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

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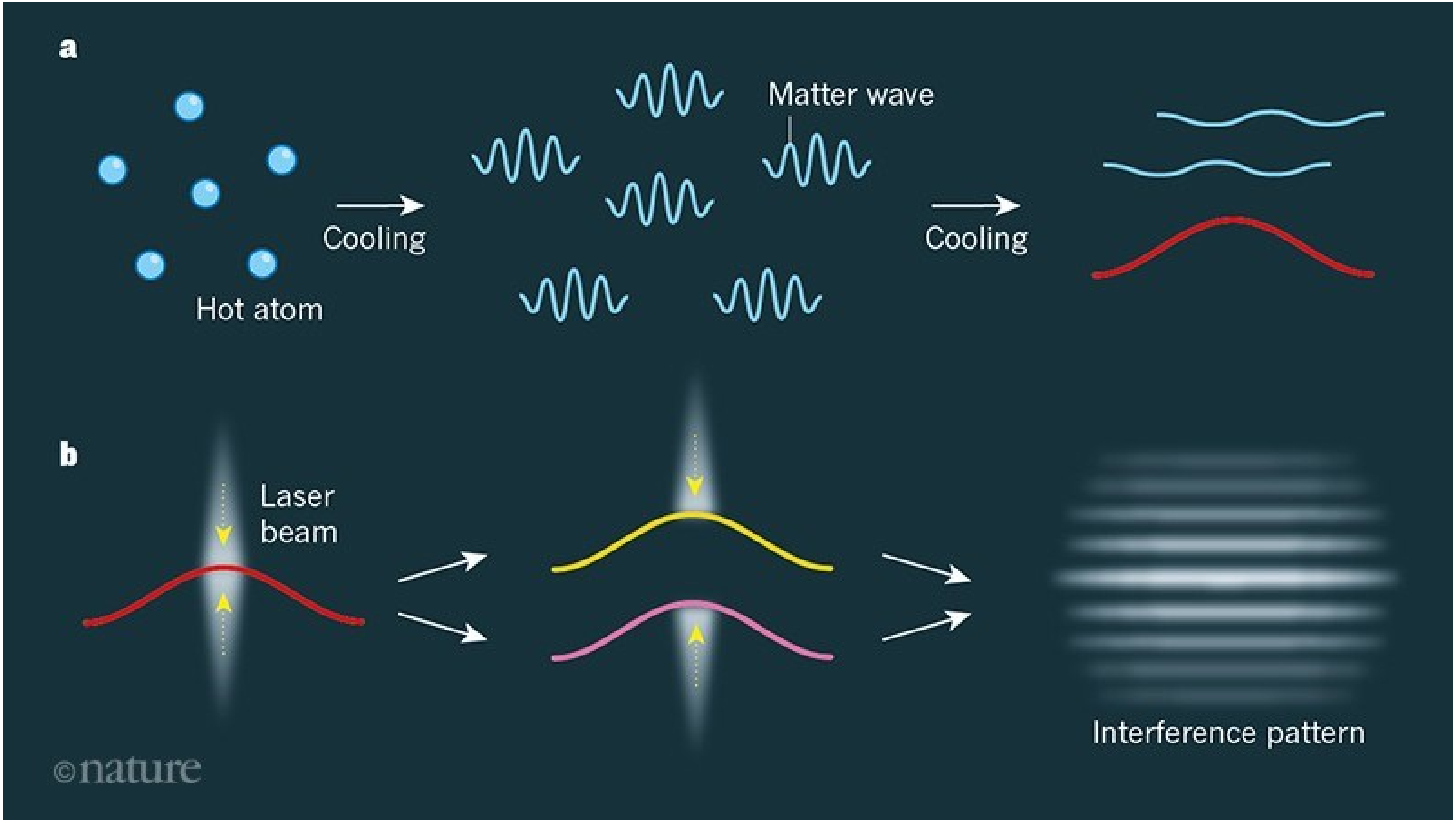
This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Cold Atoms as Quantum Sensors



Nature **562**, 351-352 (2018)

Jet Propulsion Laboratory
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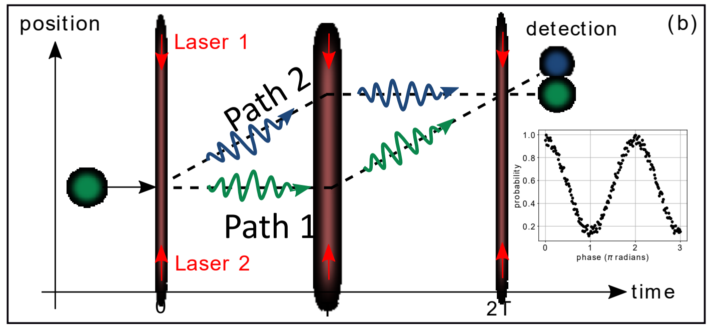
Atom Interferometry in a Nutshell

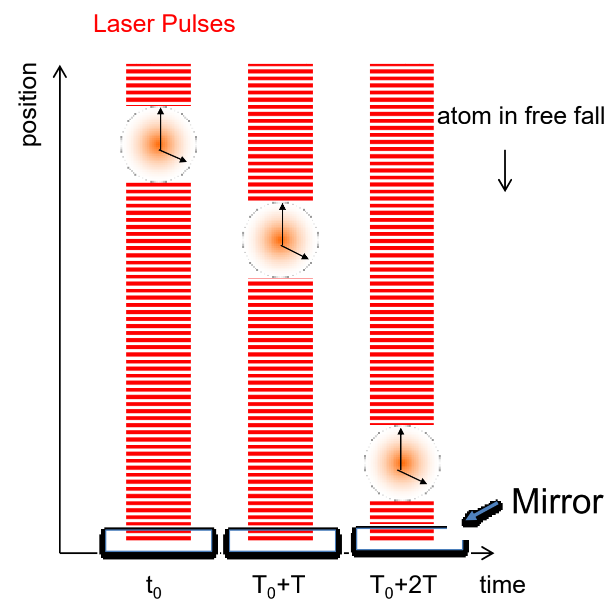
Measurement based on an ensemble of effective 2-level systems, coupled with light pulses with opposite **k**-vectors

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



arXiv:2003.12516v1

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



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)

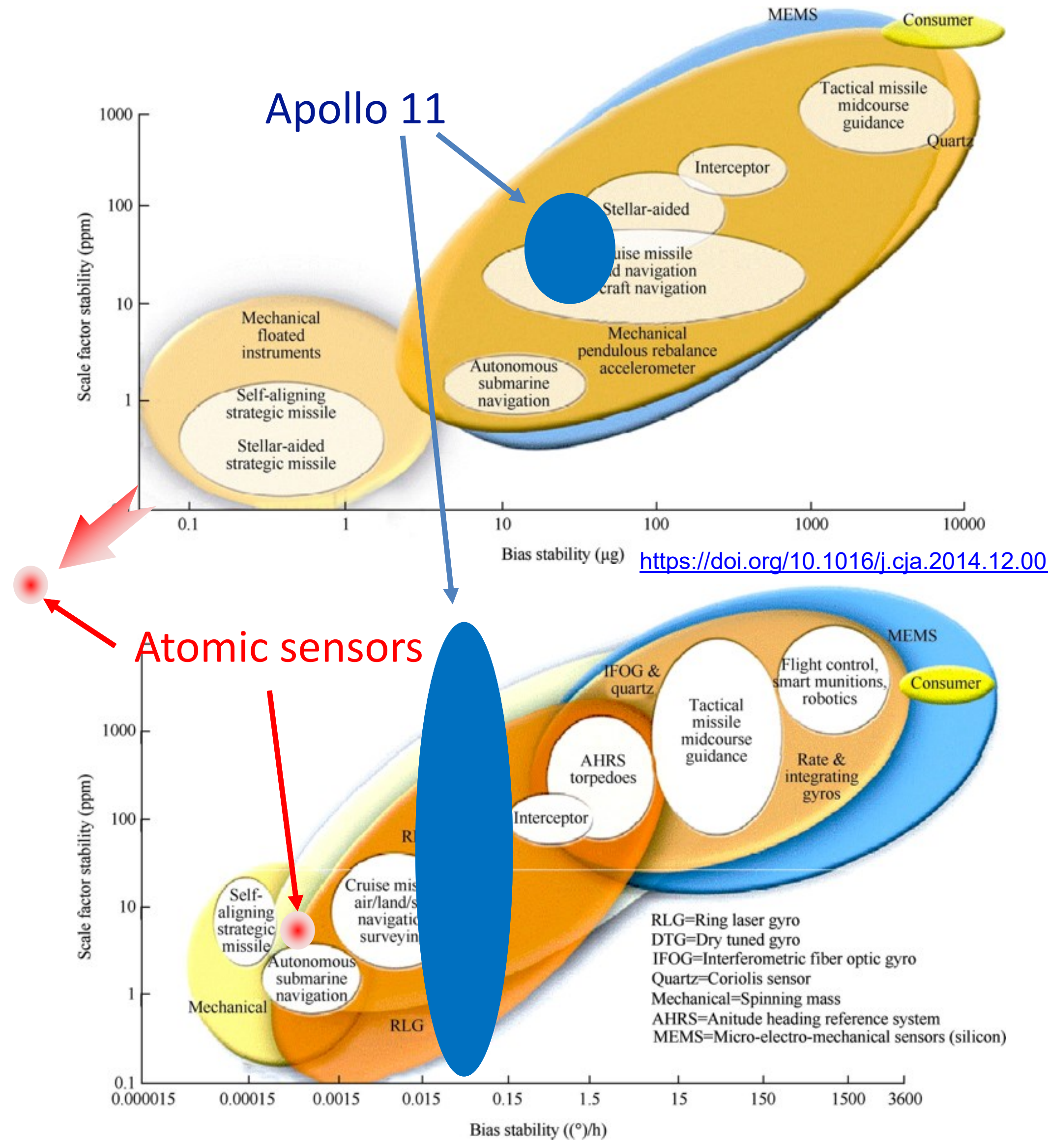
Measure relative acceleration between the free falling atoms and the mirror

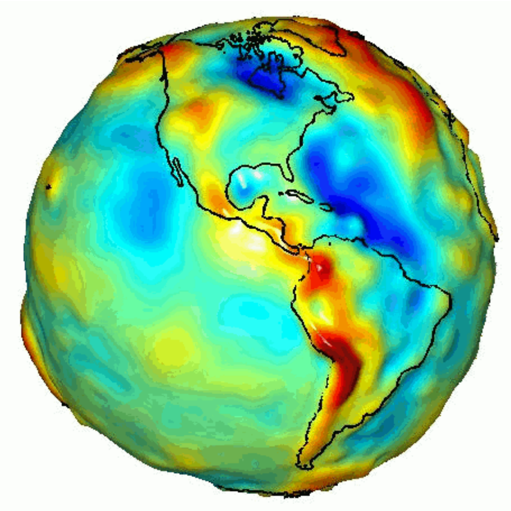
Inertial Navigation

Atomic sensors

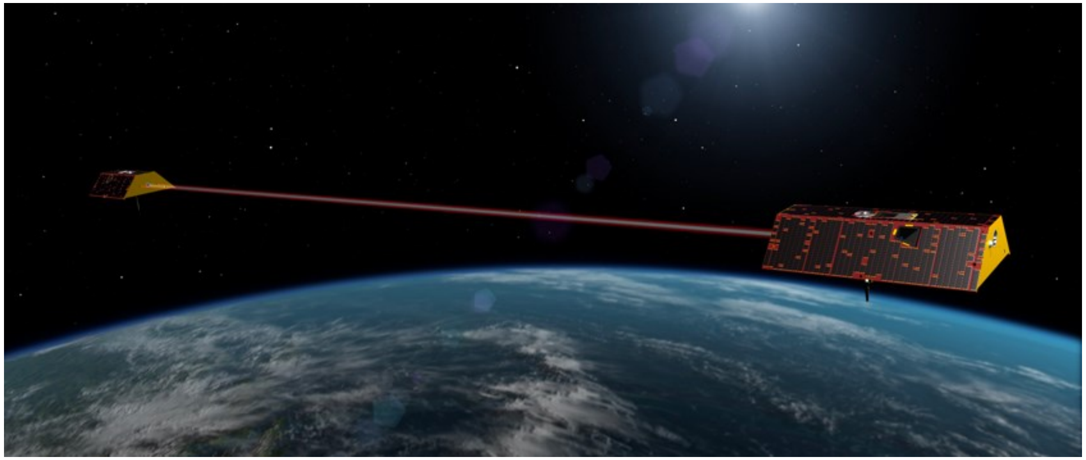
- Accelerometer
  - Bias stability < 10^{-10} g
  - Noise < 10^{-8} g/Hz$^{1/2}$
  - Scale factor < 0.0001 ppm
- Gyro
  - Bias stability < 60 µdeg/hr
  - Noise < 3 µdeg/hr$^{1/2}$
  - Scale factor < 5 ppm

- No moving parts!!





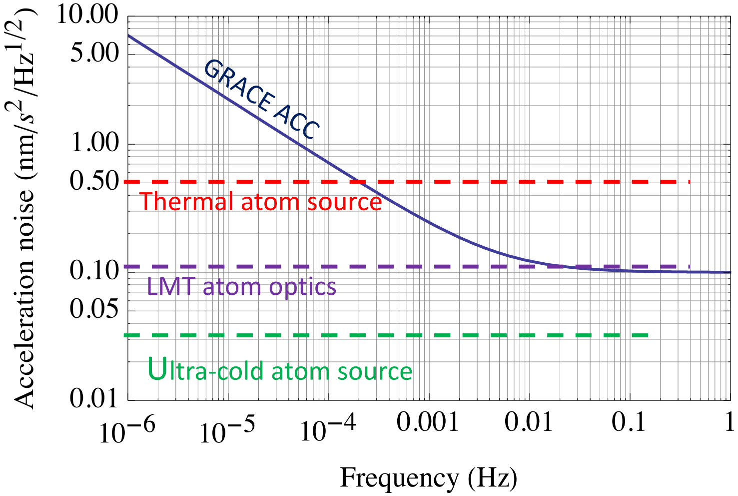
- Gravity Recovery And Climate Experiment Follow-On (GRACE-FO)
- Gravity field and steady-state Ocean Circulation Explorer (GOCE)
- Invaluable for climate change study
- Performance limited by onboard accelerometer

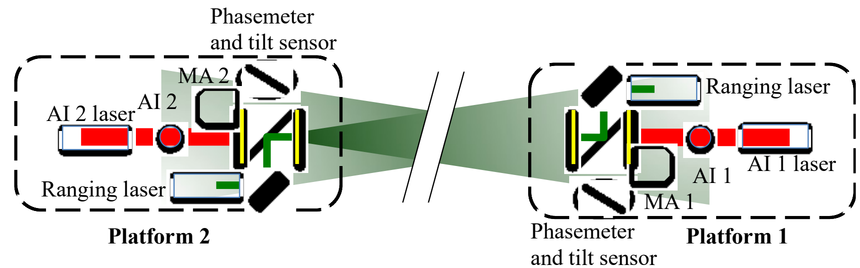


https://grace.jpl.nasa.gov/resources/6/grace-global-gravity-animation/
https://www.nasa.gov/feature/jpl/grace-fo-satellite-switching-to-backup-instrument-processing-unit
https://www.esa.int/Applications/Observing_the_Earth/GOCE

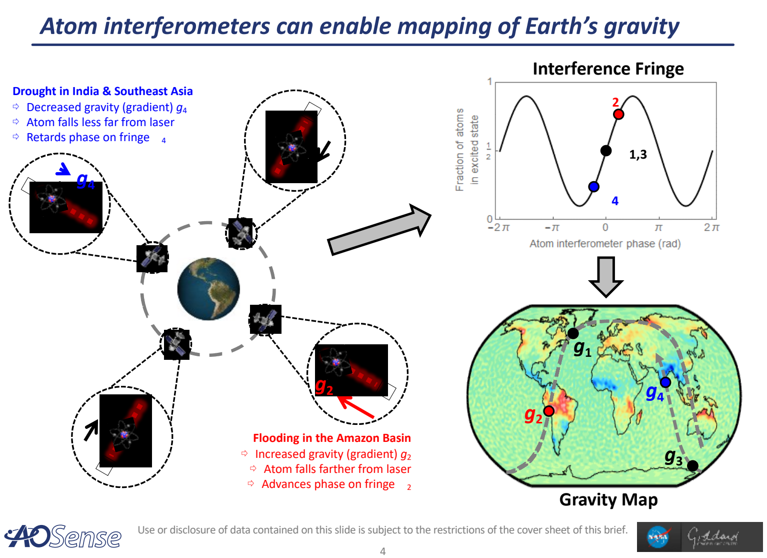
Earth Science – Gravity Gradiometry

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

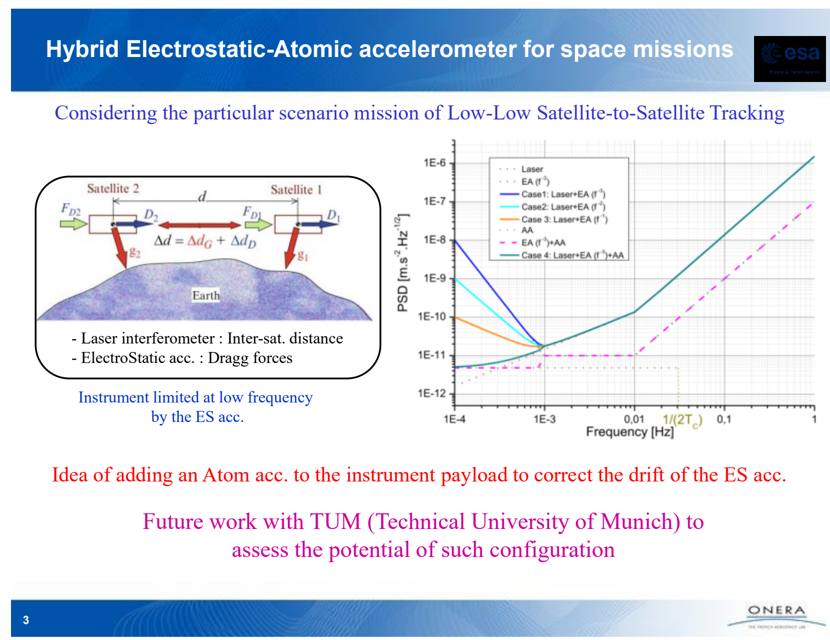




S.-w. Chiow, J. Williams, and N. Yu, "Laser-ranging long-baseline differential atom interferometers for space," Phys. Rev. A 92, 063613 (2015).



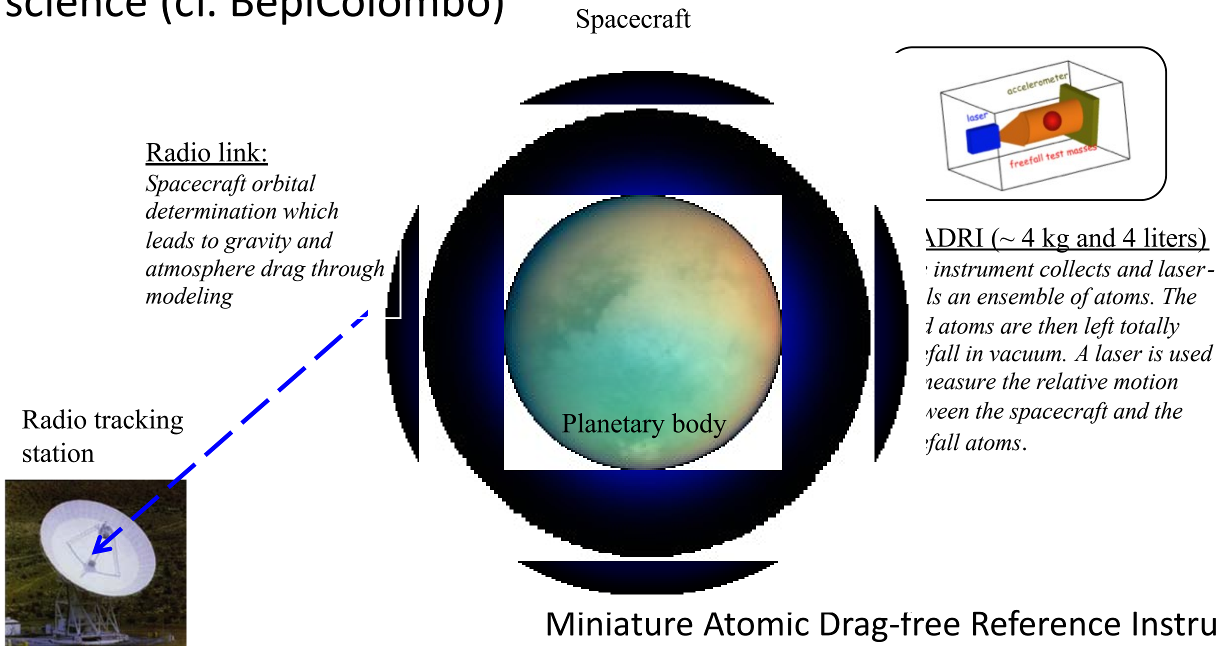
B. Saif, S. Luthcke, L. Callahan, A. Sugarbaker, and A. Rakholia, "AI Gravity Gradiometer for Earth Science," 2nd Quantum Technology - Implementations for Space Workshop 2017



C. Diboune et al, "Hybrid Electrostatic-Atomic accelerometer for space missions," 2nd Quantum Technology - Implementations for Space Workshop 2017

Planetary Science – Navigation and Gravity

- 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)

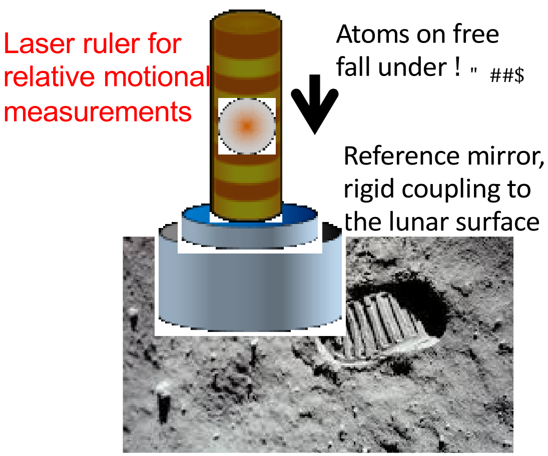


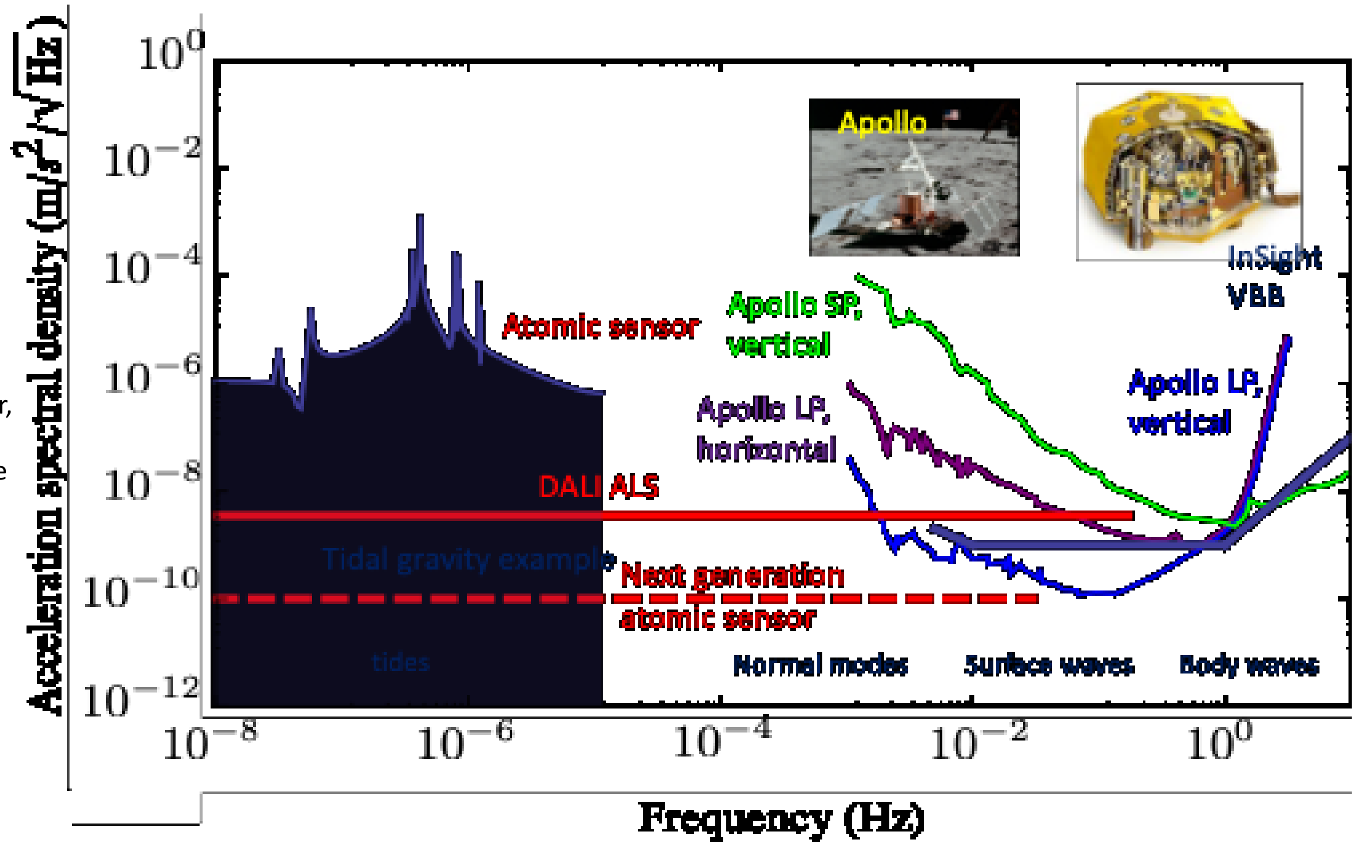
Miniature Atomic Drag-free Reference Instrument

S.-w. Chiow and N. Yu, “Compact atom interferometer using single laser,” Appl. Phys. B 124 (6), 96 (2018)

Planetary Science – Atomic Seismometer

- 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.



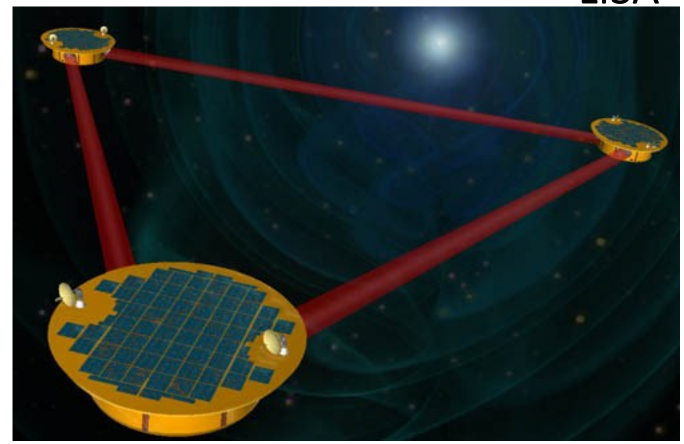


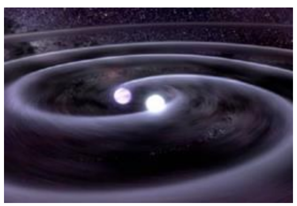
NASA Development and Advancement of Lunar Instrumentation Program (DALI)

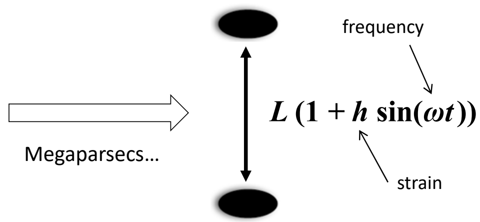
Astrophysics – Gravitational Wave Detection

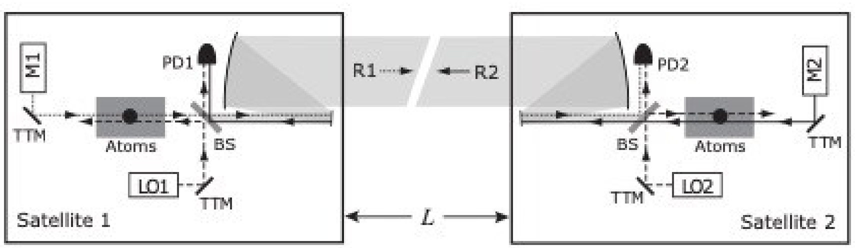
- Gravitational waves cause spacetime to ring.
- Laser ranging between inertial references picks up the call.
- Atoms are ideal inertial reference, and can remove laser noise with clever arrangements.
- Complementary to LISA and LIGO

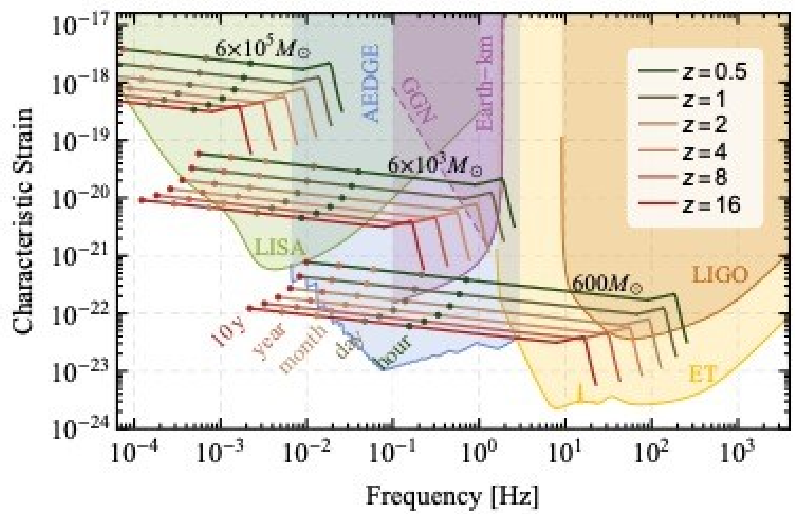
LISA









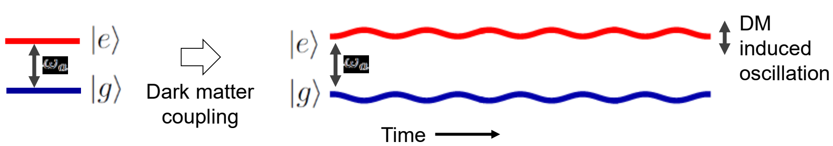


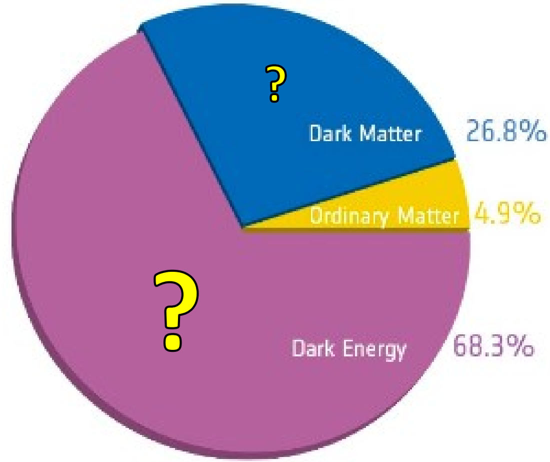
Mid-band Atomic Gravitational Wave Interferometric Sensor (MAGIS) arXiv:1711.02225
Atomic Experiment for Dark Matter and Gravity Exploration in Space (AEDGE) arXiv:1908.00802
Atom Interferometer Observatory and Network (AION) https://indico.cern.ch/event/802946/
“Space Atomic Gravity Explorer” (SAGE) arXiv:1907.03867

Astrophysics – Dark Matter

- 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:





https://science.nasa.gov/astrophysics/focus-areas/what-is-dark-energy

Courtesy of Jason Hogan!

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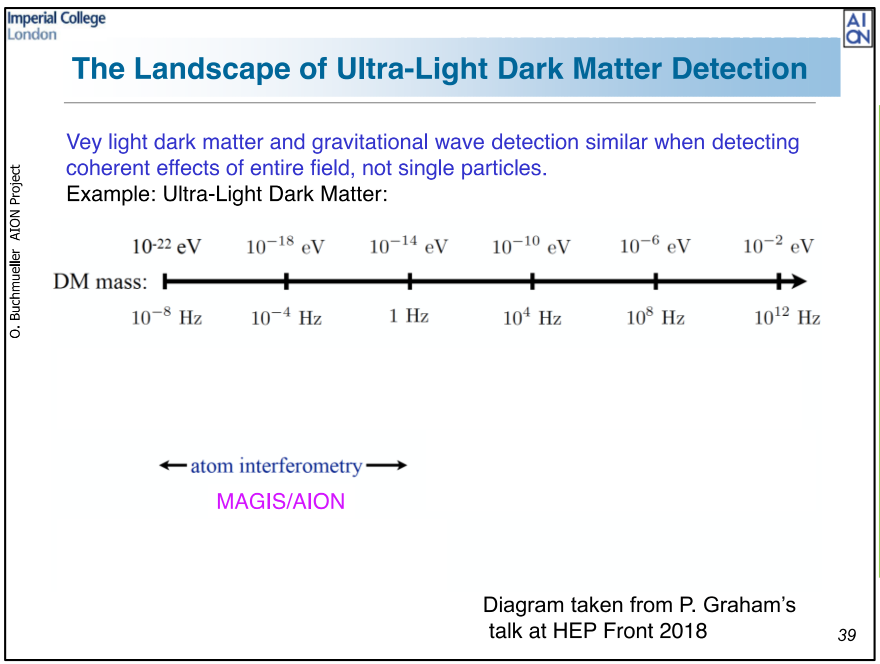
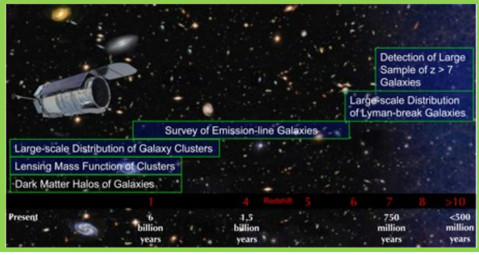


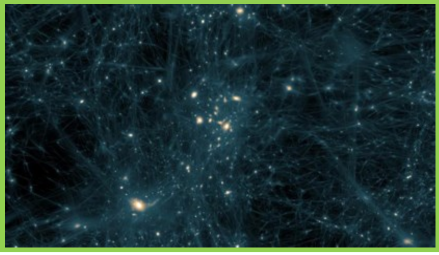
MAGIS,AION,AEDGE,SAGE,...

Observatory Project/Missions

Matter

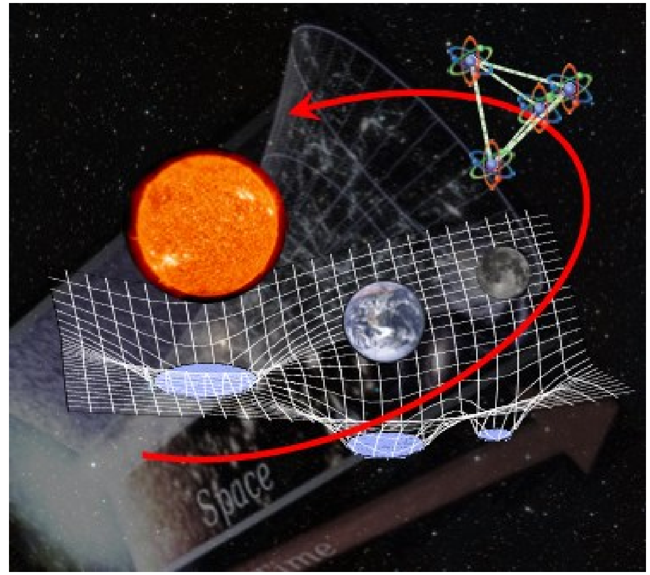
Dark Matter



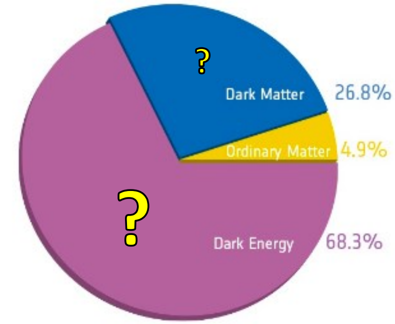


Astrophysics – Dark Energy

- 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.



NASA Innovative Advanced Concepts (NIAC)



Observatory Project/Missions

Matter + Dark Matter

Dark energy (how much)

DIRECT DETECTION

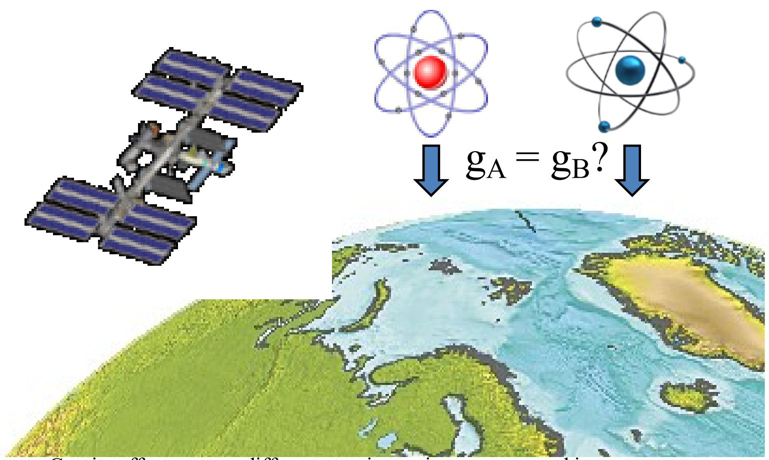
Dark energy (what is)

2 = eff

Fundamental Physics – the Equivalence Principle

David Scott on the Moon, 1971
https://youtu.be/5C5_dOEyAfk

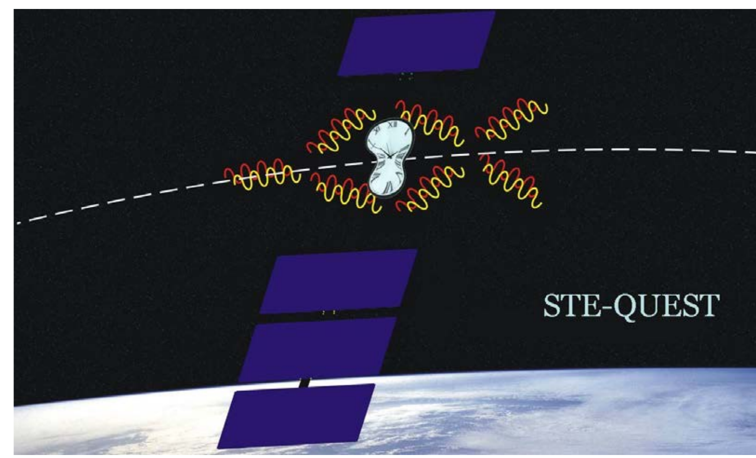
- Objects of different composition fall at the same rate. **Apollo** 15 on the **Moon**.
- MICROSCOPE uses different metal alloys and tests down to 10^{-14}
- Atomic tests will be quantum and aiming at 10^{-16}



Gravity effects on two different atomic species are compared in space

Quantum Test of Equivalence Principle and Space Time (QTEST)

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



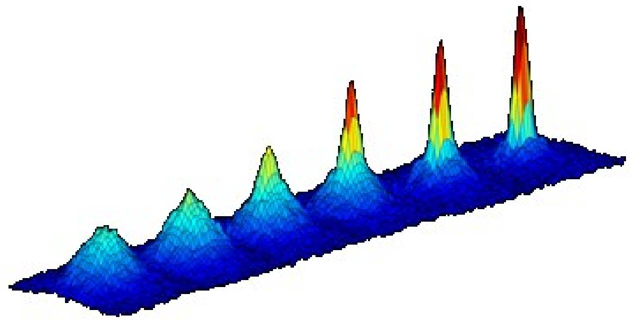
The Space-Time Explorer and Quantum Equivalence Space Test (STE-QUEST)

FPM-SA-Dc-00001

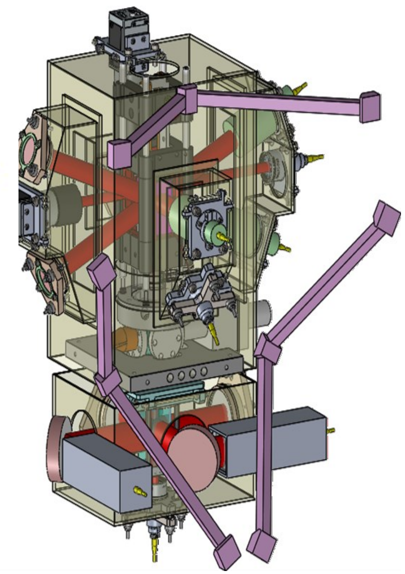
Cold Atom Laboratory Orbiting on ISS

NASA/JPL Cold Atom Laboratory (CAL) on ISS

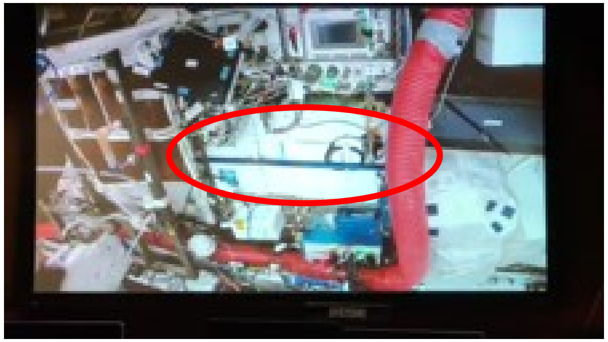
(Launched in May 2018, now operating in space)



First BEC results on orbit!



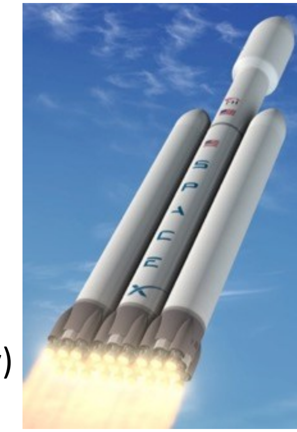
CAL Science module



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

Deep Space Atomic Clock (DSAC)

Launched
USAF STP-2
(Falcon Heavy)



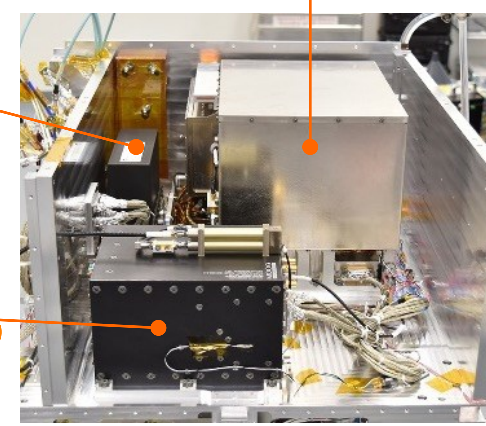
DSAC Demo Unit (DU)
Atomic Resonator (JPL)
V: 285 x 265 x 228 mm
M: 16 kg, Physics Pkg – 6.6 kg
P: 50 W, Physics Pkg – 17 W

Todd Ely; *Mission Principal Investigator/Project Manager*

Robert Tjoelker and John Prestage; *Ion Clock Co-Investigators*

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

GPS Receiver
Validation System (JPL-Moog)

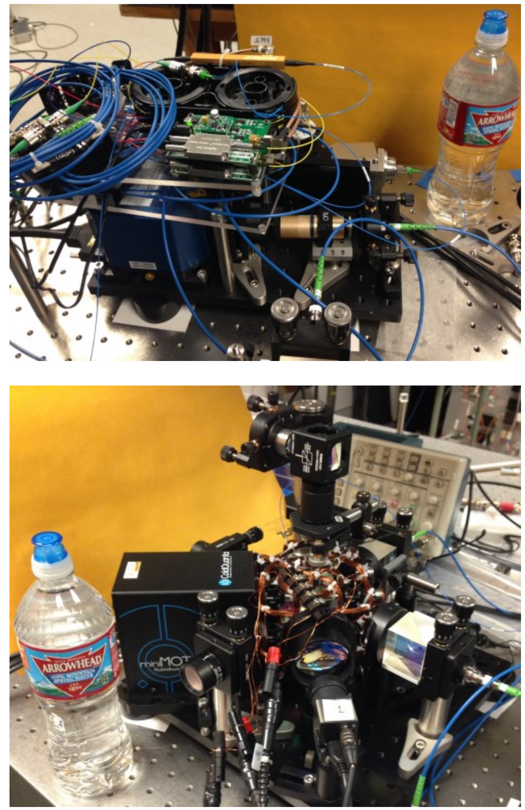


DSAC TDM Payload

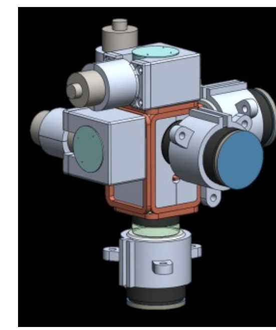
NASA TDM SCaN JPL Jet Propulsion Laboratory California Institute of Technology GENERAL ATOMICS

Miniature Atomic Drag-free Accelerometer for GPS denied environment

JPL quantum gravity gradiometer



JPL miniature atomic accelerometer



Ongoing effort

Summary

- 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.