Quantum Sensing for NASA Science

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Committee on Biological and Physical Sciences in Space Fall Meeting
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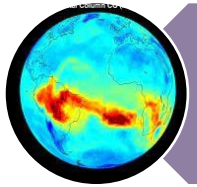
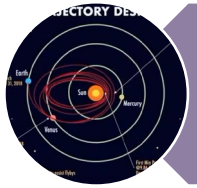
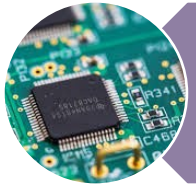
Emergent Opportunities for SMD



Artificial Intelligence and Machine Learning



Autonomous Systems



High Performance Space Computing

Quantum Sensing, Imaging, and Algorithms

Commercial Services and Private Partnerships

Sensing Opportunities for SMD Science

Biological and Physical Sciences
- Cold Atom Lab improvements
- Atomic clock? Atom Interferometer?

Astrophysics
- Advanced photon detectors
- Large-scale array readout and multiplexing
- High-contrast imaging for coronagraphy
- Quantum-enhanced telescopes
- Super-resolution imaging
- Entanglement-enhanced super-resolution imaging

Planetary Science
- Life-detection instruments
- Planetary sensors and instruments

Earth Science
- Instruments to make 20 targeted observables, continuity, climate, and decision support measurements
- Information systems to integrate and coordinate disparate data collections

Heliophysics
- In-situ particle and field observation instrumentation
- Instruments and models to enable space weather nowcasting and forecasting

Improved spectral/temporal/spatial resolution of:
- imagers, spectrometers, and radars (from radio waves to gamma-rays),
- radiometers and heat flux sensors,
- sensitive and precise particle and field sensors,
- high resolution gravity measurements and seismometers, and
- high precision navigation systems

Recent Quantum Sensing Applications in SMD

Astrophysics

- X-Ray Magnetic Micro-calorimeter flown on XRISM (Resolve imaging spectrometer)
  - 36 pixels
  - Technology is advancing:
    - Athena will fly a 2,000 pixel version
    - GSFC/MIT-LL/NIST partnership is developing a 100,000 pixel version

Planetary Science

- Single nanowire single-photon detector array used in Mount Palomar receiver for the Deep Space Optical Communications technology demonstration on Psyche
  - 64 pixels
  - Technology is advancing:
    - JPL/NIST partnership is developing a 400,000 pixel version with time-domain multiplexing readout

Note: Quantum sensing is not new to NASA.
Pioneer 10 (1972) flew an optically pumped helium vector magnetometer

Quantum Projects in Fundamental Physics

The Cold Atom Lab (CAL)

- Continuously operating on the ISS since 2018
- First dual species atom interferometry (AI) demonstrated in space, publication submitted to Nature
  - AI space applications include dark matter and energy searches, geodesy, gravitational wave detection, navigation

Space Entanglement and Annealing QUantum Experiment (SEAQUE)

- Entangled photon source with laser annealing for single photon detectors
  - Quantum comms/networks demo
- Experiment built, expect launch to ISS (NET 10/30/2024)

Bose Einstein Condensate Cold Atom Laboratory (BECCAL) – DLR

- DLR CAL follow-on
- Expected launch 2027 to ISS

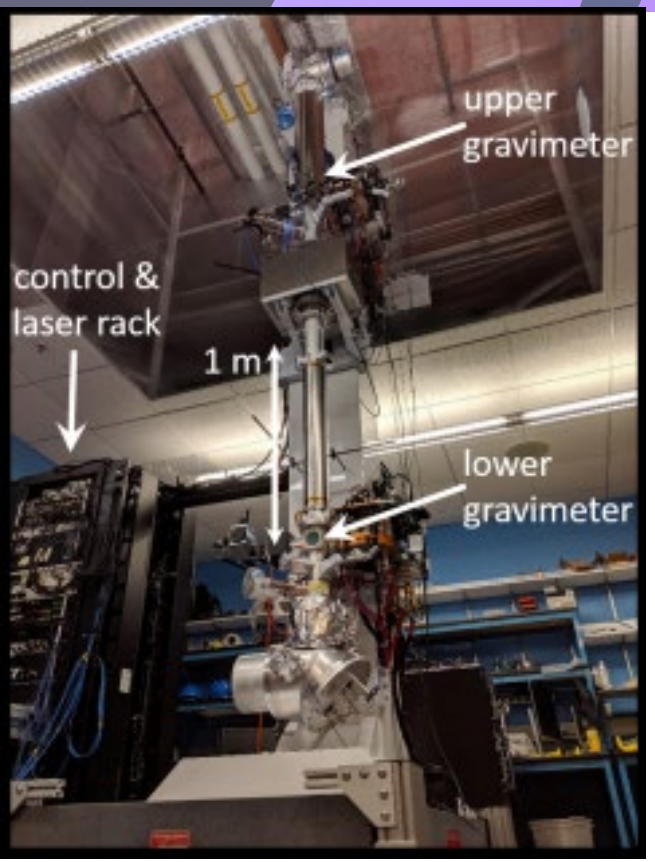
Direct Detection of Dark Energy with the Einstein Elevator (D3E3) – DLR

- Atom interferometry in the Einstein Elevator, on-going

Atomic Clock Ensemble in Space (ACES) – ESA

- Expected launch 2025

Atom Interferometer Gravity Gradiometer



Lab-based AIGG
GSFC and AOSense, Inc

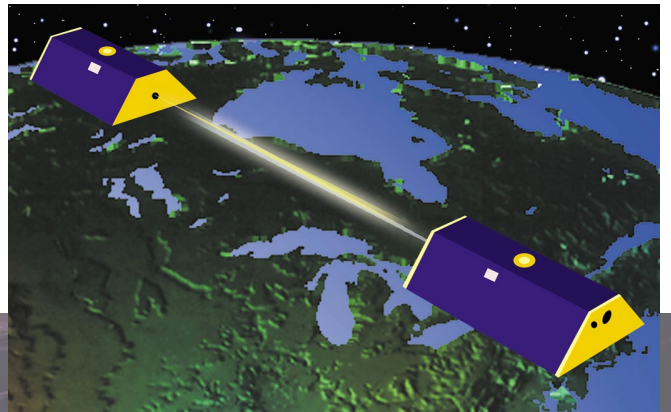
Laboratory demonstration instrument serves as a prototype to design and develop a space flight instrument

- High-performance, single-tensor-component gravity gradiometer
- Light-pulse atom interferometry using cold atoms
- Implements recent developments in atom cooling, interferometry, and detection technologies
- Fully assembled and is currently being tuned and optimized to produce laboratory observations of the gravity gradient in the terrestrial environment
- Ultra-cold atom clouds have been generated for two gravimeters and has achieved the first gravity gradiometer signals from two gravimeters
- Funded by ESTO's Instrument Incubator Program

Conceptual flight design (full sensitivity 10 µE instrument)

- 3.4 m lab-instrument repackaging possible; 2.2 m with redesign
- Factor of 7 improvement over GRACE from a single satellite that is on the same order in size, mass and power as the two GRACE satellites combined

Gravity Recovery and Climate Experiment (GRACE) uses two spacecraft to accurately map variations in Earth's gravity field

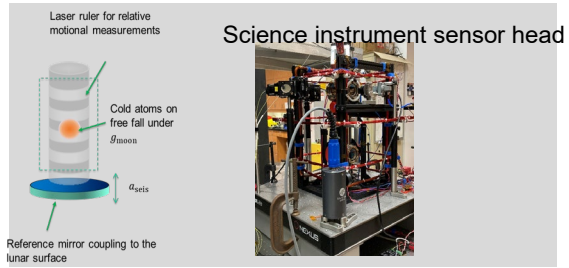


Quantum Sensing for Planetary Science

Atomic Lunar Seismometer

- Low measurement frequency (<10 mHz) cold atom interferometer to probe interior and structure by measuring seismic waves and long-period global normal modes and gravity measurements

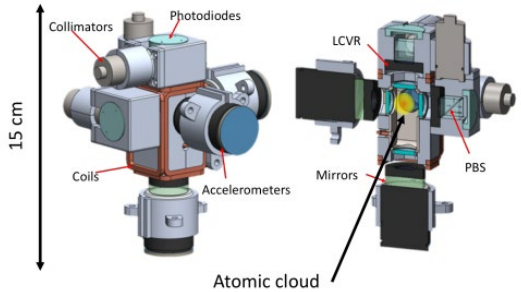
PI: Nan Yu/Jet Propulsion Laboratory



Atomic Drag-Free Accelerometer

- Compact 3-axis cold atom interferometer sensor for gravity measurements and/or non-gravitational force measurements on spacecraft
- Target sensitivity < 3x10^{-8} m/s^2/$\sqrt{Hz}$ at frequency <1 Hz

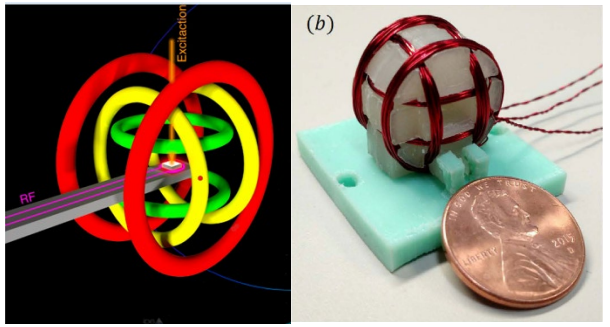
PI: Nan Yu/Jet Propulsion Laboratory



Optically Pumped Solid State Quantum Magnetometer

- 3-axis vector measurement using single color-center sensor with capability for self-calibration through atomic constants.
- Target sensitivity 10's $pT/\sqrt{Hz}$

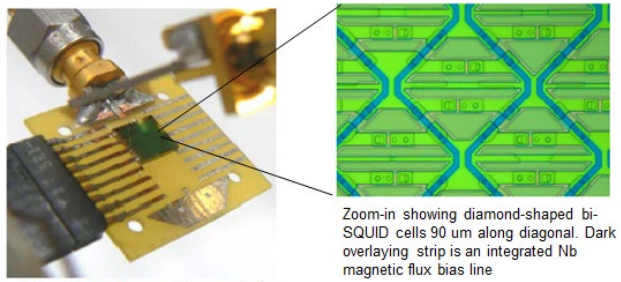
PI: Hanes Kraus JPL Co-Is: David Spry/GRC et al.



Hybrid Radio Frequency (RF) and Magneto-Inductive (MI) Transceiver for Europa Sub-Ice Communications

- Design and prototype an MI communications systems based on a superconducting quantum interference device (SQUID) and chip-scale atomic magnetometer (CSAM) for MI-to-RF bridge link

PI: Michael Cheng/JPL Co-I: Brian Vyhnalek/GRC



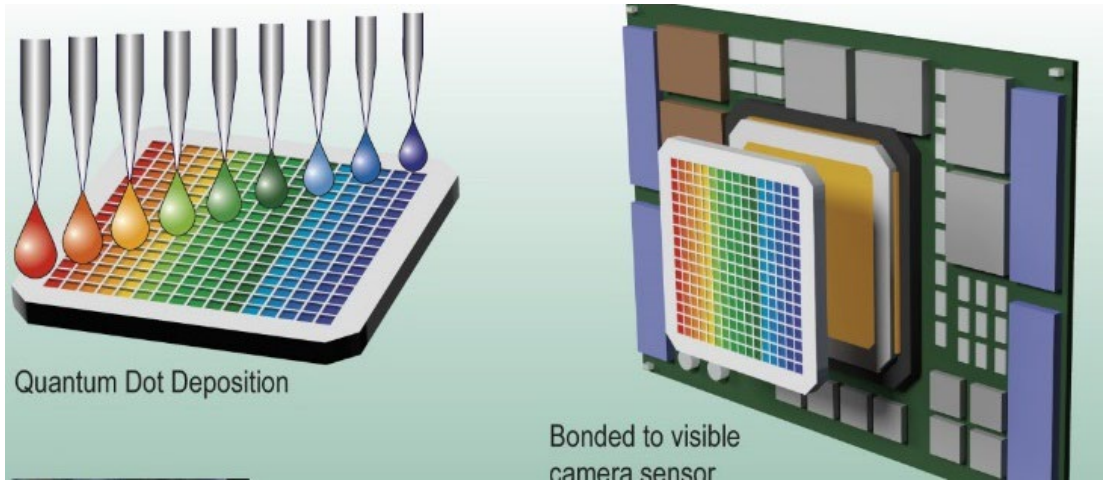
5x5 mm^2 SQUID array chip mounted on sample PCB with RF and dc connectors.

Zoom-in showing diamond-shaped bi-SQUID cells 90 um along diagonal. Dark overlaying strip is an integrated Nb magnetic flux bias line

Quantum Sensing for Heliophysics

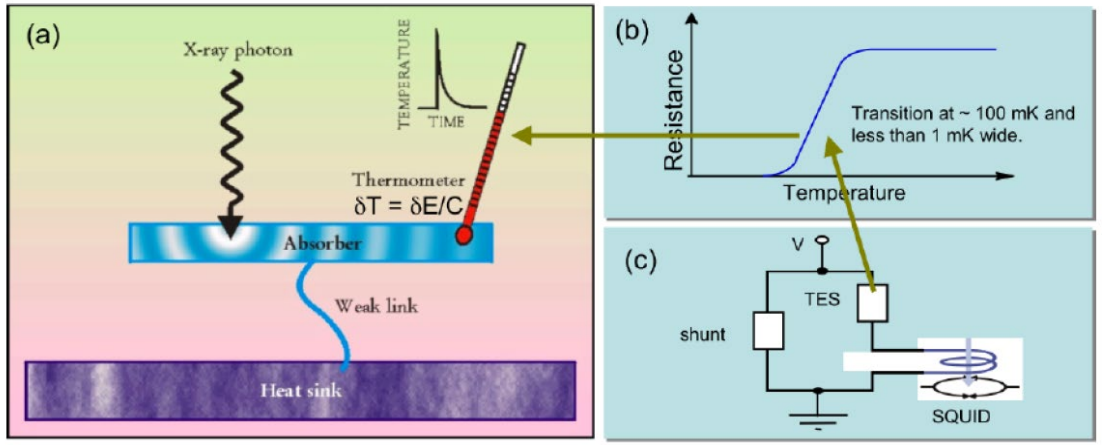
Quantum Dot Spectrometer for auroral emission

Quantum dot spectrometers eliminates the need for optical elements such as gratings and prisms significantly reducing cost and volume and enabling constellations of smallsats.
PI: Mahmooda Sultana/GSFC



Transition Edge Sensors (TES) for Solar science

Understanding the dynamics of hot plasmas in the solar corona is key to understanding the heating mechanisms of the solar corona and the origin of super-heated plasmas on the Sun. X-rays provide access to higher temperatures than EUV
Quantum microcalorimeter sensitive to individual soft x-ray photons which provide 100x better energy resolution than traditional "classical" detectors. Arrays of sensors provide imaging spectroscopy to constrain the dynamics of heating events.
PI: Simon Bandler/GSFC

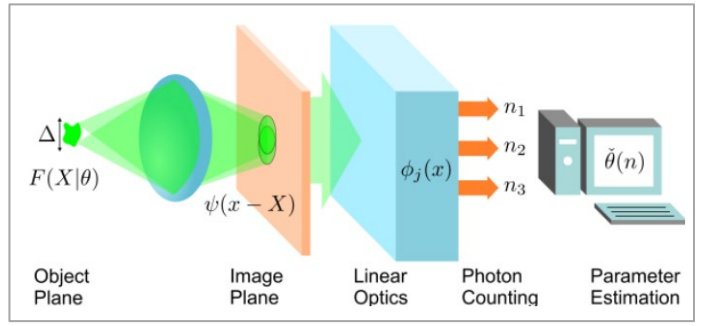


Quantum Sensing, Imaging, and Algorithms for Astrophysics

Super-resolution Detection

Spatial- mode demultiplexing (SPADE) or pre-detection mode sorting for sub-Rayleigh resolution

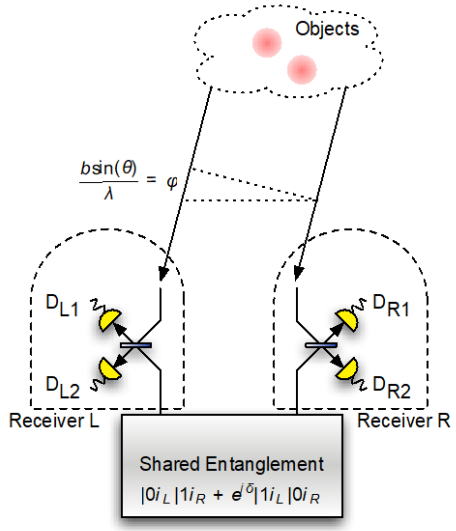
Optica, Vol.6(5), pp.534-541; 2019-05-20



Quantum Networked Telescopes

Quantum entanglement-assisted telescope array enabling very long-baseline optical imaging (ultra high resolution)

E. T. Khabiboulline, et. al. Phys. Rev. A 100, 022316



Quantum State Discrimination

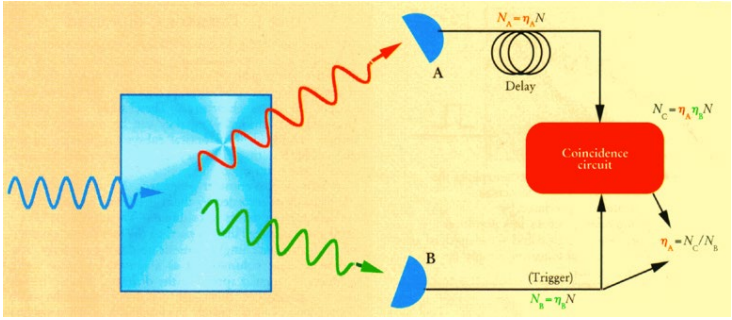
Quantum Hypothesis Testing for Exoplanet Detection

Z. Huang and C. Lupo, Phys. Rev. Lett. 127, 130502; 2021-09-23

Correlated-Photon Metrology for Photo-Detector Absolute Calibrations

Absolute calibration of a charge-coupled device camera with twin beams

A. Meda, et al. 2014, Appl. Phys. Lett. 105, 10113

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