Applications of cold atoms in space: from time keeping to fundamental physics

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CGSIC 2021, 9/20/2021
Atom Interferometry in a Nutshell

Measurement based on an ensemble of effective 2-level systems, coupled with light pulses with opposite $k$-vectors

- Ultra-cold single atoms freely falling under gravity
- Positions interrogated by three laser pulses
- Accurate and stable, governed solely by $\hbar, c, \lambda_{\text{laser}}$

$$\phi = \vec{k}_{\text{eff}} \cdot \vec{a}T^2$$

Unique Features:
- Freely falling atoms as reference
  => Ideal inertial sensor
- Fundamental constants as scaling factor
  => Stability and accuracy
- Matter-wave interference
  => Quantum effect (cf. classical or GR)

Measure relative acceleration between the free falling atoms and the mirror
Atomic sensors

- Accelerometer
  - Bias stability < $10^{-10}$ g
  - Noise < $10^{-8}$ g/Hz$^{1/2}$
  - Scale factor < 0.0001 ppm

- Gyro
  - Bias stability < 60 µdeg/hr
  - Noise < 3 µdeg/hr$^{1/2}$
  - Scale factor < 5 ppm

- No moving parts!!
• Gravity Recovery And Climate Experiment Follow-On (GRACE-FO)
• Gravity field and steady-state Ocean Circulation Explorer (GOCE)
• Invaluable for climate change study
• Performance limited by onboard accelerometer

https://grace.jpl.nasa.gov/resources/6/grace-global-gravity-animation/
https://www.nasa.gov/feature/jpl/grace-fo-satellite-switching-to-backup-instrument-processing-unit
https://www.esa.int/Applications/Observing_the_Earth/GOCE
Atom interferometers can enable mapping of Earth’s gravity

- **AI**: long-term stability allows better gravity recovery

**Graph 1:** Acceleration noise (nm/\(s^2/\sqrt{Hz}\))

- **Thermal atom source**
- **LMT atom optics**
- **Ultra-cold atom source**

**Graph 2:** Frequency (Hz)

**Earth Science – Gravity Gradiometry**

**Diagram:**
- **Platform 1**
- **Platform 2**

**Atom interferometers can enable mapping of Earth’s gravity**

- **Drought in India & Southeast Asia**
  - Decreased gravity (gradient) \(g_3\)
  - Atom falls farther from laser
  - Advances phase on fringe \(\phi_2\)

- **Flooding in the Amazon Basin**
  - Increased gravity (gradient) \(g_1\)
  - Atom falls closer to laser
  - Retards phase on fringe \(\phi_4\)

**Graph 3:**

- **Gravity Map**


**Hybrid Electrostatic-Atomic accelerometer for space missions**

- **Laser interferometer**: Inter-sat. distance
- **ElectroStatic acc.**: Drag forces

**Future work with TUM (Technical University of Munich) to assess the potential of such configuration**

**C. Diboune et al, “Hybrid Electrostatic-Atomic accelerometer for space missions,” 2nd Quantum Technology - Implementations for Space Workshop 2017**
• Orbit determination of spacecraft via radio tracking helps measuring gravity of celestial bodies.
• Interior composition of planets (including the **Moon**) is determined.
• Non-gravitational forces limit gravity recovery.
• AI onboard spacecraft can serve as ideal test mass to remove such disturbances.
• Better planetary science (cf. BepiColombo)

**Miniature Atomic Drag-free Reference Instrument (MADRI)** (~ 4 kg and 4 liters)

The instrument collects and laser-cools an ensemble of atoms. The cold atoms are then left totally freefall in vacuum. A laser is used to measure the relative motion between the spacecraft and the freefall atoms.

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**Radio link:**

*Spacecraft orbital determination which leads to gravity and atmosphere drag through modeling*

**Radio tracking station:**

**Spacecraft**

**Planetary body**

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Surface seismometer provides another means to study planetary interior.
- **Apollo 11** on the **Moon**, **InSight** on Mars
- Tidal effects only measured on Earth, but invaluable for planetary studies.
- Atomic seismometer/gravimeter can have sensitivity and stability to explore new frontiers.
Gravitational waves cause spacetime to ring.
Laser ranging between inertial references picks up the call.
Atoms are ideal inertial reference, and can remove laser noise with clever arrangements.
Complementary to LISA and LIGO

Mid-band Atomic Gravitational Wave Interferometric Sensor (MAGIS) arXiv:1711.02225
Atomic Experiment for Dark Matter and Gravity Exploration in Space (AEDGE) arXiv:1908.00802
Atom Interferometer Observatory and Network (AION) https://indico.cern.ch/event/802946/
“Space Atomic Gravity Explorer” (SAGE) arXiv:1907.03867
• DM couples to fundamental constants
• Big portion of energy spectrum not explored by high energy particle accelerators
• Atomic transition frequency changes when DM passes by.

DM coupling causes time-varying atomic energy levels:

\[ |e\rangle \rightarrow |\text{DM induced oscillation}\rangle \]

https://science.nasa.gov/astrophysics/focus-areas/what-is-dark-energy
• Dark energy not one of the known forces.
• Local scale measurements are consistent with known forces.
• DE could be screened.
• DE models imply minute extra forces
• Atoms allow direct search for extra forces in the solar system.
Objects of different composition fall at the same rate. **Apollo 15 on the Moon.**

- MICROSCOPE uses different metal alloys and tests down to $10^{-14}$
- Atomic tests will be quantum and aiming at $10^{-16}$

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Quantum Test of Equivalence Principle and Space Time (QTEST)

doi:10.1088/1367-2630/18/2/025018

The Space-Time Explorer and Quantum Equivalence Space Test (STE-QUEST)

FPM-SA-Dc-00001
NASA/JPL Cold Atom Laboratory (CAL) on ISS
(Launched in May 2018, now operating in space)

First BEC results on orbit!

CAL Science module
Deep Space Atomic Clock

A Technology Demonstration Mission

Launched in June 2019

Todd Ely; Mission Principal Investigator/Project Manager

Robert Tjoelker and John Prestage; Ion Clock Co-Investigators

DSAC TDM Payload

GPS Receiver
Validation System (JPL-Moog)

Ultra-Stable Oscillator (USO)
Local Oscillator (FEI)

Launched
USAF STP-2
(Falcon Heavy)

DSAC Demo Unit (DU)
Atomic Resonator (JPL)
V: 285 x 265 x 228 mm
M: 16 kg, Physics Pkg – 6.6 kg
P: 50 W, Physics Pkg – 17 W
Miniature Atomic Drag-free Accelerometer for GPS denied environment

Ongoing effort

JPL quantum gravity gradiometer  JPL miniature atomic accelerometer
• Atom interferometer technology has advanced beyond research laboratory and is taken off in the practical applications.

• Atomic quantum sensors enable a broad range of applications in space in LEO and in the solar system.

• Technology advancement and maturation for space environment are ongoing.

• Atomic quantum sensors are still at infancy and innovative methods are still being discovered.