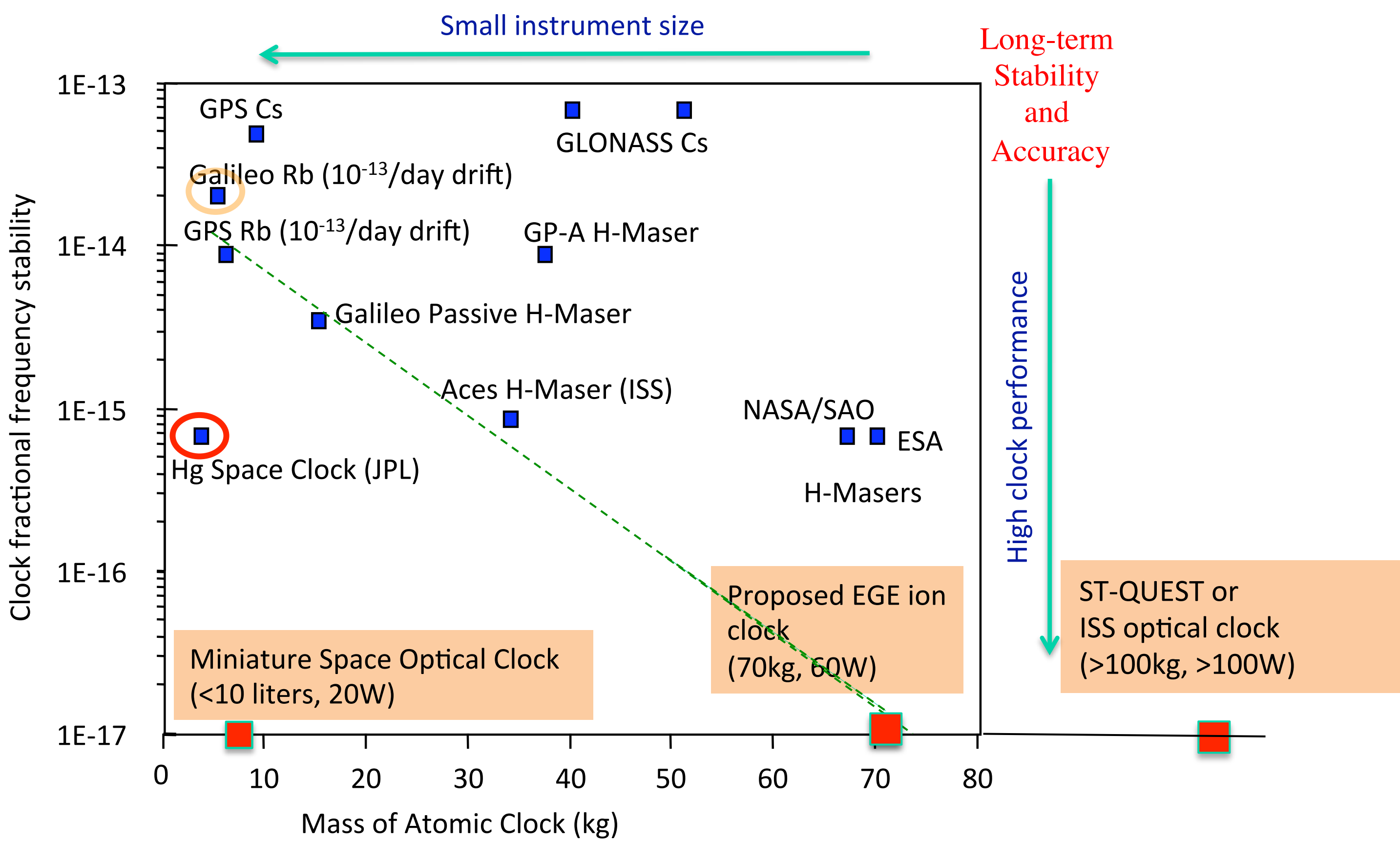


Single trapped ion standard

To realize the ultra-compact optical clocks

- Miniature physics packages
- Whispering gallery mode (WGM) resonator based narrow line lasers
- WGM resonator stabilized optical local oscillator
- WGM resonator comb generation

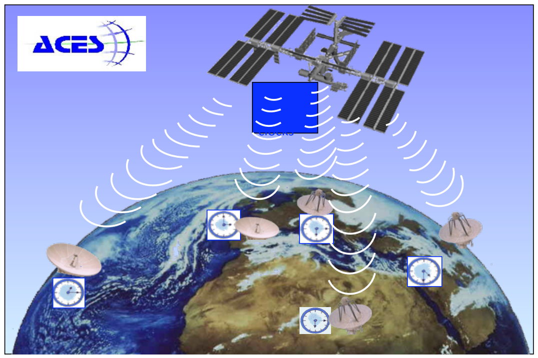
Space clock size vs. performance

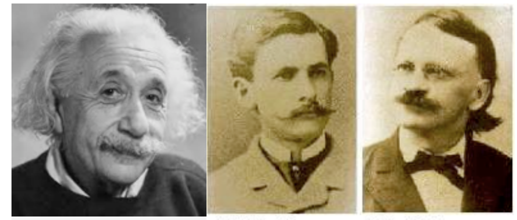


(Based on chart from J. Prestage)

Applications of high-performance atomic clocks

Primary frequency standards, timekeeping, and global time scale and access.

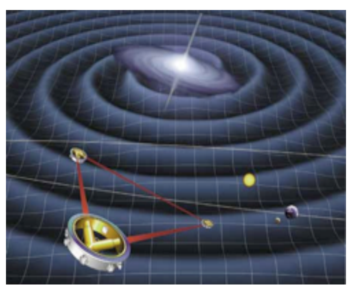




A. Einstein — A.A. Michelson 1852 - 1931 — E.W. Morley 1838 - 1923

Clock-based fundamental physics tests in space: Gravitational redshift, Shapiro time delay, Lorentz Invariances, Equivalence Principle, variations of fundamental constants, …..

High-performance frequency standards are universal tools for precision measurements in space, including laser interferometers, VLBI, relativistic geodesy,

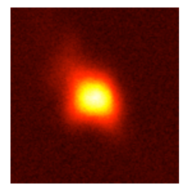


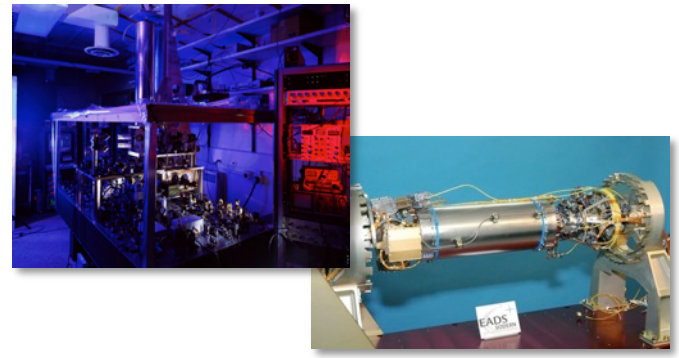
Stable reference sources for global and Deep Space Network (DSN) tracking, positioning, timing, and communication needs. Also enable tracking based science measurements – planetary gravity science, occultation, ….

Clocks and Sensors

Digital watches

clocks

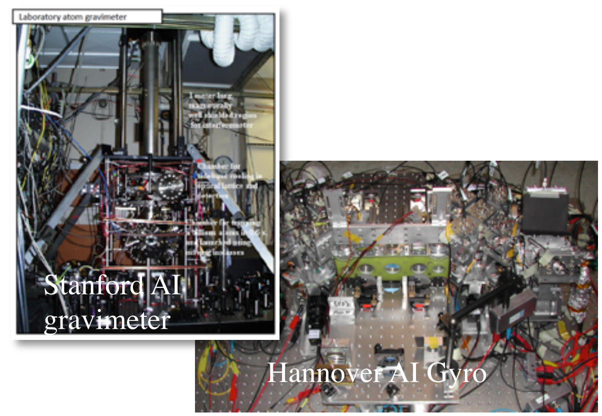




Cold atom clocks

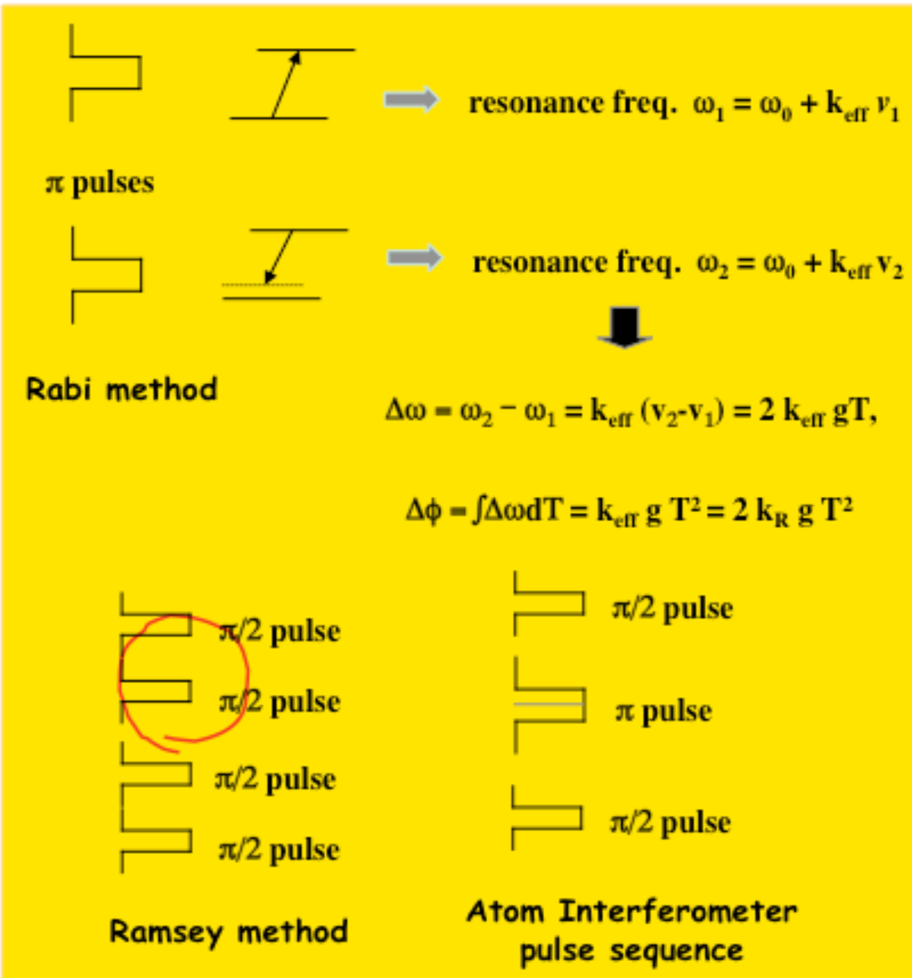
Quartz microbalances

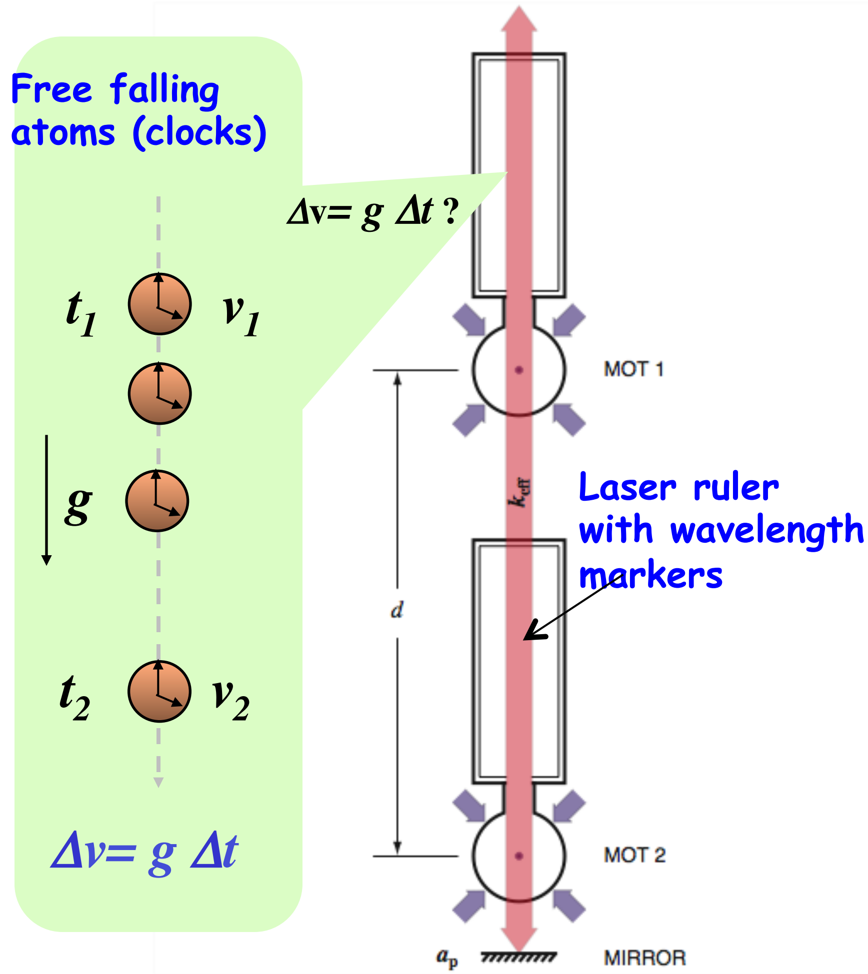
sensors



Atomic inertial sensors

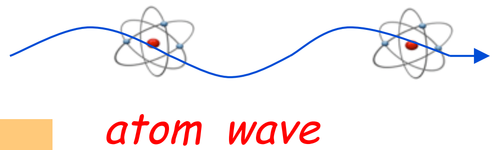
Atoms as free fall clocks





Matter-wave Interferometer

Quantum particle-wave duality



de Broglie wave: $\lambda_{dB}=h/mv$

h – Planck constant = 6.6×10^{-34} m^2 kg / s

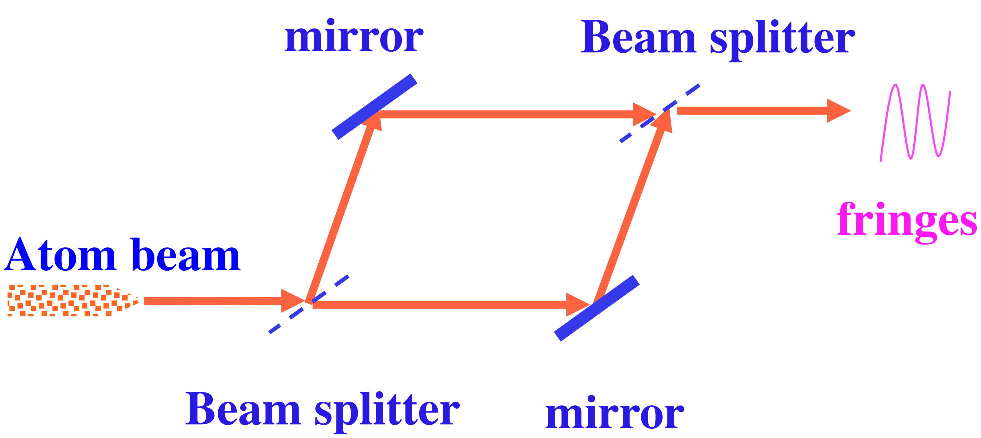
Why ***atom interferometer***?

1. Larger mass, shorter wavelength
   Cs atoms, at $2\ \mu$K, $\lambda_{dB} \approx 160\ nm$.

2. Extremely high inertial force sensitivity
   $(mc^2/h\nu)$ enhancement factor over comparable photon devices:
   $> 10^{10}$ theoretically

3. Possessing internal states
   Easier to control and manipulate
   ⇒ laser cooling, trapping, detection, and atom optics.

Atom-wave Mach-Zehnder Interferometer



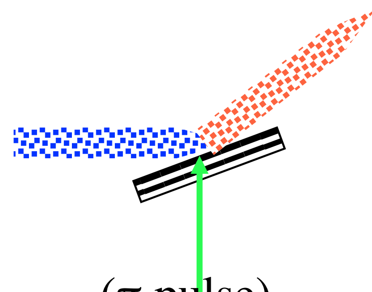
Atom Optics: Beam Splitting and Deflection

In the light pulse scheme, photon recoils are used to coherently split and redirect atom beams (waves).

Photon absorption process (π pulse)

$|\bullet\rangle \Rightarrow |\bullet\rangle$

deflection (mirror)

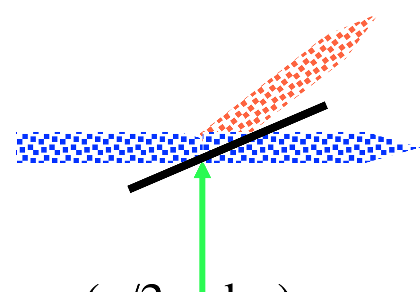


(π pulse)

Superposition state (π/2 pulse)

$|\bullet\rangle \Rightarrow |\bullet\rangle + |\bullet\rangle$

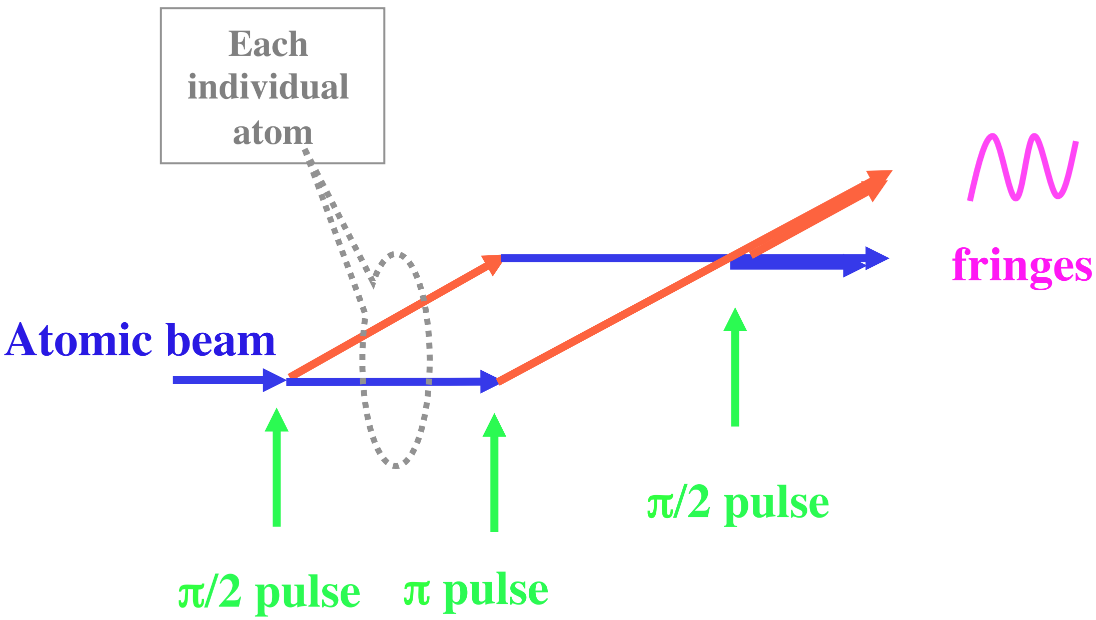
beam splitter



(π/2 pulse)

Atom Interferometer with Light Pulses

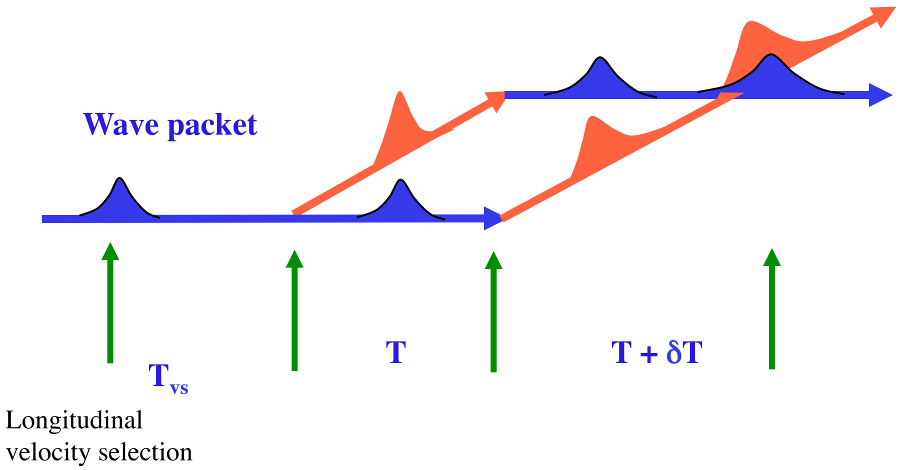
A straightforward atom interferometer implementation consists of a light pulse sequence of π/2-π-π/2*



- The interferometer loop area can be either in spatial space (gyroscope) or momentum space (accelerometer).
- The amount of splitting is determined by the photon recoil.

* Ref: M. Kasevich and S. Chu *Phys. Rev. Lett.* **67**, 181 (1991)

Atom Wave Packet Size and Dispersion



$$\sigma_x \sigma_p \le \frac{\hbar}{2}$$

$$\sigma_x^2 = \frac{\hbar^2}{4\sigma_p^2}\left(1 + \frac{4\sigma_p^4}{\hbar^2}\frac{t^2}{m^2}\right)$$

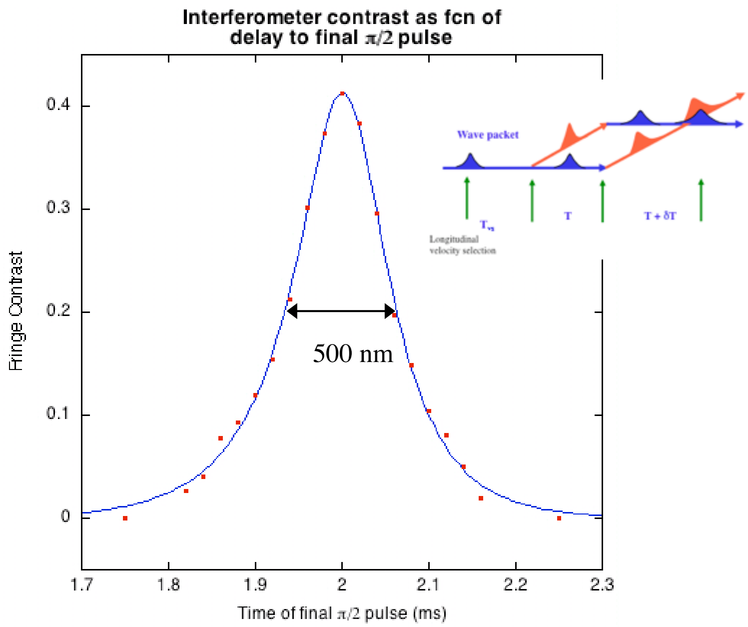
- Initial velocity selection pulse 240 μs; a FWHM sinc function frequency width 5.4 kHz; a velocity group with spread Δv = 2.3 mm/s. This is the initial wave packet preparation, corresponding to a minimum uncertainty wave packet with spread of 450 nm.

- Dispersion of the atom wave packet: $\Delta x(t) = (\Delta x_0^2 + \Delta v^2 t^2)^{1/2}$. At the end of $2T$ (4 ms), the spread of the wave packet becomes 9.2 μm, >> initial x_0 = 0.45 μm.

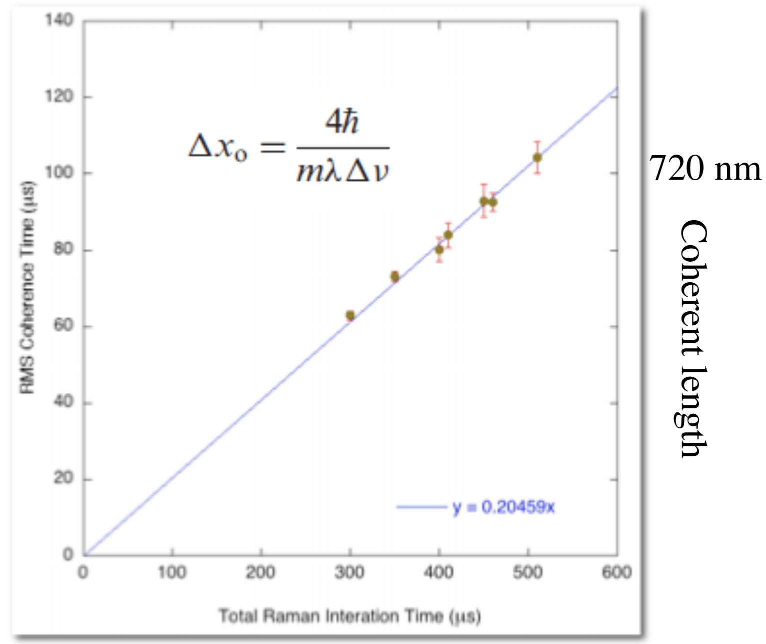
- The rate of relative displacement between two separated wave packet is about 7.2 mm/s (two photon recoil). The separation of the two wave packets change at the rate of 7.2 μm per ms.

J. R. Kellogg, N. Yu, J. M. Kohel, R. J. Thompson, D. C. Aveline, and L. Maleki, "Longitudinal coherence in cold atom interferometry," J. Modern Optics, **54**:16, 2533 (2007).

Coherent Length of Cold Atoms



The contrast loss over the length of initial wave packet size, not the actual wave packet size.



Coherent length, over which the contrast is lost, depends on the initial velocity selection pulse length.

Conclusion: at the point of the interference, the wave packets mostly overlap. The coherence is determined by the initial velocity spread of the atom wave, given by the quantum uncertainty principle.*

- Similar observation and proof were made for neutron matter waves. Ref: Kaiser, H. S., Werner, A. and George, E. A. *Phys. Rev. Lett.* **50**, 560 (1983); Klein, A. G., Opat, G. I., and Hamilton, W. A. *Phys. Rev. Lett.* **50**, 563 (1983).

J. R. Kellogg, N. Yu, J. M. Kohel, R. J. Thompson, D. C. Aveline, and L. Maleki, "Longitudinal coherence in cold atom interferometry," J. Modern Optics, **54**:16, 2533 (2007).

AI Accelerometer Phase Shift

For atom interferometer accelerometer

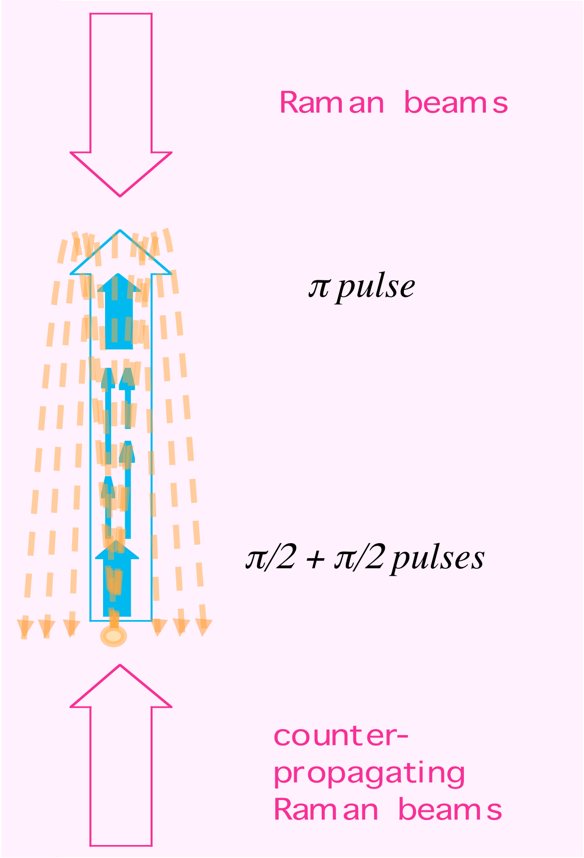
$$\Delta\Phi = 2\,k\,a\,T^2$$

- Independent of atom initial velocity
- *k*, the laser wavenumber is the only reference parameter
- Sensitivity goes with T^2

With over 10^6 atoms, the shot-noise limited SNR ~ 1000.
Per shot sensitivity = $2\times10^{-10}/T^2$ m/s^2, or about $10^{-11}/T^2$ *g*.

Great enhancement of the sensitivity can be gained in microgravity in space!

Atomic fountain on ground



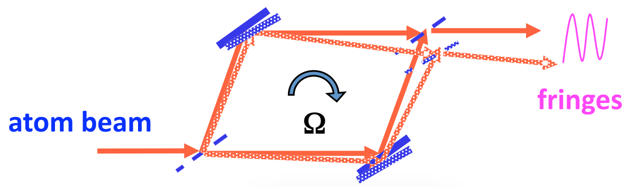
For example: in microgravity, 10^{-13} g Hz$^{-1/2}$ possible with >10 s interrogation time.

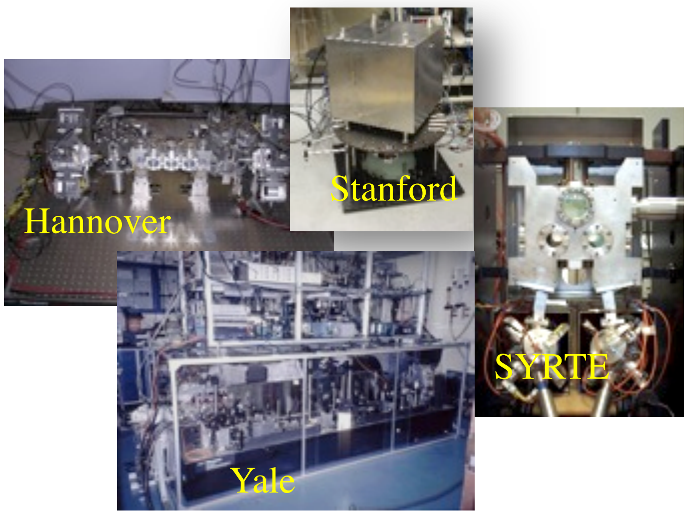
"Quantum Gravity Gradiometer Sensor for Earth Science Applications," Nan Yu, James M. Kohel, Larry Romans, and Lute Maleki, *NASA Earth Science and Technology Conference* 2002. Paper B3P5. Pasadena, California. June 2002.

Atom Interferometer Inertial Sensors

Rotational sensing

Sagnac effect $\Delta\Phi = 8\pi(A\bullet\Omega)/\lambda v$

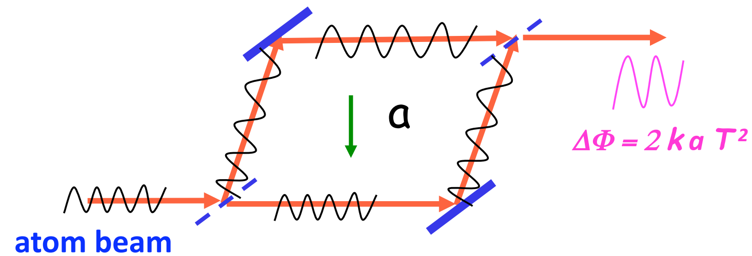


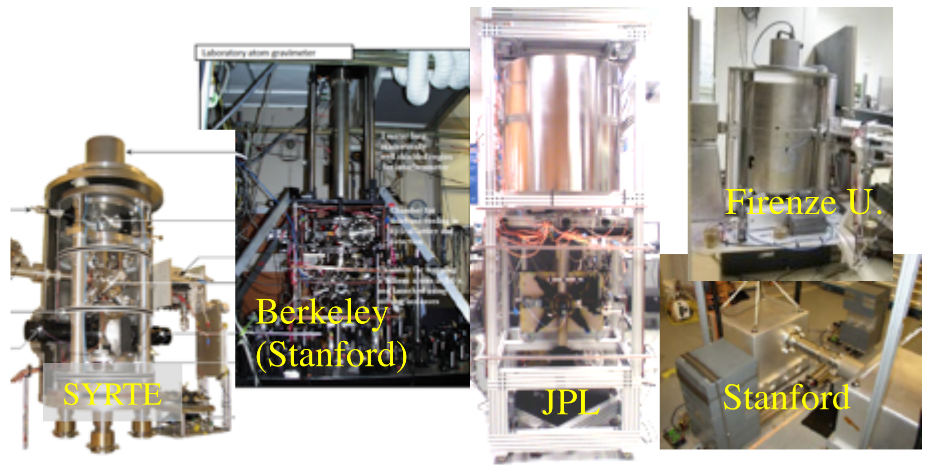


e.g. Laboratory AI gyroscope has a sensitivity of 6×10^{-10} rad s^{-1} $Hz^{-1/2}$. [T. L. Gustavson *et al.*, Class. Quantum Grav. **17**, 2385 (2000)]

Acceleration/gravity sensing

Phase shift due to acceleration $\Delta\Phi = 2\,k\,a\,T^2$

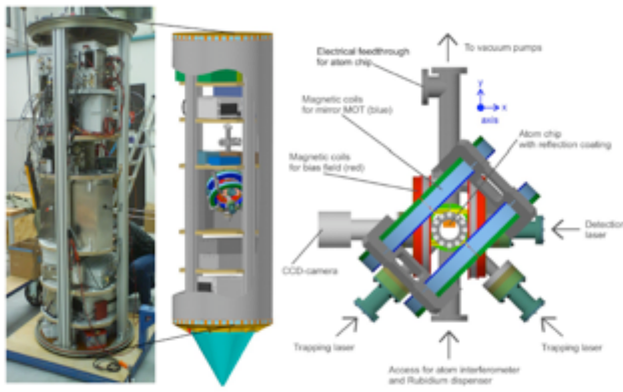




e.g. Laboratory atomic accelerometer measured *g* with a resolution of $2 \times 10^{-8}g$ in 1 second, and $3 \times 10^{-9}g$ overall precision. [A. Peters *et al.*, Metrologia, **38**, 25 (2001)]

There are also many activities of atom interferometers with BEC and guided atom chips.

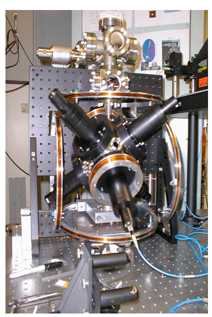
Technology Developments towards Space Applications



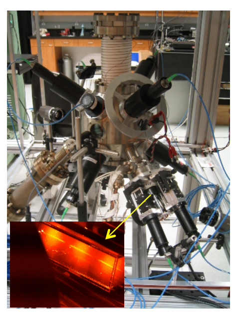
Drop tower Experiments with cold atoms and BEC, Quantus collaboration, DLR

Atom interferometer in 0-*g* flight, I.C.E. collaboration, France

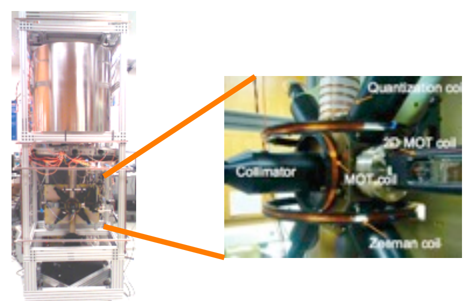
JPL atom interferometer gravity gradiometer development



First tabletop experiment



2nd generation laboratory system

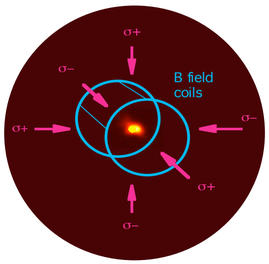


Transportable unit

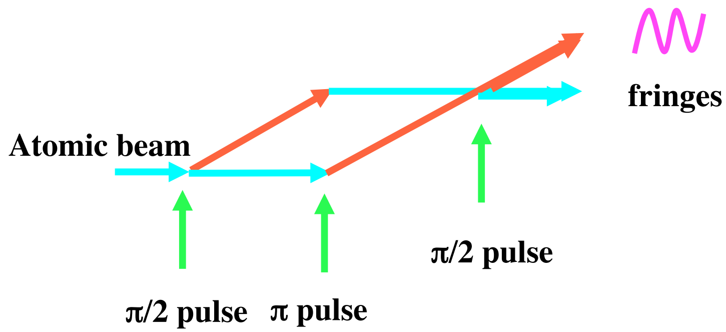
Jet Propulsion Laboratory
California Institute of Technology
National Aeronautics and Space Administration

Atomic Freefall Test Mass in Space

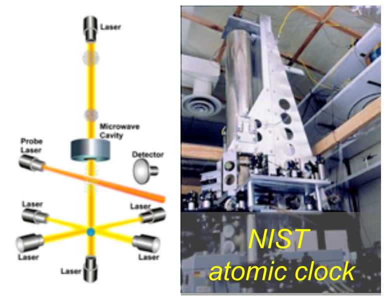
Freefall test mass **+** ***Displacement Detection*** **+** ***Atomic system stability***



Laser-cooled Cs atom cloud at μK



atom-wave interferometer (laser-based atom optics)



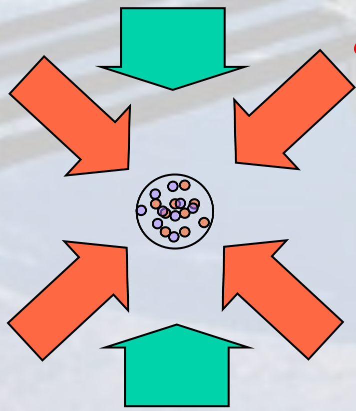
Atoms are stable clocks

- Use totally freefall atomic particles as ideal test masses
  identical atomic particles are collected, cooled, and set in free fall in vacuum with no external perturbation other than gravity/inertial forces; laser-cooling and trapping are used to produce the atomic test masses at μK and nK; no cryogenics and no mechanical moving parts.
- Matter-wave interference for displacement measurements
  displacement measurements trough interaction of lasers and atoms, pm/Hz$^{1/2}$ when in space; laser control and manipulation of atoms with opto-atomic optics.
- Intrinsic high stability of atomic system
  use the very same atoms and measurement schemes as those for the most precise atomic clocks, allowing high measurement stabilities.
- Enable orders of magnitude sensitivity gain when in space
  microgravity environment in space offers long interrogation times with atoms, resulting orders of magnitude higher sensitivity compared terrestrial operations.

Test of Weak Equivalence Principle on ISS

Two species differential accelerometer

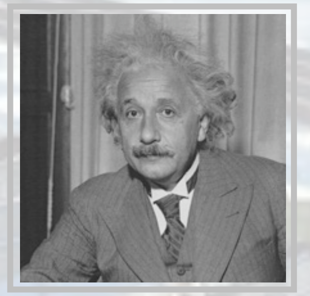
$$\Delta g = g_A - g_B = ?$$



$$\Phi_A = 2k(g_A + a)T^2$$

$$\Phi_B = 2k(g_B + a)T^2$$

$$\Delta\Phi_{AB} = 2k\,(g_A - g_B)\,T^2$$

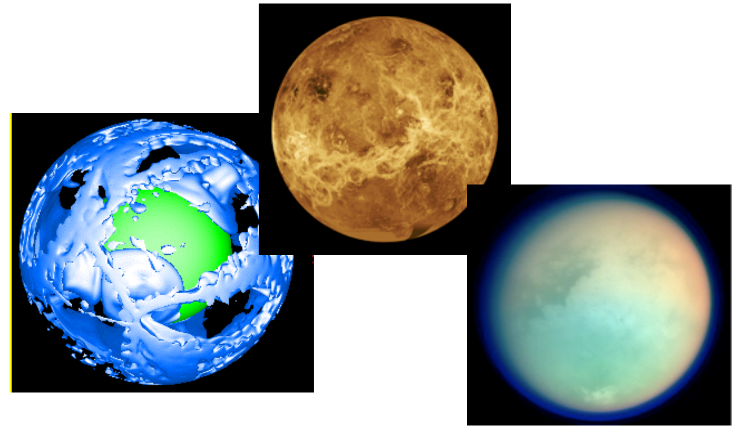


- Single axis differential acceleration of two co-located matter wave interferometers with different atomic species
- Seek a violation of Einstein's Equivalence Principle by improving the test limit by three orders of magnitude, to 1×10^{-15} level and better.
- First non-trivial precision experiment of quantum particles under the influence of gravity, and may stimulate discussions of General Relativity in the framework of quantum mechanics.

NASA QuITE
ESA QWEP

- Advanced gravity mission for Earth and planetary sciences

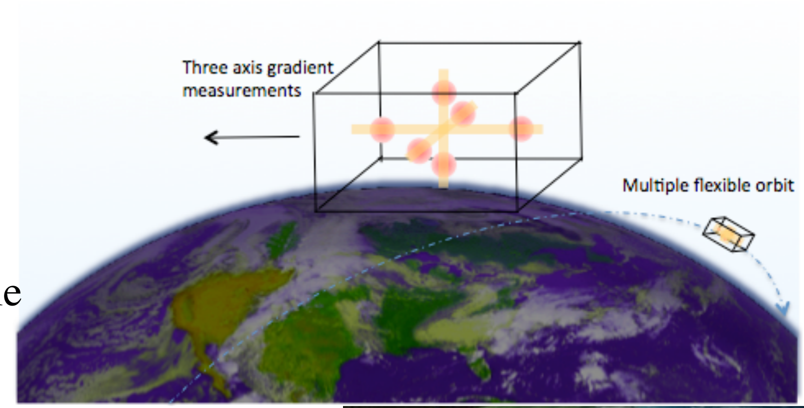
- **Cold atoms as truly drag-free test masses**
- **Gravity gradiometer (better resolution)**
- **Simpler mission architecture (single spacecraft)**
- **More flexible orbits and satellite constellation (more comprehensive data for data analyses)**



Geodesy

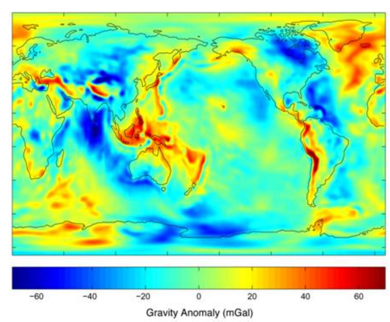
Earth and Planetary Interiors

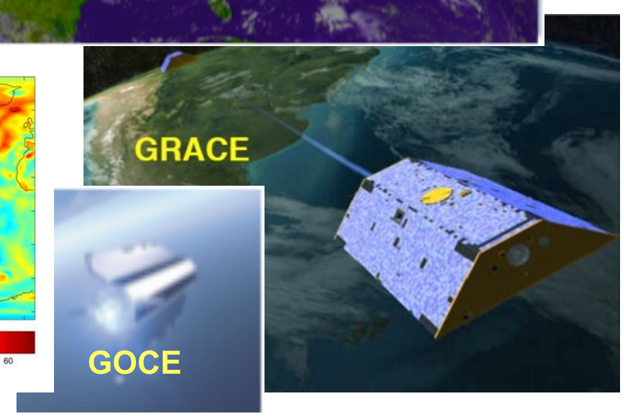
- Lithospheric thickness, composition
- Lateral mantle density heterogeneity
- Deep interior studies
- Translational oscillation between core/mantle



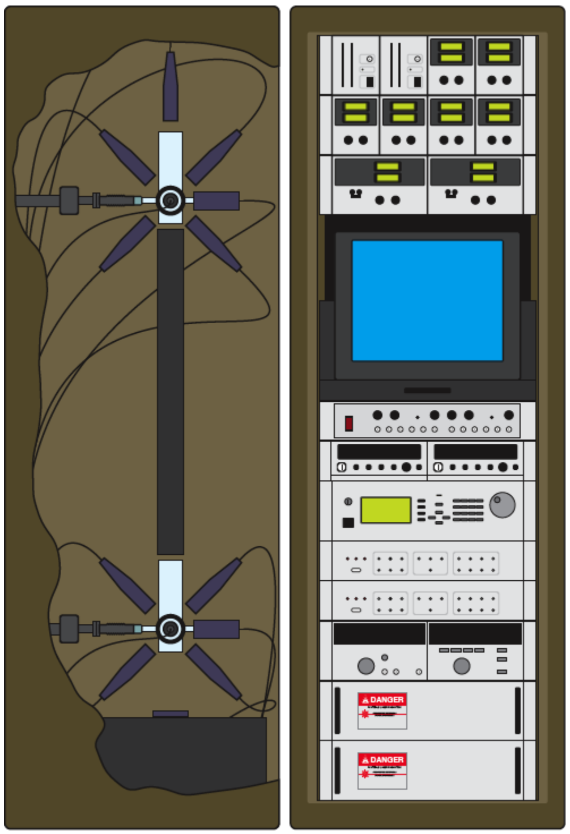
Earth and Planetary Climate Effects

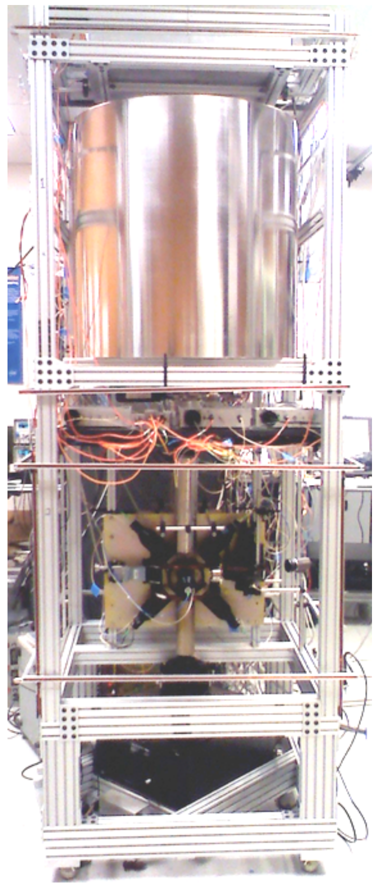
- Oceanic circulation
- Tectonic and glacial movements
- Tidal variations
- Surface and ground water storage
- Polar ice sheets
- Earthquake monitoring

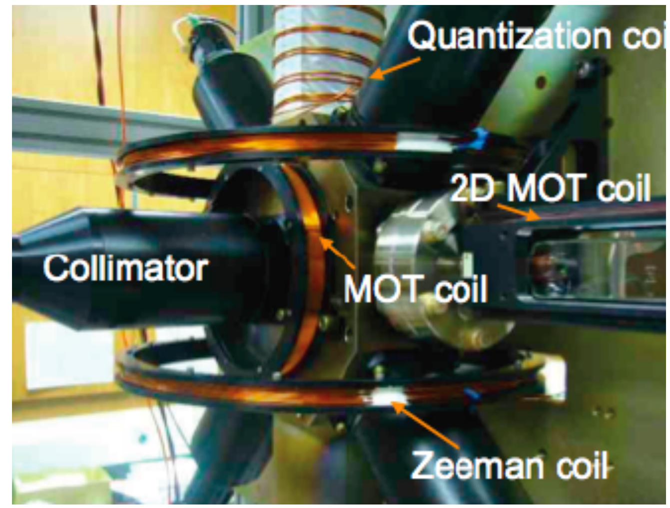


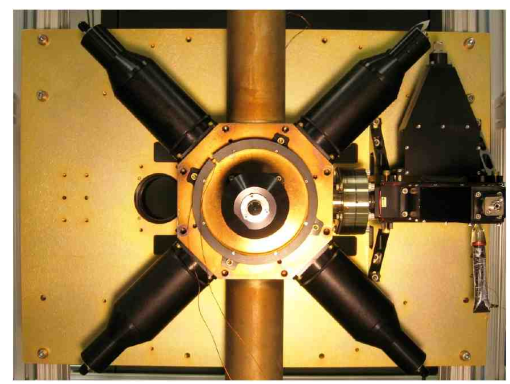


Transportable atomic gradiometer instrument





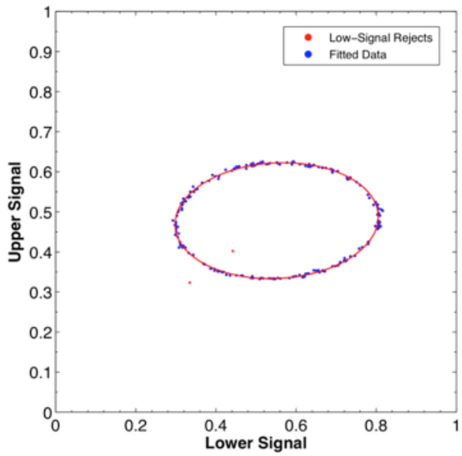


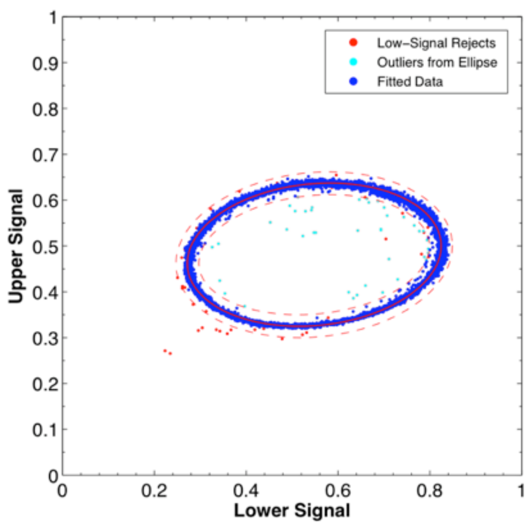


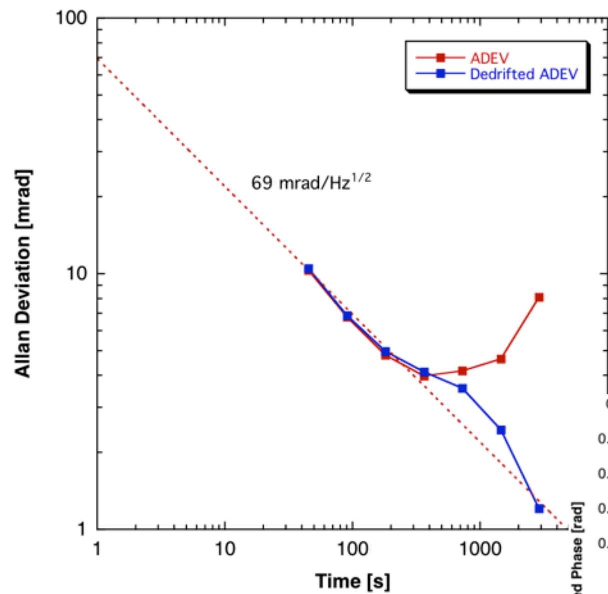
James Kohel, James Kellogg, Rob Thompson and Dave Aveline

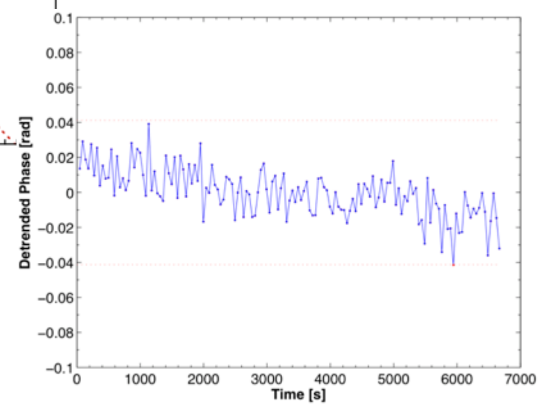
Experimental results

Instrument phase measurement revolution









Data are for a total interrogation time of greater than 300 ms.

James Kohel and James Kellogg

Summary

- ✓ 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 WEP; 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.
- ✓ We are developing a number of quantum technologies with atomic systems (clocks and gravity sensor devices) in support of NASA missions, including Earth Science, Space and Planetary Sciences.

Quantum Sciences and Technology Group

Situated in JPL Frequency Standard Laboratory, which is Responsible for technology development, generation, and distribution of ultra-stable reference frequencies and synchronized timing signals for NASA's Deep Space Network (DSN).

Group research areas and activities:

Frequency Standards and Clocks

Linear ion trap clocks (space clocks)

Small and micro atomic clock

Optical clocks

Atomic Quantum Sensors

Atom interferometers and gravity gradiometer

BEC and guided atoms on chips

Laser pumped magnetometers

Light and Microwave Photonics

Photonic oscillators

MIR and THz photonics

Micro resonator research and devices (lasers, filter, modulator, nonlinear device, spectrometer, and sensor)

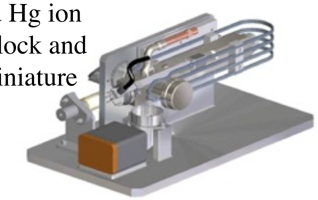
Laser and Coherent Control

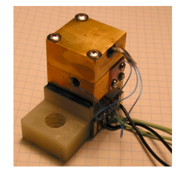
Narrow-line and ultra-stable lasers

Frequency comb

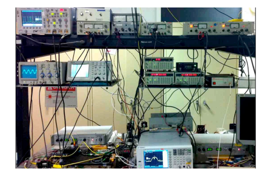
Optical phase locking and control

Trapped Hg ion Space clock and other miniature clocks

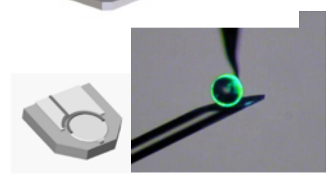




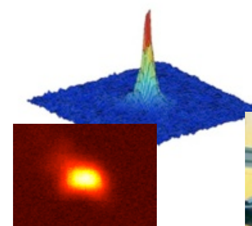
Laser stabilizations



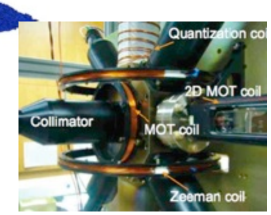
Optical phase control and photonics



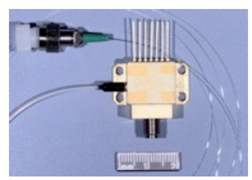
Whispering Gallery mode resonators and devices



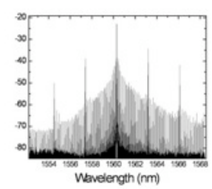
Laser cooling and Fundamental Physics



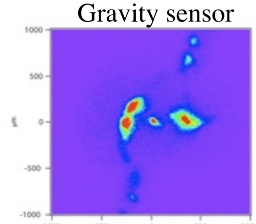
Atom interferometer Gravity sensor



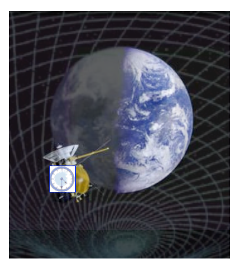
Mid infrared lasers



Optical frequency combs



Single ion trapping and optical clocks



Gravity and fundamental physics through precision measurements in space