Towards Precision Measurements In Space With Clocks And Atom Interferometers

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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

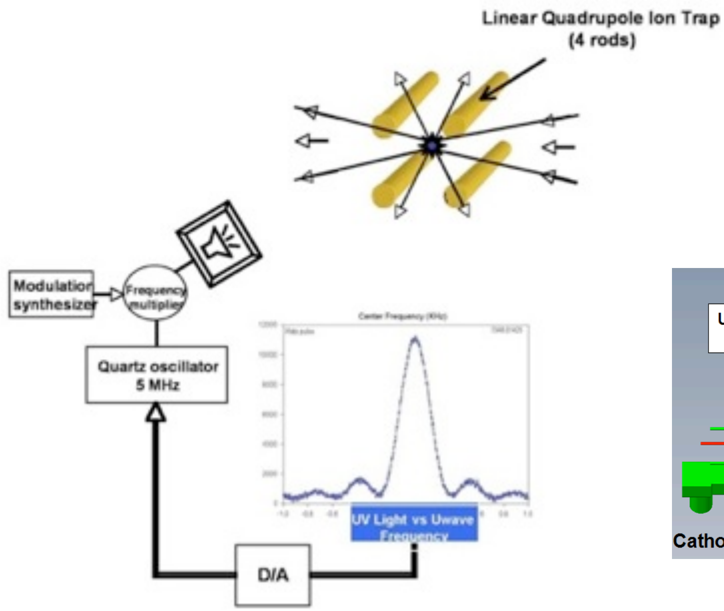
- Global access
- Free from atmospheric interference
- Microgravity
- Low vibration
- Large spatial extent
- Large gravitational field variation
- Inertial frame

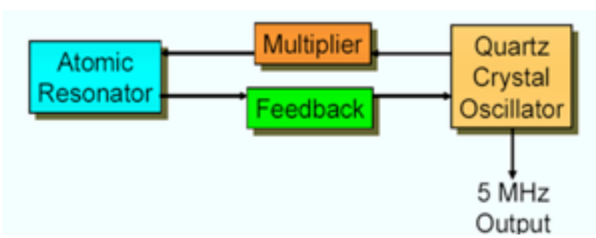
Fundamental Physics and Applications

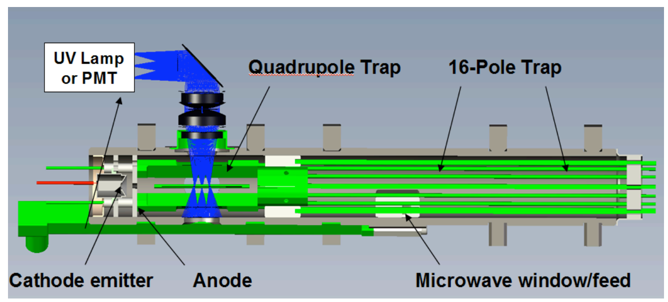
- Relativity theories
- Standard Model
- Equivalence Principle
- Gravity physics
- Cosmology and quantum decoherence
- Gravitational wave detection
- Earth and planetary gravity measurements
- Astrophysics observations
- Communication
- Navigation
- Geodesy
- Global timekeeping

JPL Linear Ion Trap Clock Development

Mercury ion clock technology







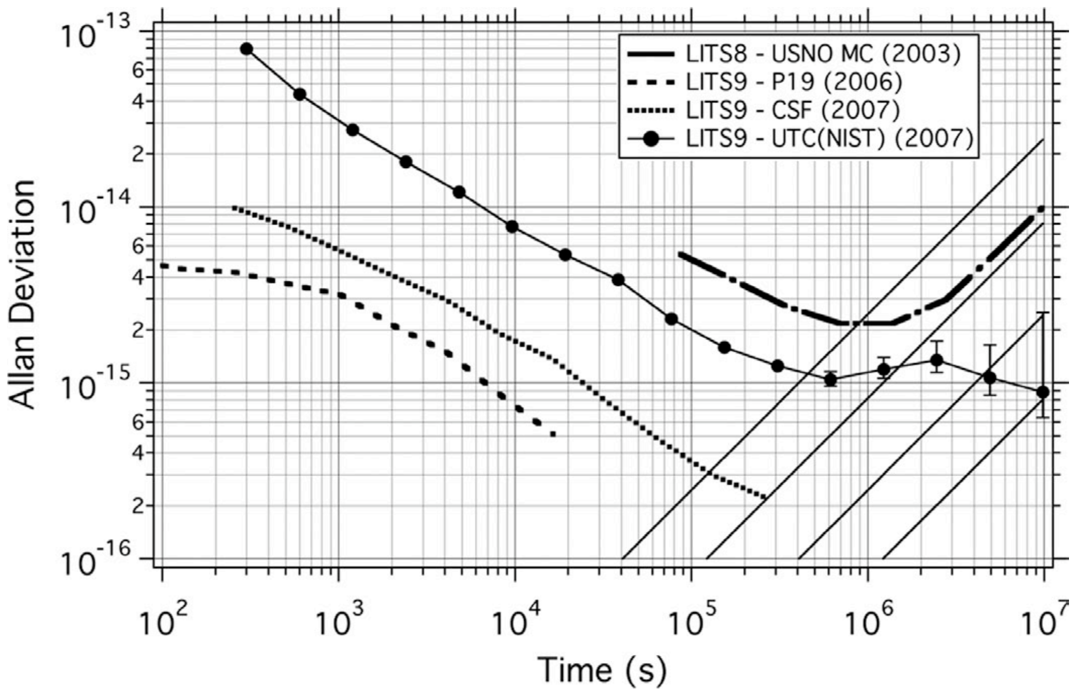
J. Prestage et al.

Ground LITS clock

Tjoelker et al.

Demonstrated LITS Clock Technology Capability

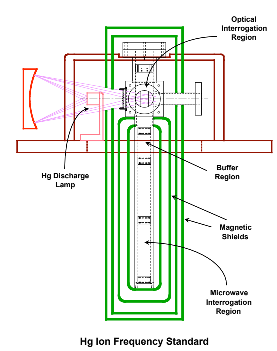
LITS-9 clock based on the Trapped Ion Mercury Ion Technology demonstrated long-term fractional frequency deviations of < 3e-17/day over a 9-month period

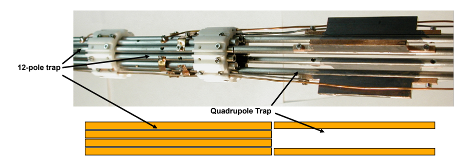


E.A. Burt, W. A. Diener, and R.L. Tjoelker, "A Compensated Multi-pole Linear Ion Trap Mercury Frequency Standard for Ultra-Stable Timekeeping," IEEE Trans. UFFC 55, 2586 (2008).

Many innovations have been made at JPL to provide ultra-high stability with continuous operation:

- ☆ Linear ion trap (1989)
- ☆ Ion Shuttling (1993)
- ☆ Multi-pole trap (2000)
- ☆ Second-order Doppler shift compensation (2008)





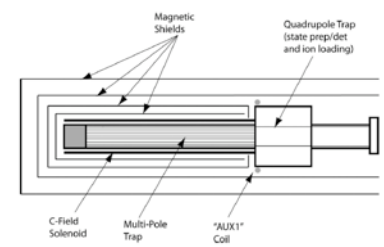
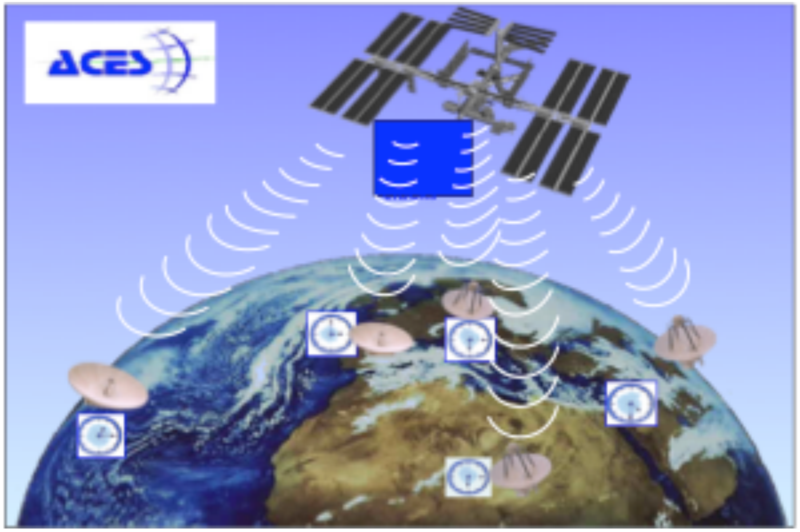
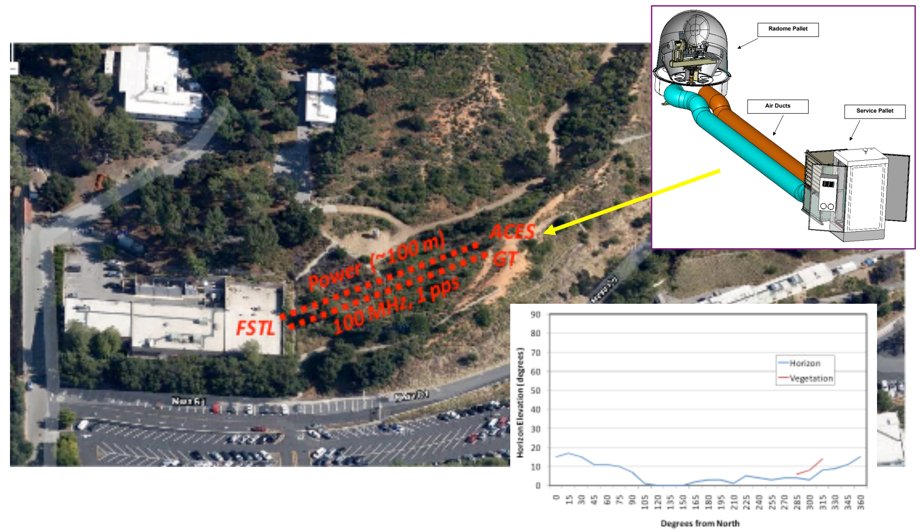


Fig. 1. Schematic of the multi-pole LITS physics package. The enclosure surrounding the quadrupole trap region contains windows (not shown) used for state preparation and detection. There is no optical access to the sensitive multi-pole trap region.

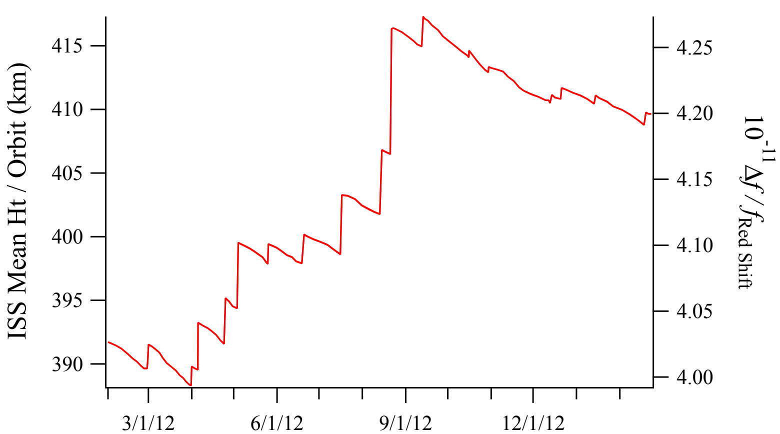
Long-term Stability Of Linear Ion Trap Clock

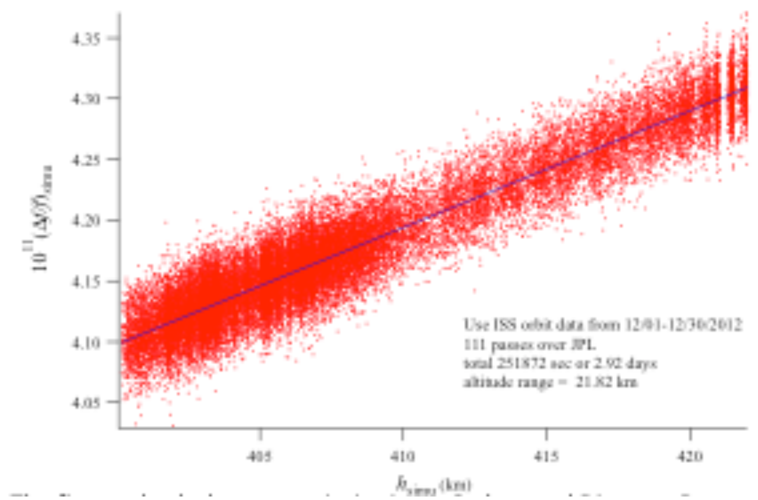


JPL ACES Ground Terminal Site Preparation

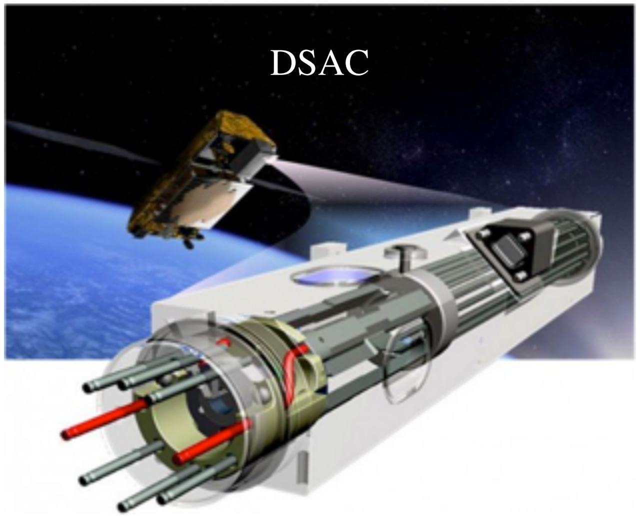


ISS Orbit Decays





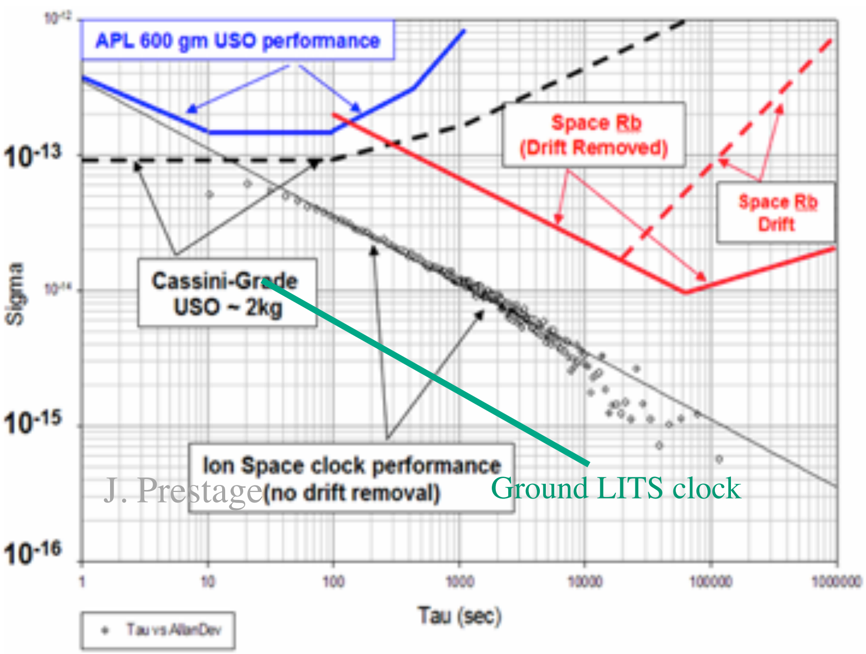
Compact Linear Trapped Ion Clocks

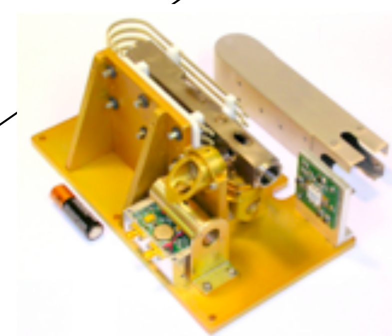


Technology Challenges: Miniaturize Ion Clock Technology to 1kg

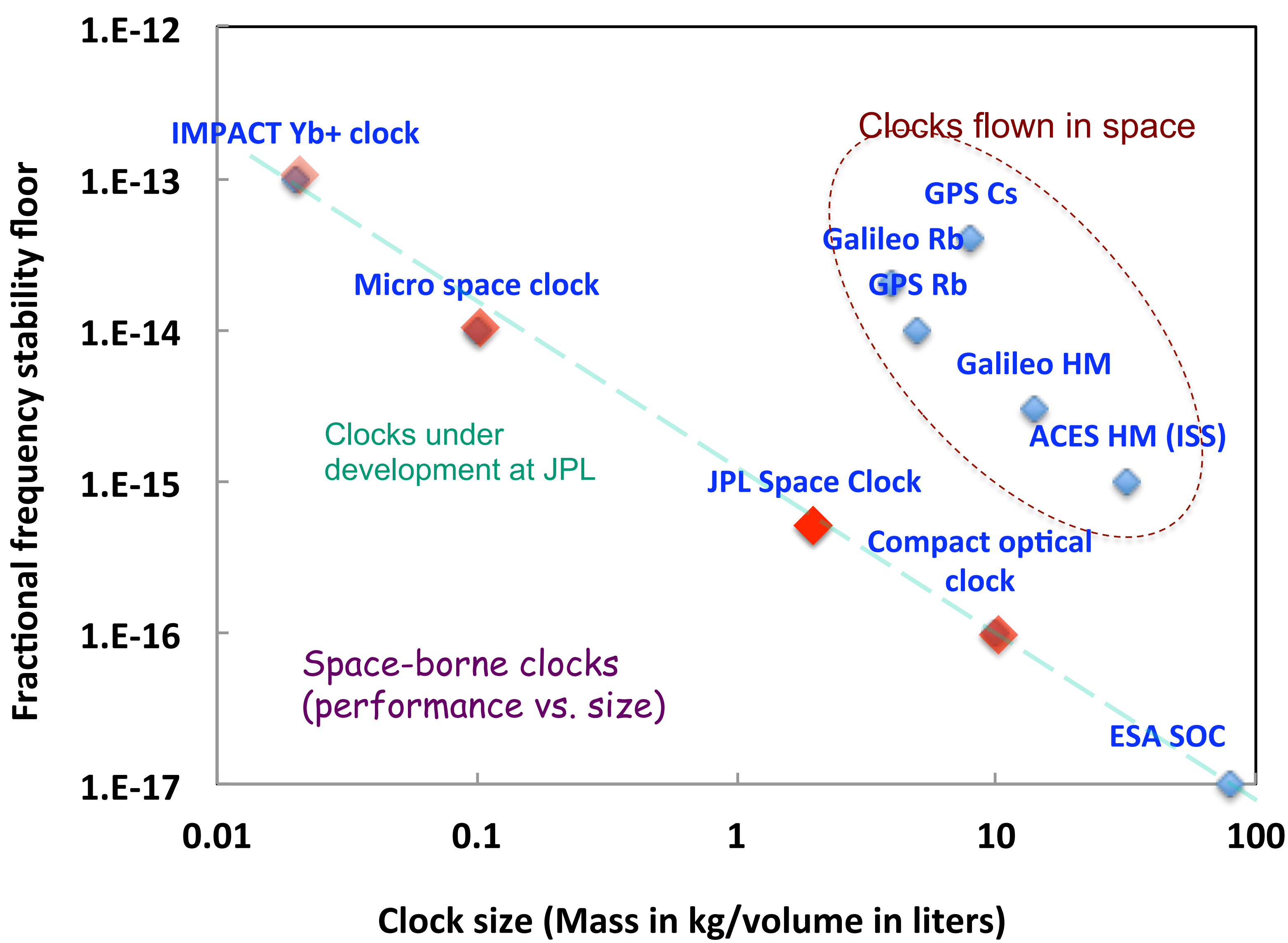
- Eliminate moving parts, ovens, vacuum pumps, pressure gauges, buffer gas flow w/ heaters, ~1000x volume reduction.
- Employ vacuum methods of space TWTA Tube devices.
  - Tube materials, UV windows seals must withstand 400 C vacuum bake-out. (Sapphire/Alumina and Titanium)
  - Bulk chemical Getters 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)

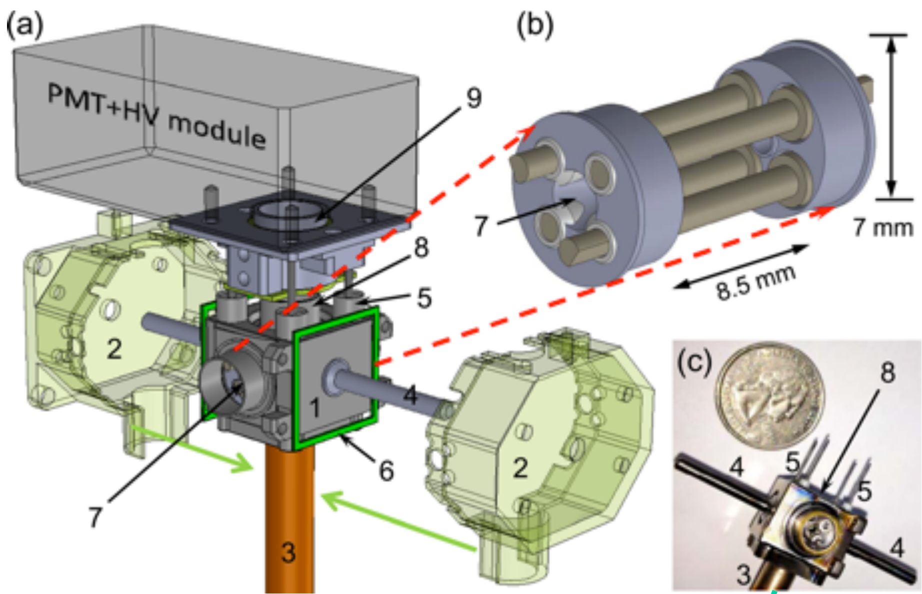




Space Clock Size Vs. Performance

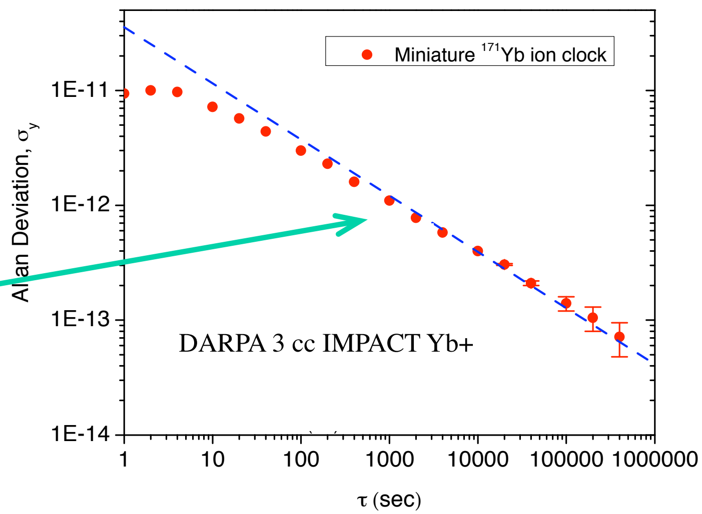


3-cc Sealed Ion Trap Vacuum Tube Package



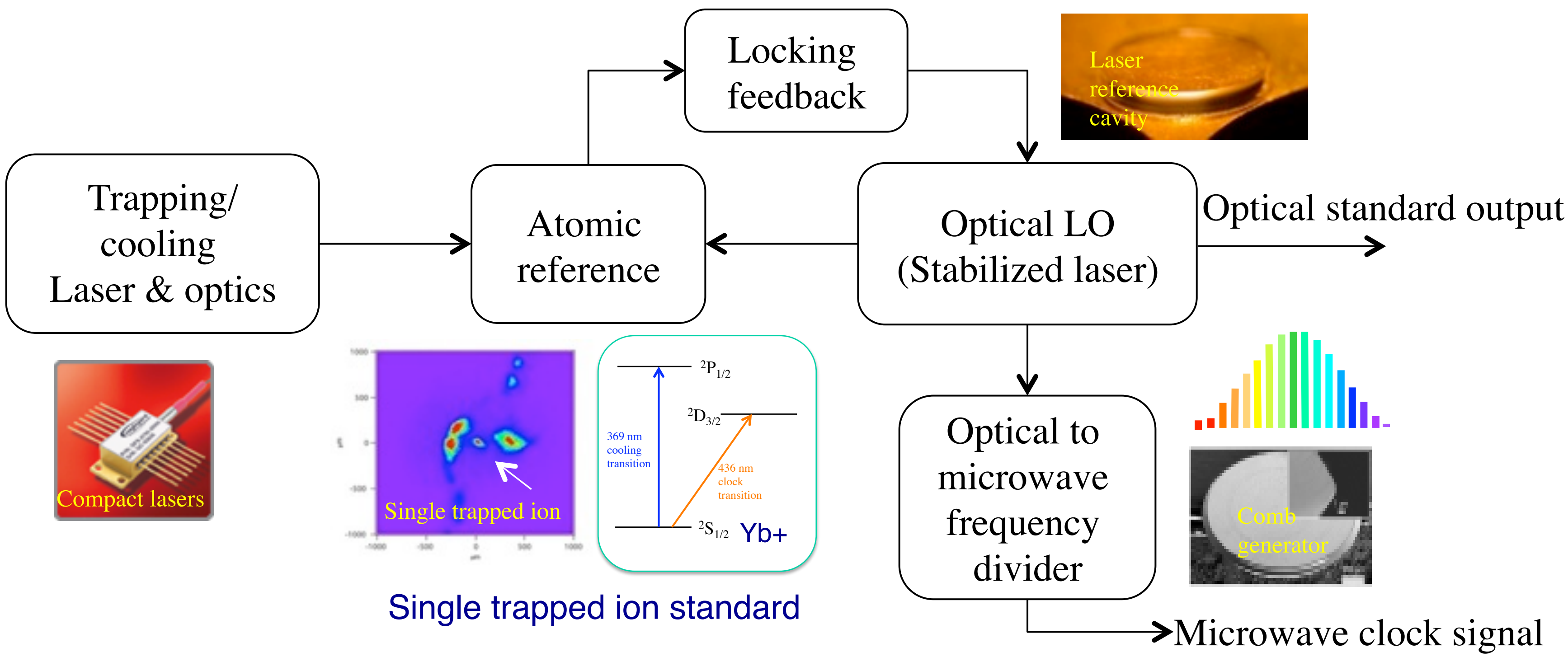
Y. Jau, et al. Appl. Phys. Lett. (2012)

JPL 3 cc trap vacuum package



JPL developed and delivered phase I (10 cc) and II micro trap vacuum package (3 cc)

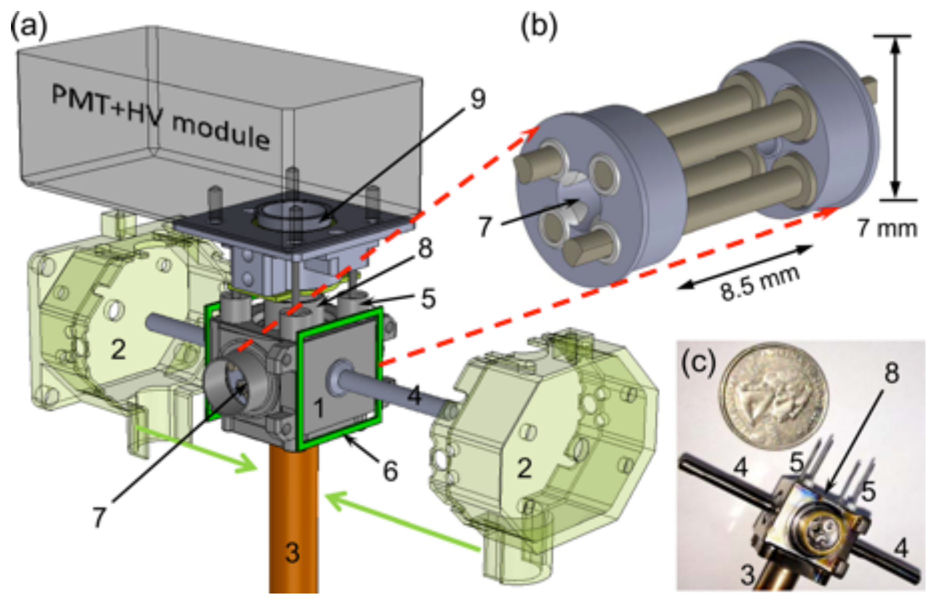
Towards an Ultra-compact Optical Clock



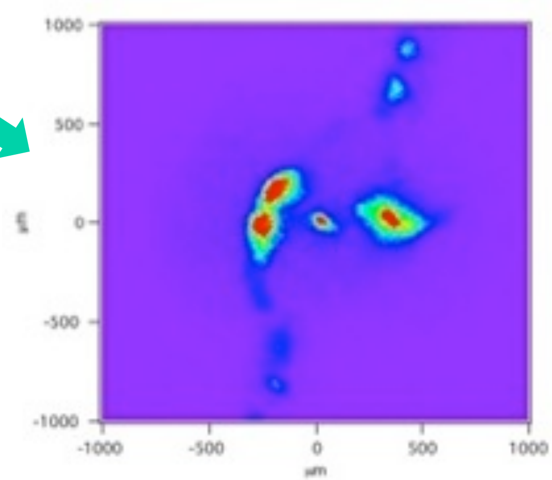
To realize the ultra-compact optical clocks

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

Micro Ion Trap Vacuum Tube Package



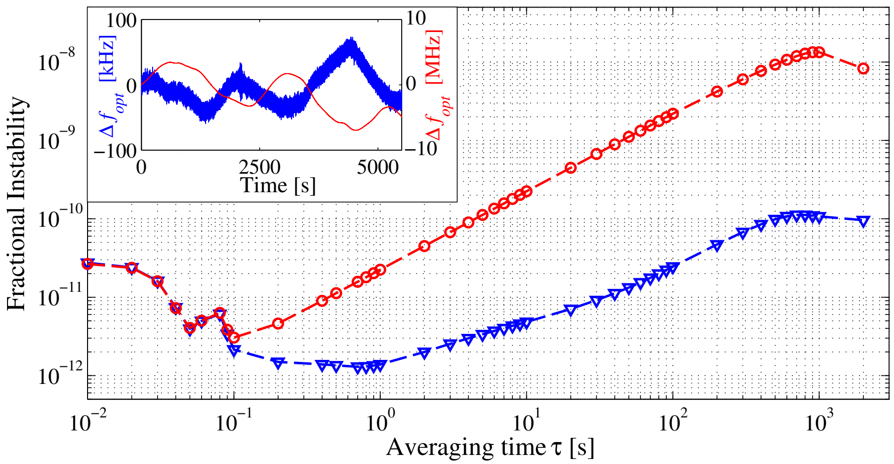
JPL 3 cc trap vacuum package



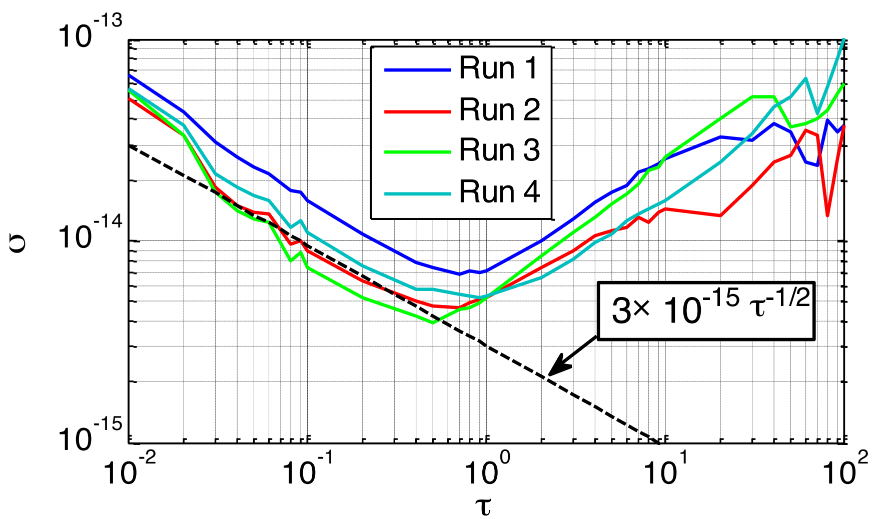
[10]

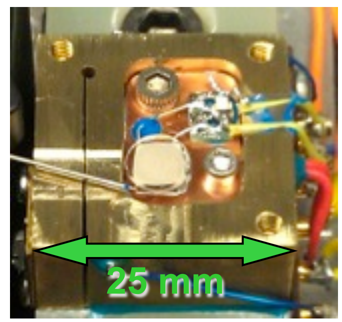
Laser Stabilization with Micro Resonator

Dual mode stabilized frequency stability.



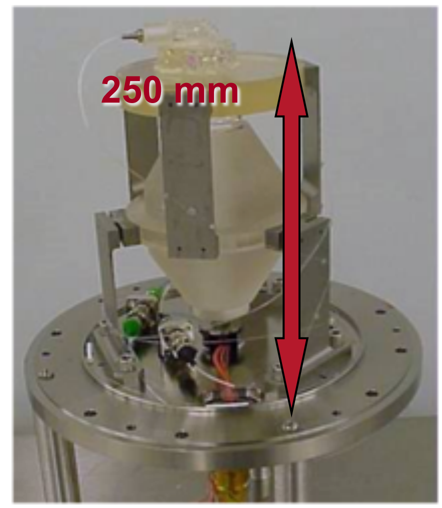
L. Baumgartel, et. al. 31 December 2012 / Vol. 20, No. 28 / OPTICS EXPRESS 29798





WGMR Cavity

vs.

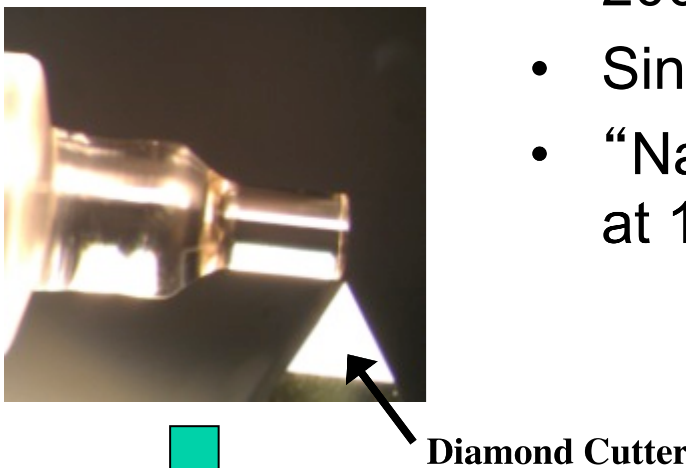


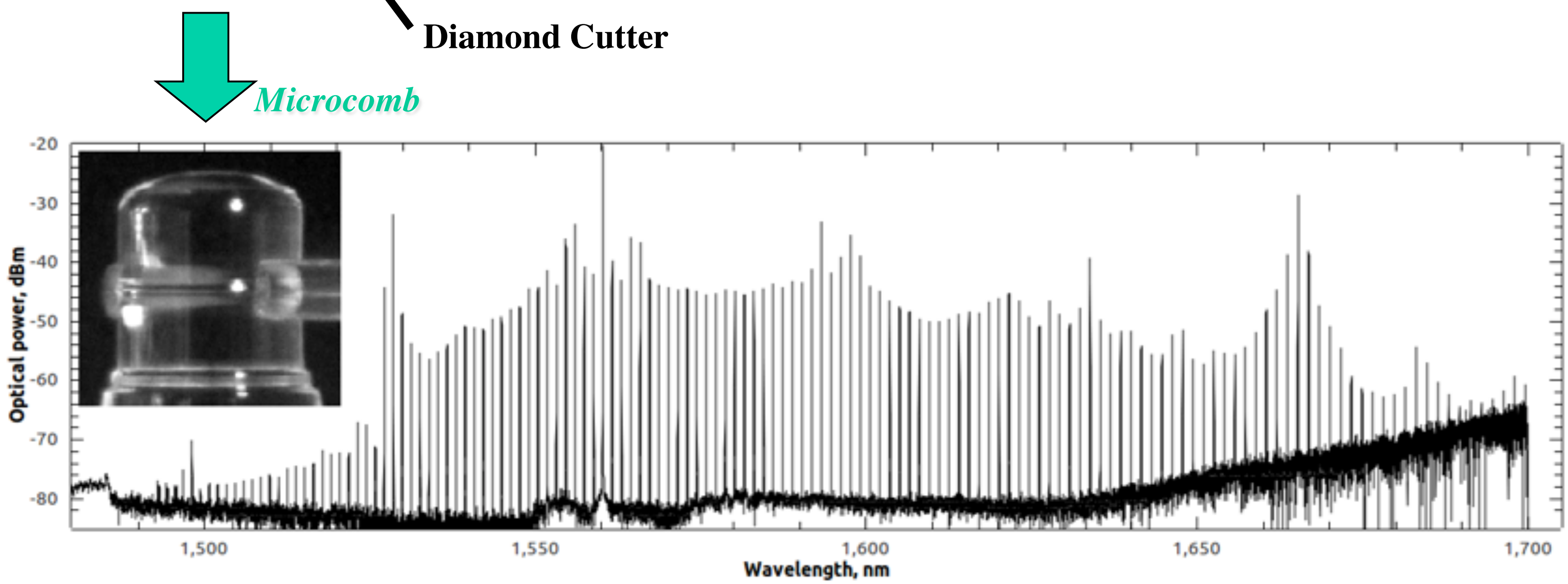
Fabry Pérot Cavity
(GRACE Follow-on)

Nonlinear Frequency Comb Generation

- 200 nm width from 52 mW pump
- Single mode resonator
- “Native” spacing, first tooth appears at 1 FSR.

➔ Coherent comb

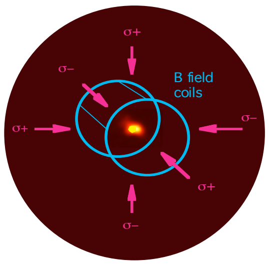




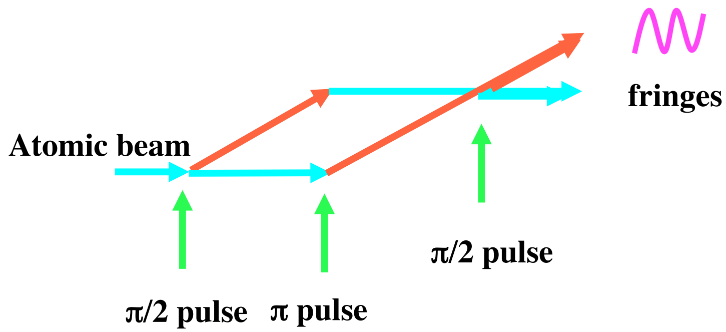
[Grudinin et al., *Opt. Exp.,* Vol. 20, pp 6604 (2012)]

Atomic Free fall Test Mass in Space

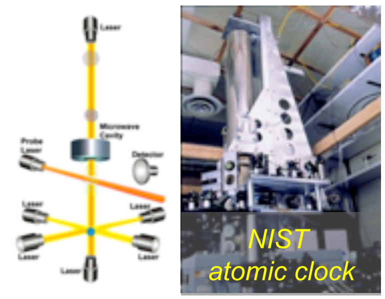
Freefall test mass **+** ***Displacement Detection*** **+** ***Atomic system stability***



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

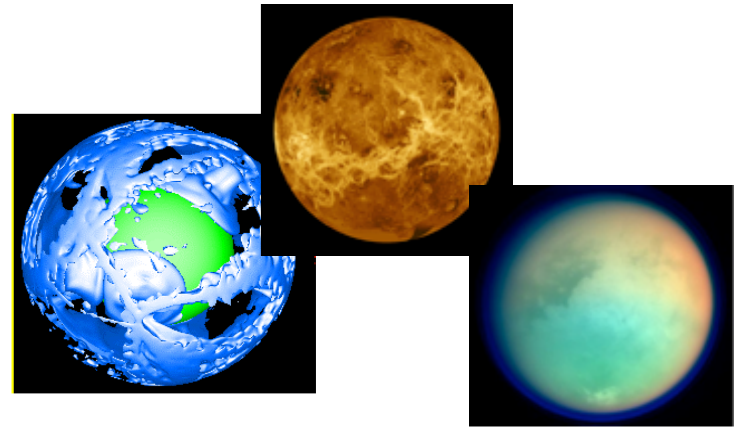
  use the very same atoms and measurement schemes as those for the most precise atomic clocks, allowing high measurement stabilities.

- 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.

Advanced Gravity Missions

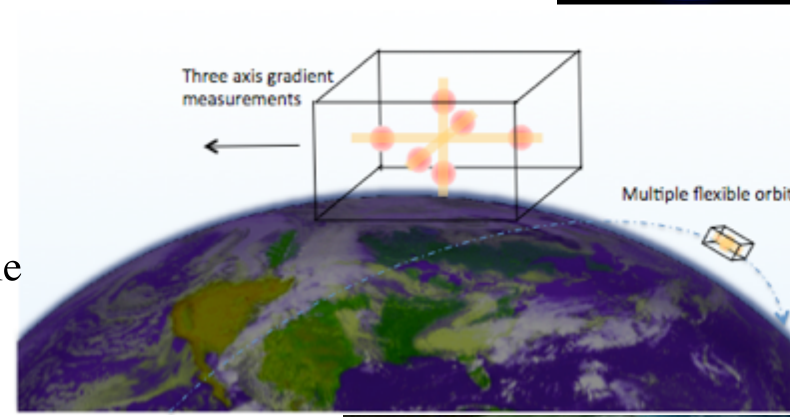
- **Cold atoms as truly drag-free test masses**
- **Gravity gradiometer (better resolution)**
- **Simpler mission architecture (single spacecraft)**
- **More flexible orbits and satellite constellation (more comprehensive data for data analyses)**



Geodesy

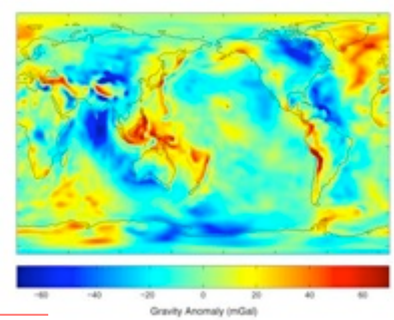
Earth and Planetary Interiors

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



Earth and Planetary Climate Effects

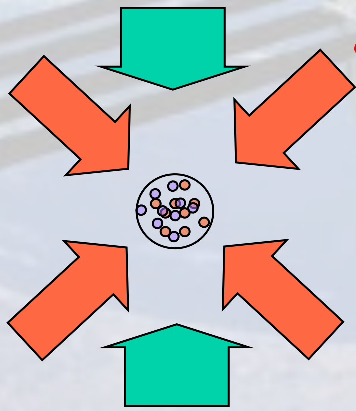
- Oceanic circulation
- Tectonic and glacial movements
- Tidal variations
- Surface and ground water storage
- Polar ice sheets
- Earthquake monitoring



Test of Equivalence Principle with Atomic Test Masses

Two species differential accelerometer

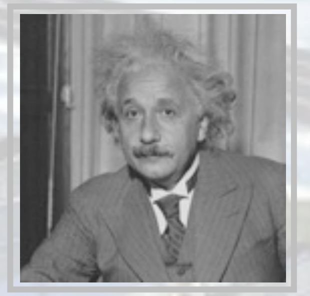
$$\Delta g = g_A - g_B = ?$$



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

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

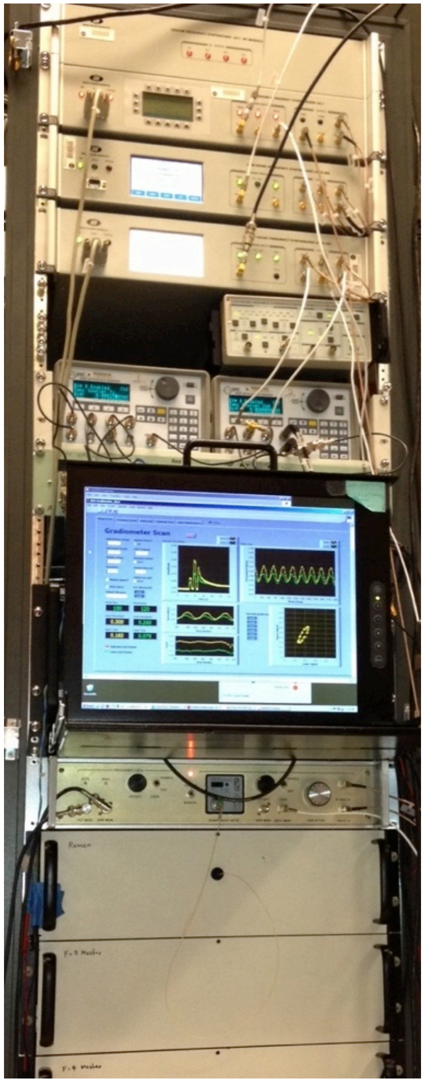
$$\Delta\Phi_{AB} = 2k\,(g_A - g_B)\,T^2$$

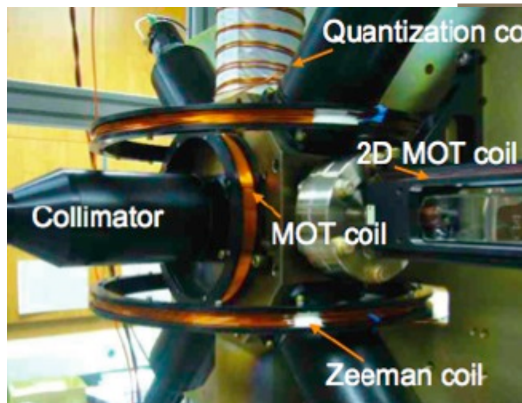


- Single axis differential acceleration of two co-located matter wave interferometers with different atomic species
- Seek a violation of Einstein's Equivalence Principle by improving the test limit by three orders of magnitude, to 1×10^{-15} level and better.
- First non-trivial precision experiment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

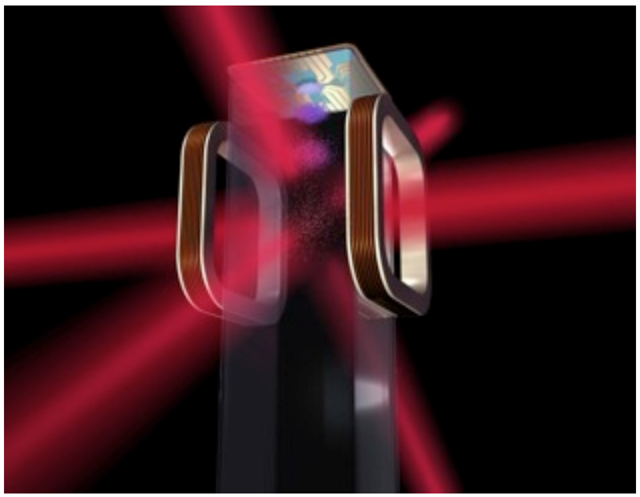
NASA is supporting US collaboration in QWEP, investigating science significance and systematics. NASA is also very much interested in the area of EP and fundamental physics tests with atom interferometers.

Atom Interferometer Instrument





Cold Atom Laboratory - a multi-user microgravity facility



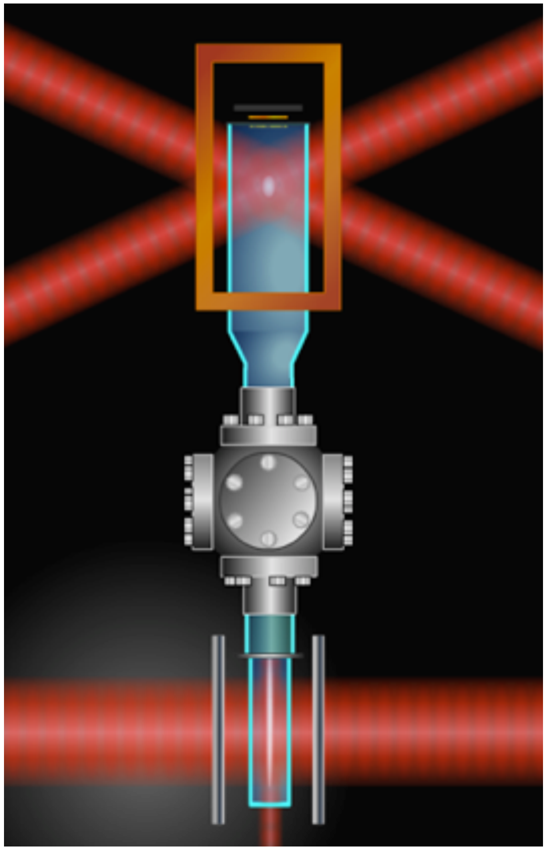
coldatomlab.jpl.nasa.gov

Project manager: Anita Sengupta
Project Scientist: Robert J. Thompson

CAL Objectives

- **Study ultra-cold quantum gases in the microgravity environment of the International Space Station**
- **Study Rb^{87}, K^{41} and K^{40} , and interactions between mixtures of Rb and either of the K isotopes**
- **Study quantum gases with residual kinetic energy below 100 pK (goal 20 pK); with free expansion times greater than five seconds (goal 10 seconds)**
- **Study the properties of both Rb^{87}, K^{41}, and K^{40} quantum gases loaded into optical lattices, in the presence of external magnetic fields tuned near interspecies and single species Feshbach resonances**

CAL at a glance

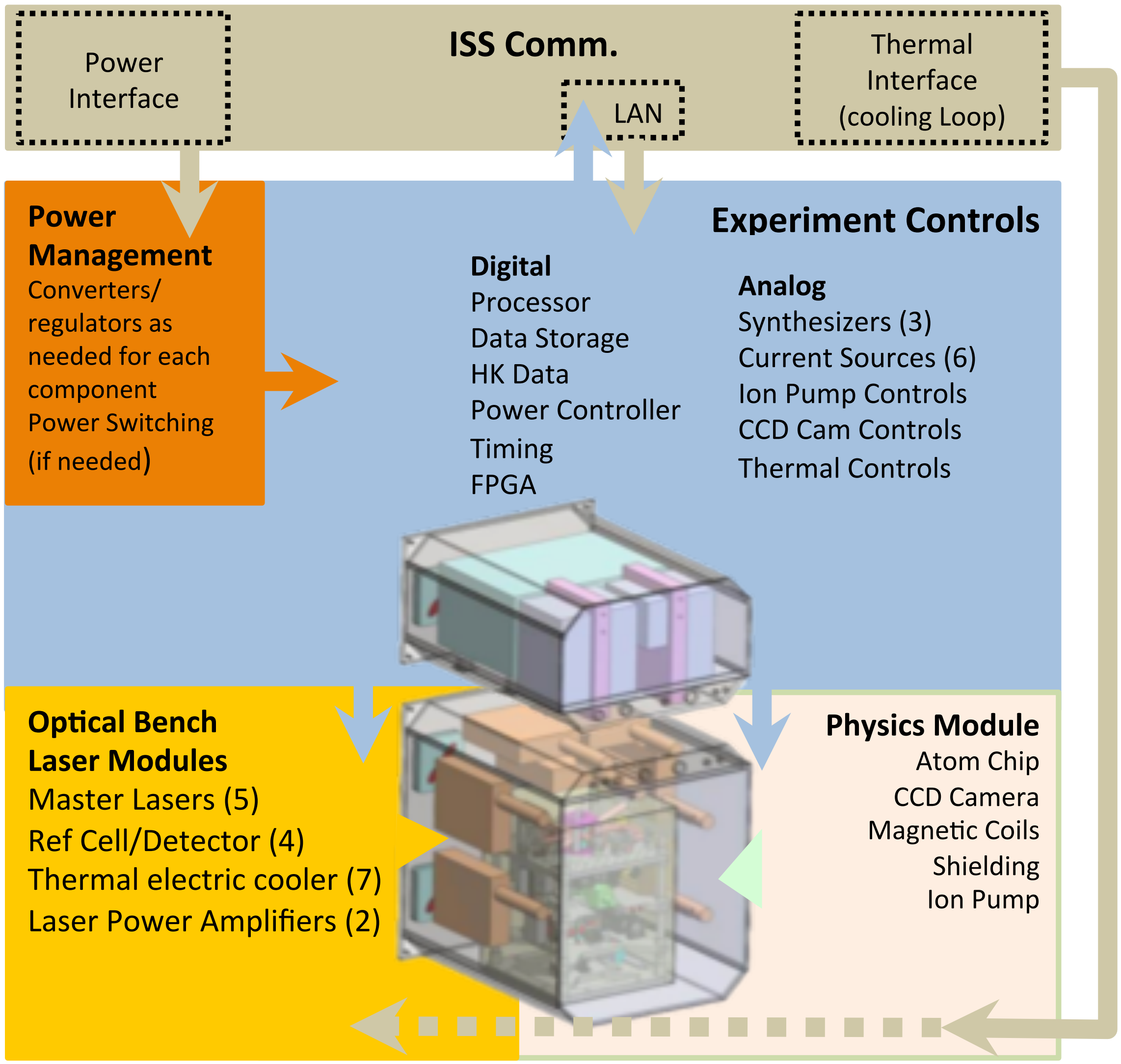


Atom Chip based apparatus

Dual species ^{87}Rb and ^{40}K or ^{41}K

- Target > 200,000 Rb atoms at BEC transition
- Target > 30000 K atoms in degenerate Fermi Gas ($E < 0.1E_F$)
- Condensate lifetime > 10 seconds
- Optical lattice at 850 nm w/ depth up to 10X recoil energy
- Observe Feshbach resonances up to 225 G
- State control via microwave, rf

CAL instrument



CAL Mission Architecture and Schedule

Science Definition Sept 2012 → Development 2012-2015 → Delivery Dec 2015 → Launch April 2016 → Mission Operations April 2016-2017

Phase A