*AN OVERVIEW OF NASA'S PROGRAM FOR FUNDAMENTAL PHYSICS RESEARCH ON THE INTERNATIONAL SPACE STATION**

Ulf Israelsson, Jet Propulsion Laboratory,
California Institute of Technology
Mark Lee, NASA Headquarters

October 15, 2013

Quantum to Cosmos 6

Nice, France

AGENDA

- NASA/JPL's ISS Cold Atom Laboratory project (early 2016 launch)
- NASA/JPL phase A study for the ISS Quantum Test of Equivalence and Space Time project (QTEST)
- NASA participation in current and planned ESA projects.
- Conclusions

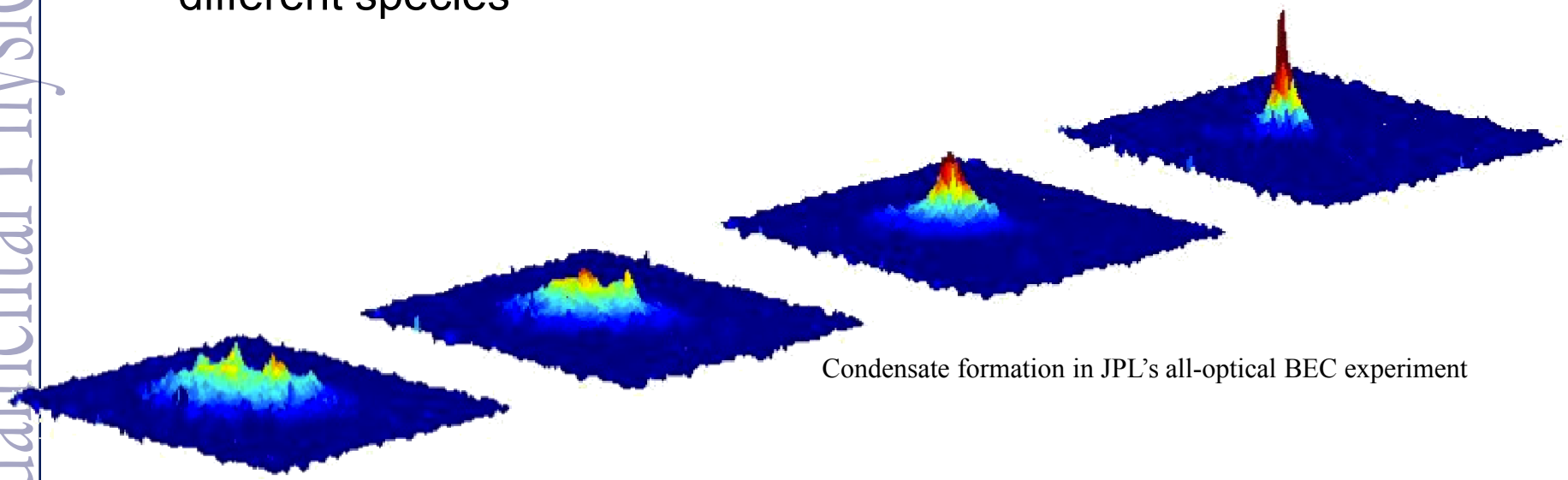
Cold Atom Laboratory Objectives

- An ISS multi-user facility for the study of ultra-cold quantum gases in the microgravity environment;
- Study Rb^{87}, K^{41} and K^{40}, and interactions between mixtures of Rb and either of the K isotopes;
- Study delta-kick cooling techniques to produce samples with residual kinetic energy below 100 pK and free expansion times greater than five seconds; and
- Study the properties of ^{87}Rb, ^{41}K, and ^{40}K quantum gases loaded into optical lattices, in the presence of external magnetic fields tuned near interspecies and single species Feshbach resonances.

CAL Contact: Robert Thompson, JPL (Project Scientist)

Advantages of Space for CAL

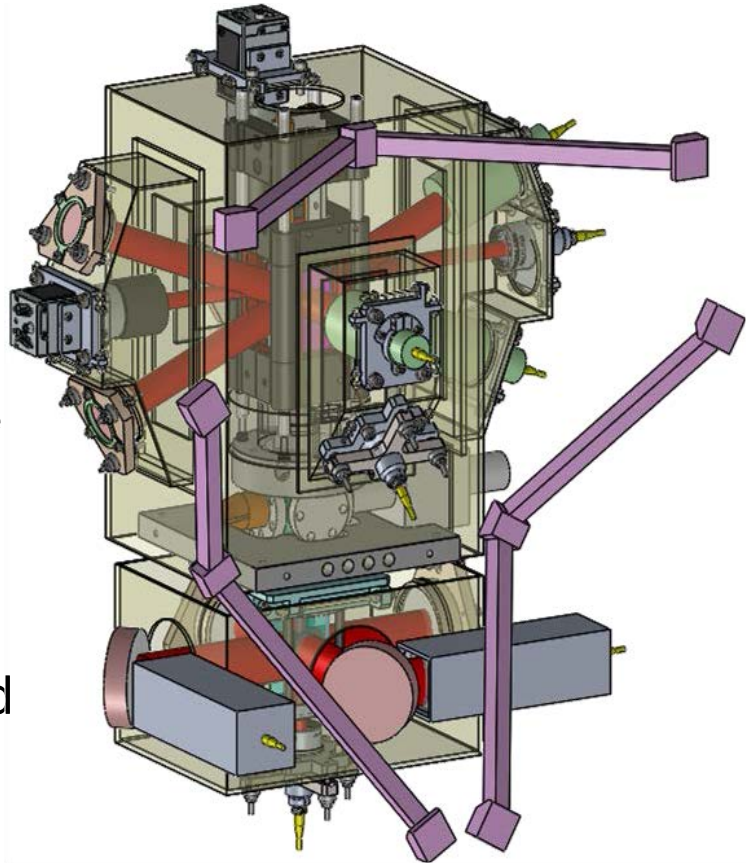
- Long interaction time in perturbation free environment
- Very weak trapping forces result in low temperatures
- Absence of density stratification and separation of mixtures of different species



Condensate formation in JPL's all-optical BEC experiment

CAL Physics Package

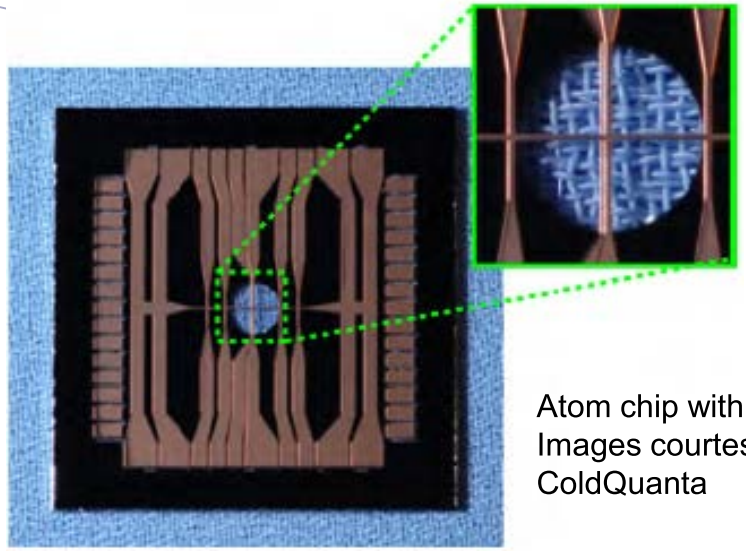
- Atom Chip
- Dual species Rb and K
  - Target >200,000 Rb atoms at BEC transition
  - Target >30000 K atoms in degenerate Fermi Gas, below $0.1E_F$
  - Condensate lifetime >10 seconds
- Simple COTS based laser system and electronics



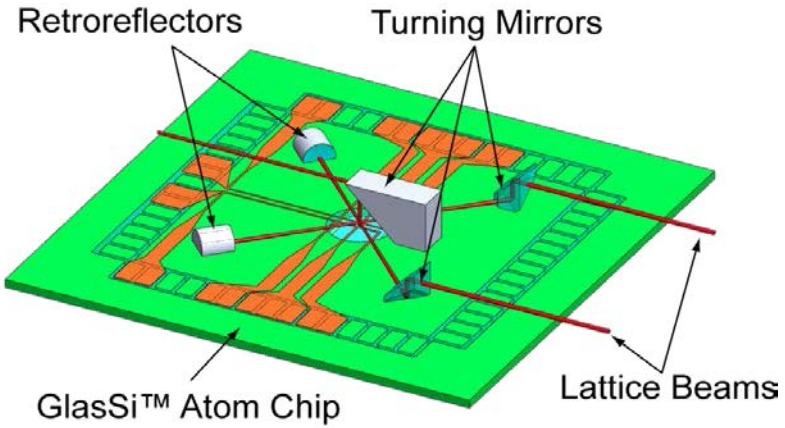
Fundamental Physics

Additional CAL features

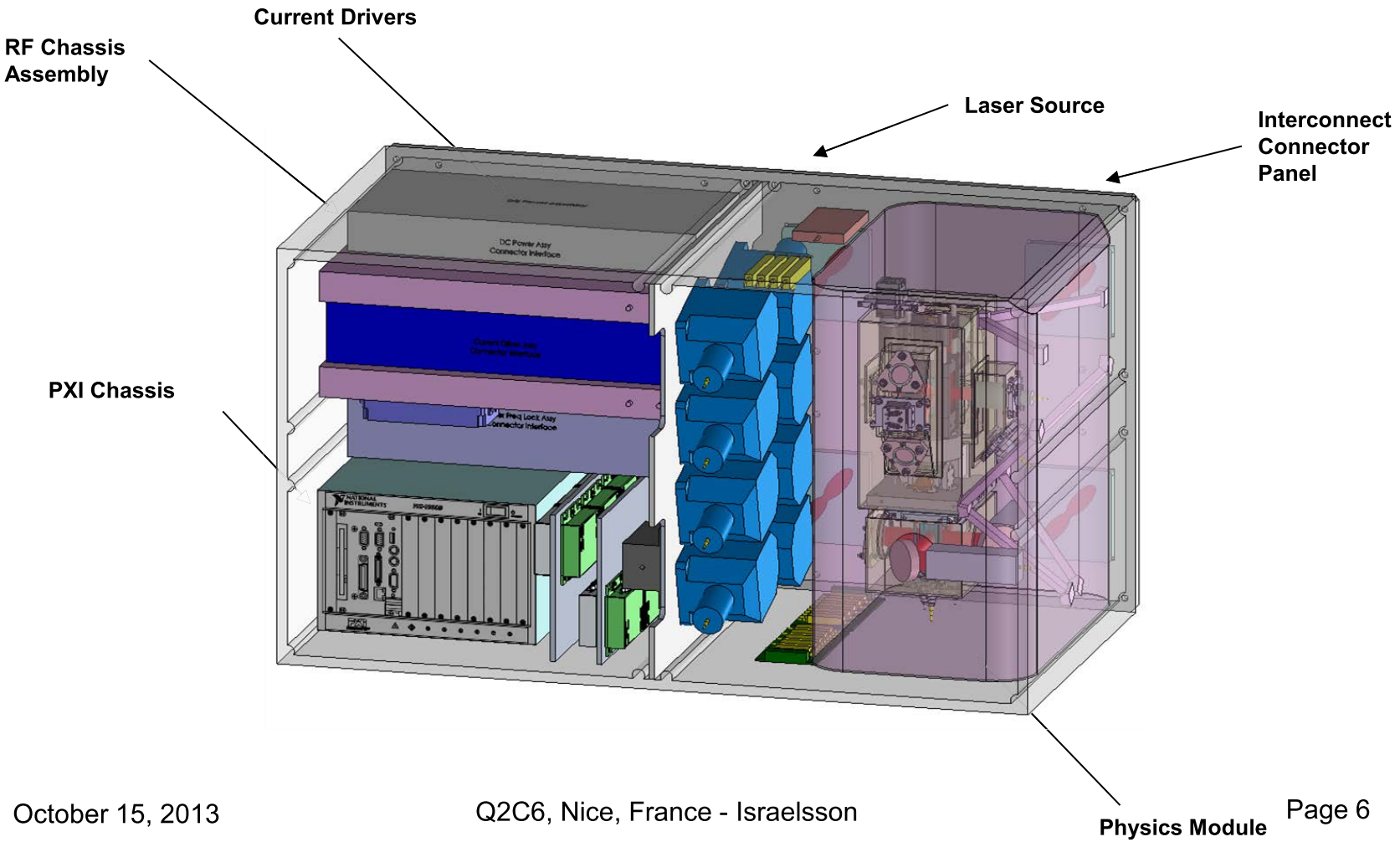
- Optical Lattice
- Window in chip for in situ, high resolution, imaging
- External magnetic field to probe Feshbach resonances
- State control via adiabatic rapid passage and microwave antenna
- Isotope enriched Rb and K dispensers



Atom chip with window.
Images courtesy
ColdQuanta



CAL EXPRESS Rack Accommodation



Fundamental Physics

Launch and ISS Environment

- Benign launch and ISS dynamics and thermal environments:
  - Launch in Soft Stowage bag
  - Controlled temperature environment both on launch and in orbit
- Generous mass and power allocations possible

CAL is a Pathfinder

Atom Interferometers

Fundamental Physics

- Weak Equivalence Principle tests
- Measurement of fundamental constants
- Time variations of fundamental constants
- Tests of the Newton's law at short distances
- Gravitational wave detection

Applications

- Inertial navigation
- Earth observation and monitoring
- Gravity and gravity-gradient mapping
- Planetary exploration

Degenerate Quantum Gases

Fundamental Physics

- Macroscopic wavepackets
- Vortex formation and relaxation
- BEC coherence properties in microgravity
- Role of interactions in BEC: dipolar forces and short range interactions
- Dynamics of Bose-Bose and Bose-Fermi mixtures in microgravity
- Quantum reflection
- 3D Anderson localisation
- Efimov Physics
- Spinor-Dynamics & Correlation
- Sub healing length physics
- Artificial Electromagnetism
- Non-abelian atom optics

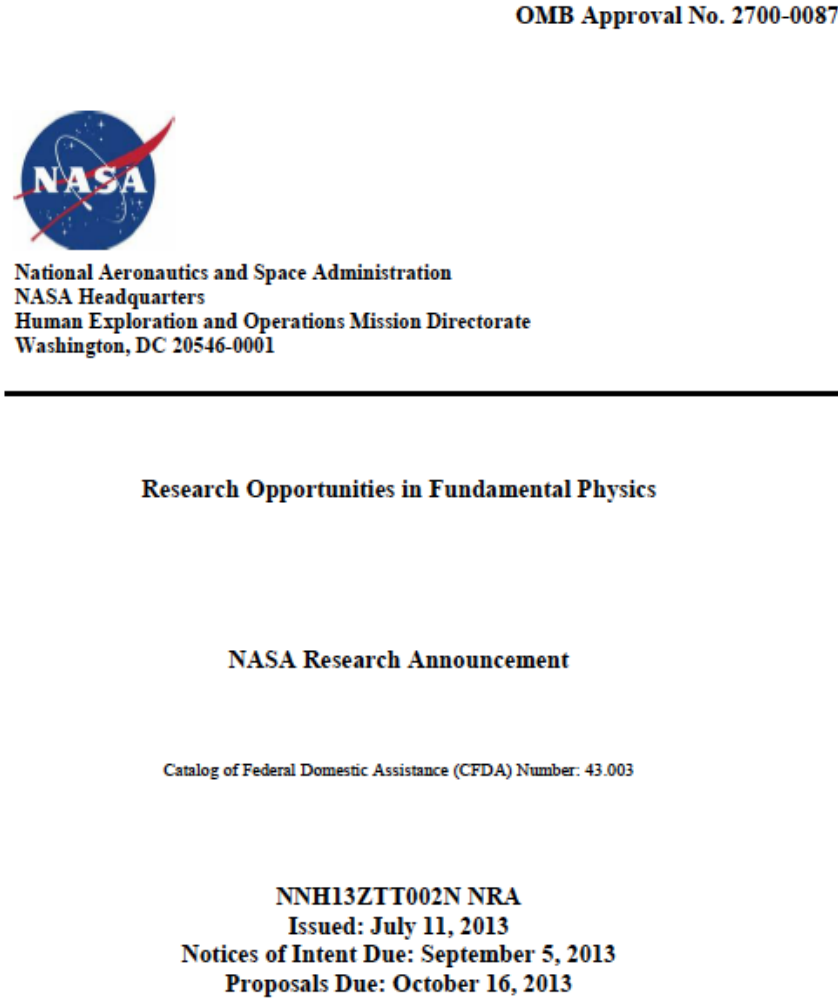
Applications

- Atomic sources for atom interferometry
- High-resolution interferometric measurements with dilute coherent matter waves
- Atom lasers and Holography
- (De-)Coherence
- Evolution of BEC

Fundamental Physics

CAL NASA Research Announcements

- First CAL NRA underway
- ISS facility for studies of ultra-cold samples of several atomic species.
- Upgradable to meet the needs of future investigations.
- Soliciting research in 3 categories
  1. Flight research on ultra-cold atoms and degenerate quantum gases using CAL.
  2. Ground research on ultra-cold atoms and quantum gases for future flight experiments using CAL, or future follow-on missions.
  3. Research uses the German Aerospace Center (DLR) drop tower facilities in Bremen, Germany.
- Second CAL NRA release planned in 2015



OMB Approval No. 2700-0087

National Aeronautics and Space Administration
NASA Headquarters
Human Exploration and Operations Mission Directorate
Washington, DC 20546-0001

Research Opportunities in Fundamental Physics

NASA Research Announcement

Catalog of Federal Domestic Assistance (CFDA) Number: 43.003

NNH13ZTT002N NRA
Issued: July 11, 2013
Notices of Intent Due: September 5, 2013
Proposals Due: October 16, 2013

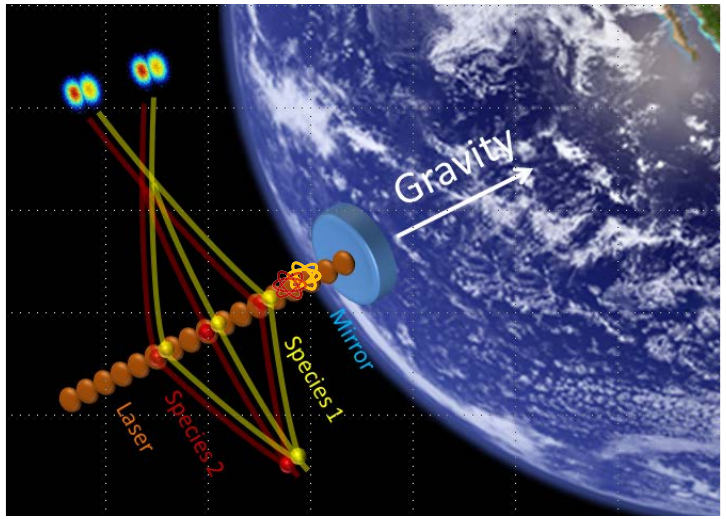
Fundamental Physics

Quantum Test of Equivalence and Space Time (QTEST)

- The QTEST ISS experiment aims to explore gravity's influence on quantum and classical systems
- 18 month Phase A study initiated in August 2013
- Nan Yu, JPL study lead
- Local study team formed
- European participation welcomed on study team
- Organizing workshop in 2014
- Strong Synergy with ESA activities
  - QWEP and STE-QUEST

QTEST Motivation

- Improve the limit on violation of Einstein's equivalence principle (EEP)
- Test EEP in the quantum regime
  - indirect limits on antimatter
  - tests of non-Newtonian gravity
  - opportunity for discovery: violations of EEP, quantum mechanics on macroscopic scales
- Achieve more precise photon recoil measurement
  - Establish the most precise primary mass standard in the proposed SI.
  - Measurement of the fine structure constant
  - Test of Quantum Electrodynamics
  - Opportunity for discovery: inner structure of electron at LHC energy scale



A high priority research area identified in the 2010 National Research Council's Decadal survey report.

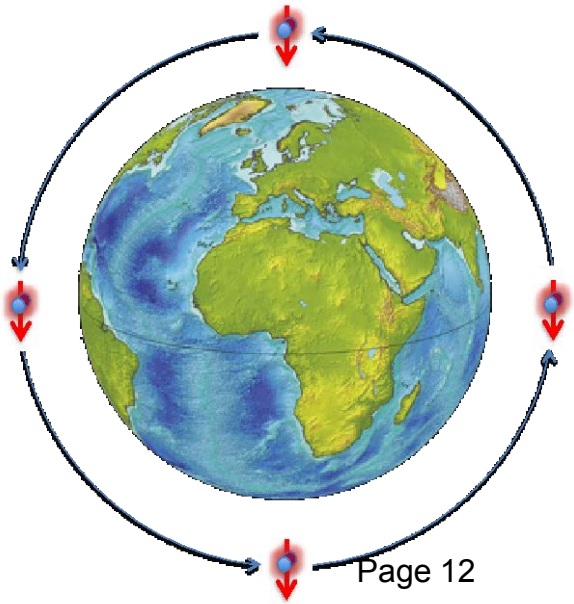
QTEST Overview

Approach

- Atomic drag-free test masses
- Dual-atomic Rb species differential accelerometer
- Atom interferometer in microgravity
- Use of inertial frame of reference
- Leverages CAL experience with cold atoms
- ISS platform: External module or pressurized cabin
- 12 months ISS utilization
- International partnerships
- Class D hardware classification; COTS HW where possible

Potential experiments:

- Differential gravitational acceleration of ^{87}Rb and ^{85}Rb wave packets
- Measurement of h/m and the fine structure constant α
- Evaluation of atomic drag-free test masses

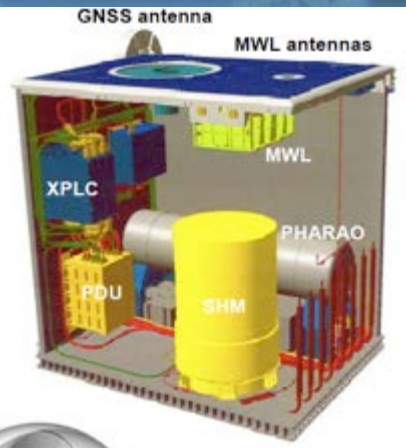


Fundamental Physics

ESA's Atomic Clock Ensemble in Space

Objectives

- Demonstrate an atomic clock on the ISS accurate to one part in 10^16, measure the Earth's gravitational redshift to two parts in 10^6, and test relativistic effects in the frequency comparisons of moving clocks.
- Search for a time variation of the fine structure constant to one part in 10^17 over one year of integration time.
- Search for Lorentz transformation violations to the one part in 10^10 level.
- Perform time synchronization and time transfer experiments (space-to-ground and ground-to-ground) and compare ground clocks to a fractional frequency resolution of 10^-17 in a few days of integration time.



NASA funded investigators on the ACES IWG.

- Nan Yu, JPL (Microwave Link)
- Tom O'Brian, NIST (Microwave Link)
- Kurt Gibble, Penn State University (Clock evaluation)
- Leo Hollberg, Stanford University (Time transfer)

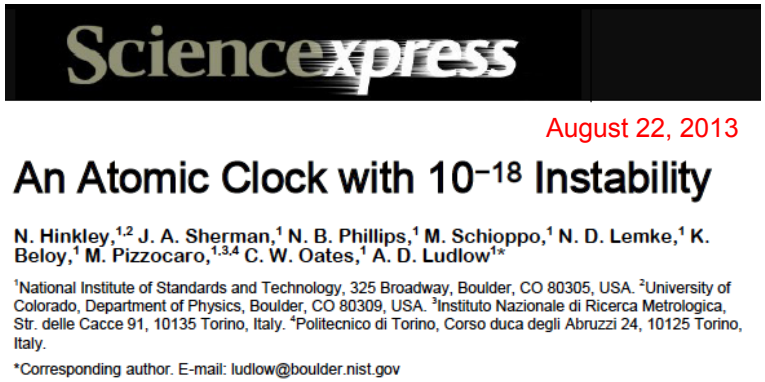
ESA's Space Optical Clock

SOC Objectives

- Demonstrate an optical clock on the ISS accurate to one part in 10^17, measure the Earth's gravitational redshift to two parts in 10^7, and test relativistic effects in the frequency comparisons of moving clocks.
- Perform a null measurement of the Sun's gravitational redshift to two parts in 10^7.
- Perform differential geo potential measurements with 1 cm height resolution on the geoid; such measurements are based on the comparison of distant clocks on ground
- Perform time synchronization and time transfer experiments (space-to-ground and ground-to-ground) and to allow comparison between ground clocks to a fractional frequency resolution of 1 part in 10^18

NASA funded Investigators

- Scott Diddams, NIST (optical microcomb)
  - Co-I Kerry Vahala, Caltech
- Chris Oates, NIST (10^17 Yb optical clock)


Sciencexpress

August 22, 2013

An Atomic Clock with 10^{-18} Instability

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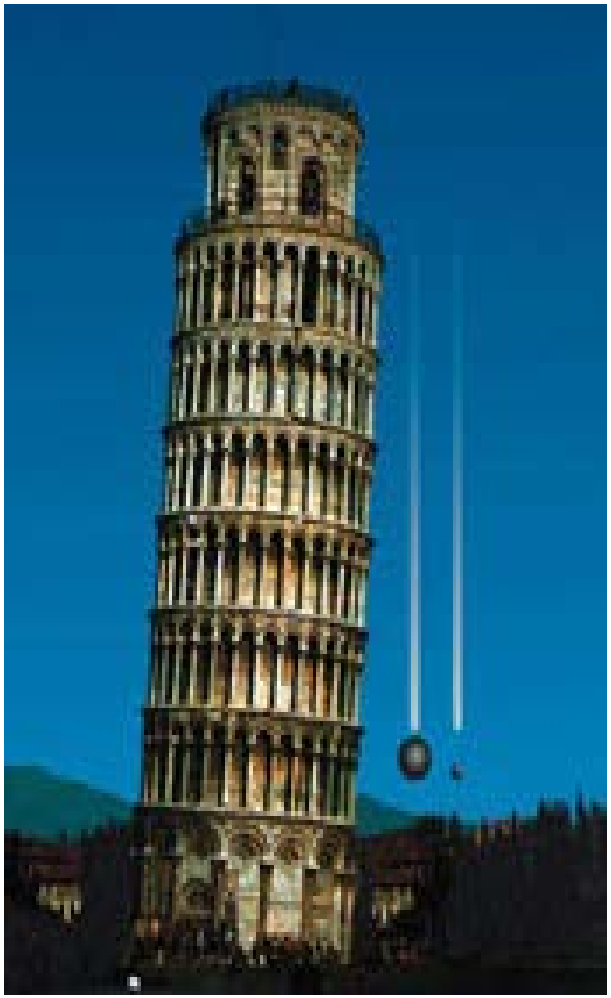
ESA's Quantum Weak Equivalence Principle

QWEP Objectives

- Test the Weak Equivalence Principle using quantum particles approaching ~ 1:10^15
- Validate the technology for a matter wave sensor in space through demonstration of differential atom interferometry and gravity gradiometry measurements.
- Investigate condensate properties in microgravity
- Demonstrate atom interferometry with ultra-cold atom sources in space

- ***NASA funded Investigators on QWEP IWG***
  - Holger Mueller, UC Berkeley
    - Co-I Nan Yu, JPL



NASA Funded Investigators

DECLIC-ALI: Launch 2011	**CNES Led**
eller - University of California, Berkeley **Nan Yu - Jet Propulsion Laboratory**	**QWEP Analysis and Optimization** **Co-I to Mueller**

Fundamental Physics

Summary

- Cold Atom Laboratory is a recent new EXPRESS rack NASA/JPL facility planned for launch in 2016.
  - Collaborations with European scientists are encouraged through 2013 and 2015 NRA.
- A NASA/JPL Phase A study for the Quantum Test of Equivalence and Space Time (QTEST) is on-going.
  - Participation by European scientists encouraged
  - International workshop planned in 2014
- NASA funded researchers are participating on ESA/CNES/DLR ISS activities
- NASA is expanding its cadre of fundamental physics researchers through new projects and collaborations with ESA led activities