National Aeronautics and Space Administration

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Quantum Technology for Earth Science

Robert Connerton
Technology Development Manager, ESTO

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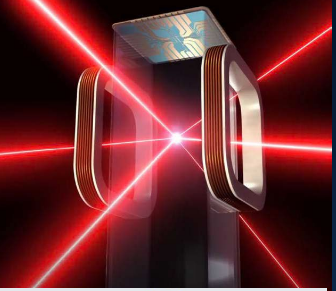
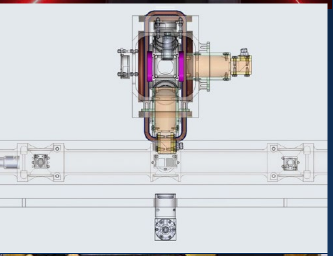
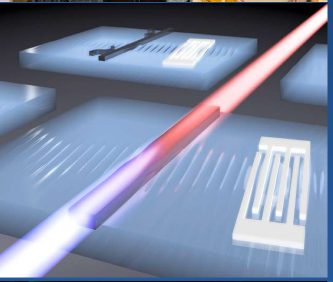
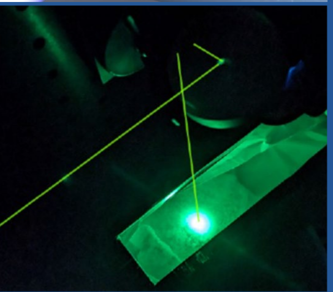



Quantum Sensing Investments

ESTO has made numerous investments in quantum sensing instruments, components, and design studies, normally through the Instrument Incubator Program (IIP) and the Advanced Component Technology (ACT) program. A few selected, active projects are as follows:

Quantum Atomic Rydberg Radiometer for Earth Measurements (QuARREM) – Eric Bottomley, Infleqtion
A novel vapor cell for eliciting and controlling Rydberg atoms, which is essential for developing new radar instruments.

DECALS: Development of a Cold Atom Laser System – Matthew Cashen, Vector Atomic
Rubidium-based cold atom laser system that leverages robust telecom components to support rapid, low-cost deployment of atomic sensors in space.

QGGPf: Quantum Gravity Gradiometer Pathfinder – Sheng-wey Chiow, NASA’s Jet Propulsion Laboratory
Demonstrate critical technologies and observation technique for a QGG, using an architecture that could lead to a science-grade instrument

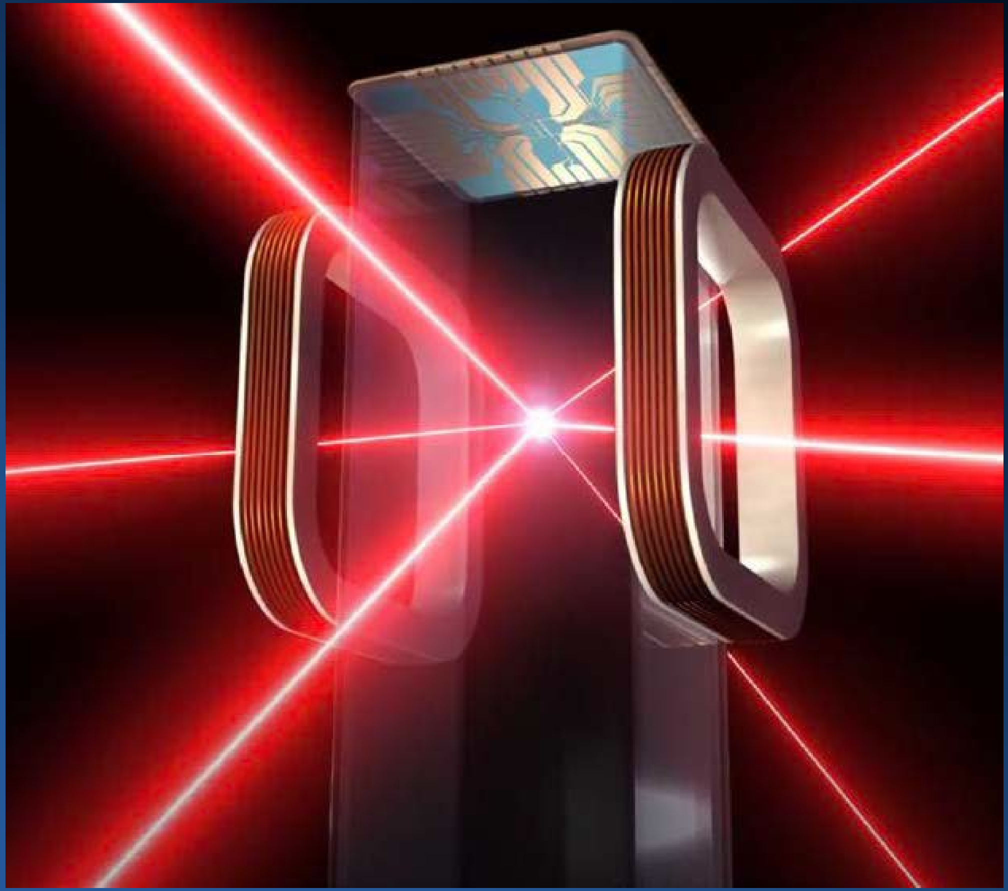
Low-power Integrated Acousto-Optics for Atomic Quantum Sensors – Peter Rakich, Yale University
Acousto-optical subsystems for manipulating atomic states, an essential milestone for developing space-based atom interferometers.

Low SWaP-C Modular Laser Architecture for Quantum Sensors and Atomic Clocks – Kurt Vogel, Vescent Photonics
A compact laser system for space-based, light-pulse atom interferometry, a key subsystem for space-based QGGs

Rydberg Radar – Darmindra Arumugam, NASA’s Jet Propulsion Laboratory
Instrument concepts for CubeSat-based Rydberg Radar instruments, which could dramatically improve researchers’ ability to measure targets like snow, vegetation, and ocean winds.

Quantum Parametric Mode Sorting (QPMS) Lidar – Carl Weimer, BAE Systems
New lidar technique that leverages quantum frequency conversion to minimize background noise.

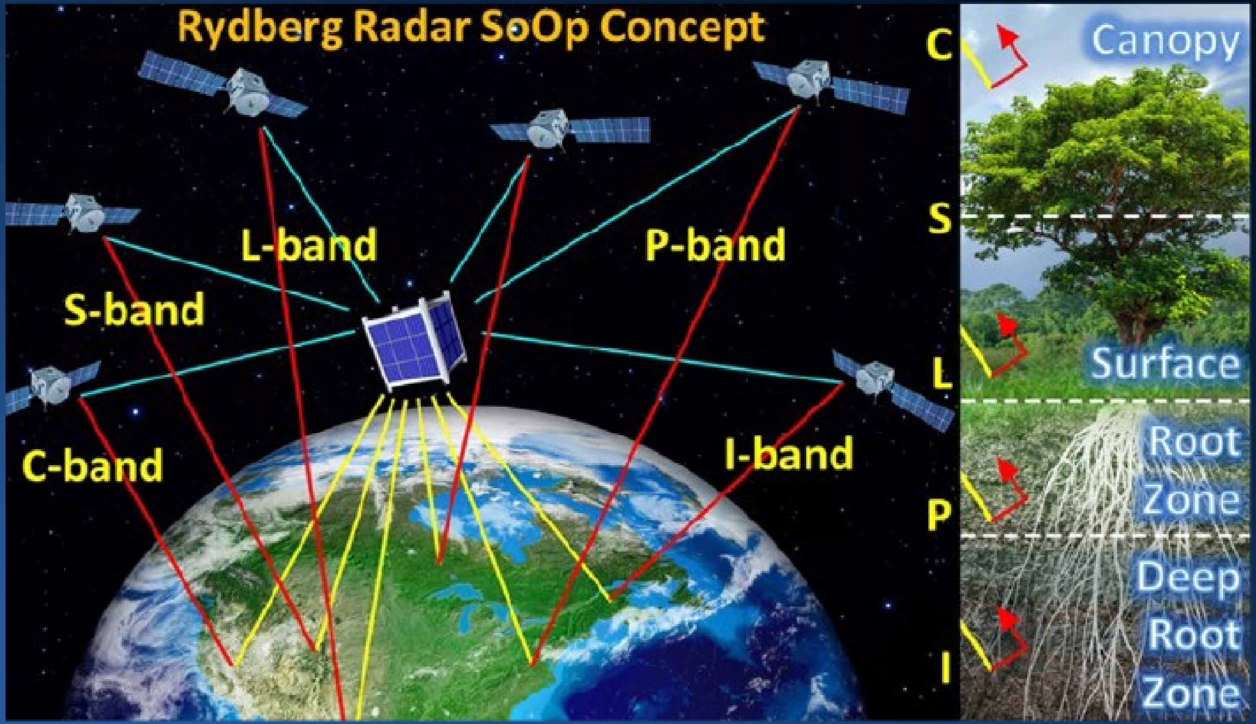
QuARREM: Quantum Atomic Rydberg Radiometer for Earth Measurements



- QuARREM will advance an innovative hyperspectral microwave radiometer concept that utilizes quantum phenomena
- Potential to achieve state-of-art high sensitivity, low-noise, ultra-broadband coverage with no need for RF front-end/mixers, for a vast improvement in size and sensitivity-to-bandwidth (4-40x) over classical microwave radiometer systems
- In this approach, the excited states of Rydberg atoms act as a sensitive detector replacing microwave amplifiers
- Use case: atmospheric temperature and humidity profiles needed for improved Planetary Boundary Layer measurements

PI: Eric Bottomley, Infleqtion

Rydberg Radar: A quantum architecture for multi-science signal of opportunity remote sensing

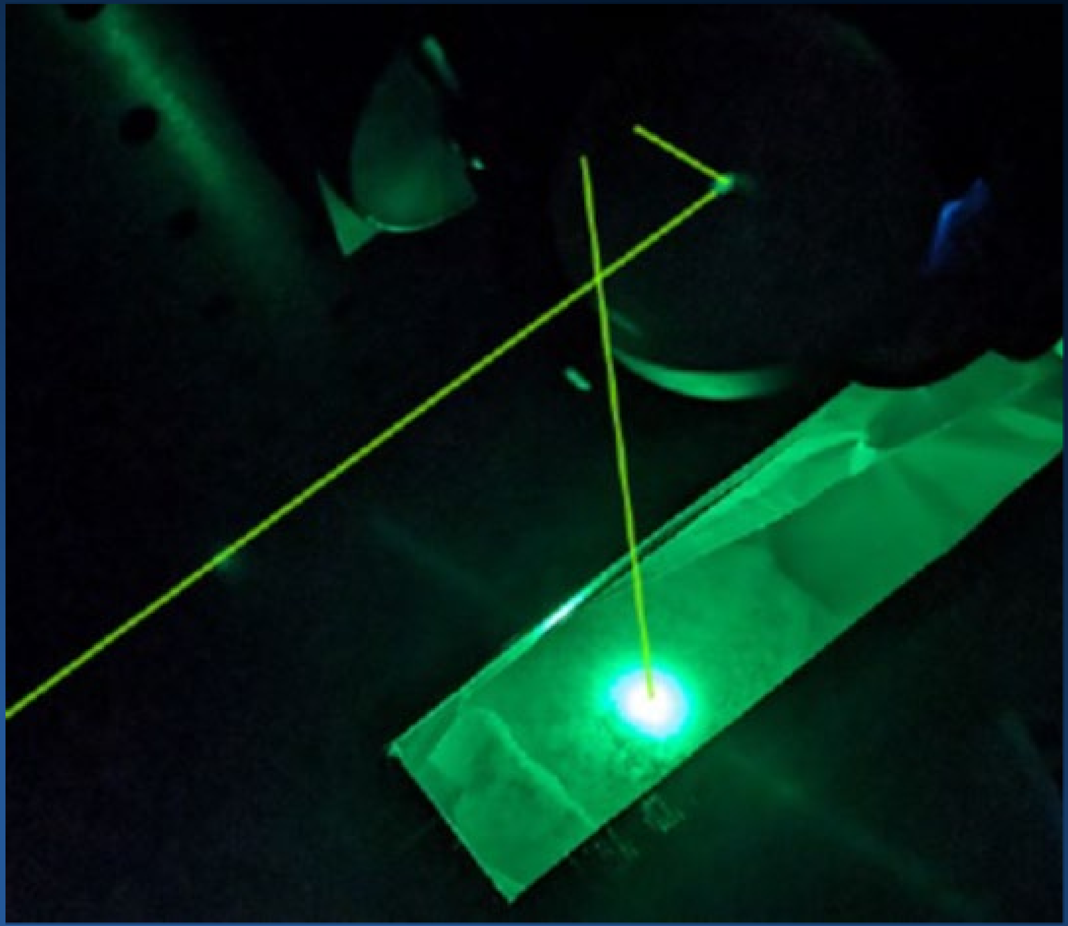


Mission concept of Rydberg Radar in view of multiple SoOp navigation and communication satellites

- This radar instrument concept will use quantum Rydberg atomic receiver technology to achieve state-of-the-art sensitivity, low-noise, and ultra-broadband capabilities on a single compact detector
- With no antenna or RF front-end, a Rydberg radar would be lighter and more powerful than traditional instruments, and could be dynamically tuned to frequency bands from 10 kHz-1 THz
- While a CubeSat-ready Rydberg Radar would be beneficial to numerous Earth system studies, it will be especially useful as part of a coordinated, multi-satellite signal of opportunity (SoOp) system dedicated to addressing dynamics and transients in land surface hydrology

PI: Darmindra Arumugam, JPL

QPMS: Quantum Parametric Mode Sorting Lidar



- This project is a concept study to determine whether the Quantum Parametric Mode Sorting (QPMS) lidar technique could observe Earth systems like snow and inland/nearshore water from SmallSats in low Earth orbit

- QPMS technique could offer reduced interference caused by solar background light and cloud cover, increasing the accuracy of gathered lidar data

- While the QPMS lidar technique has already been explored within the 1550 nm telecom band, this effort aims to demonstrate its utility for observing targets in the visible wavelength where water and snow are transmissive

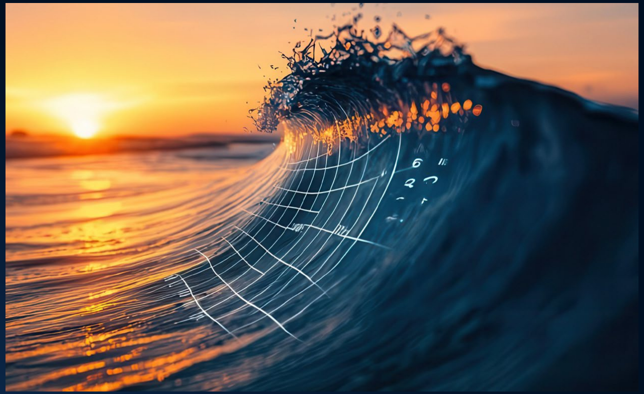
PI: Carl Weimer, BAE Systems

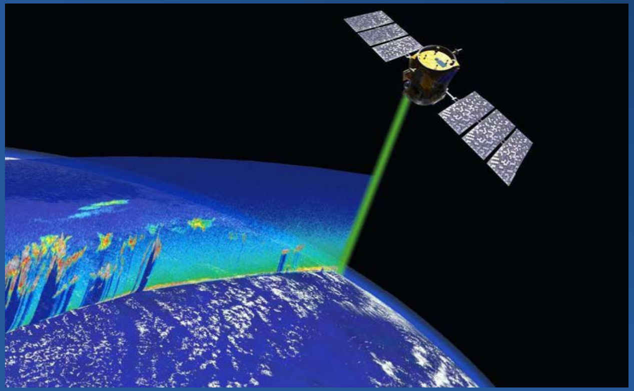
Quantum Computing Investments

ESTO also makes investments that seek to realize the full potential of quantum computing – developing efficient quantum algorithms and building scalable, fault-tolerant systems to handle vast troves of Earth and space science data. Examples include:

Stochastic Parameterization of an Atmospheric Model via Quantum Annealing
– Alex Guillaume, NASA Jet Propulsion Laboratory
Leverages quantum annealing via D-Wave to implement a Restricted Boltzmann Machine (RBM) for analyzing cloud data.

Physics-Aware Quantum Neural Network Modeling
– Eleanor Rieffel, NASA Ames Research Center
New methods for solving complex partial differential equations using classical and quantum machine learning.





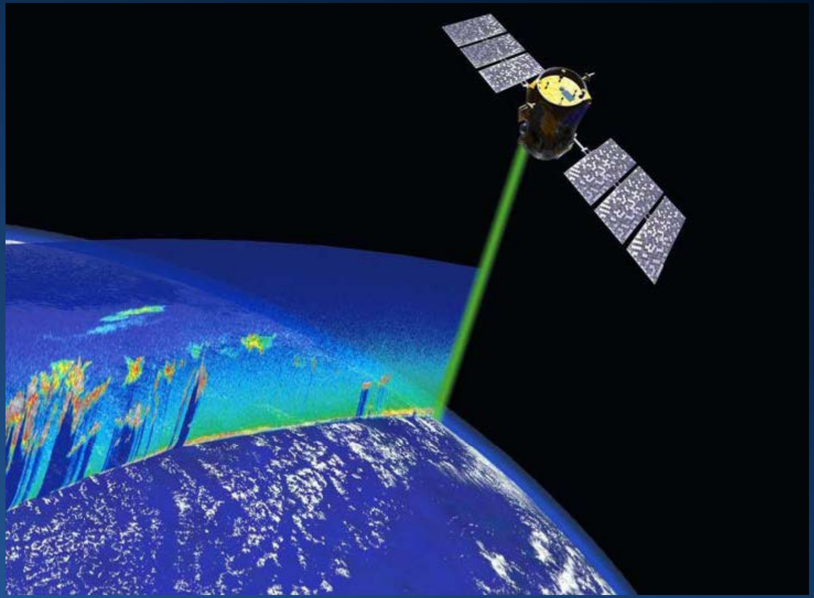
An Innovative Sunlight Denoising Technique To Improve Future Spaceborne Lidar
– Yongxiang Hu, NASA Langley Research Center
A quantum computing technique to mitigate the effects of sunlight noise in spaceborne lidar data analysis.

Stochastic Parameterization of an Atmospheric Model via Quantum Annealing

- Developing a quantum computing framework for improving our ability to model cloud physics, especially within the planetary boundary layer.
- Could enable the full characterization of an atmospheric stochastic parameterization using remote sensing data (until now, too computationally expensive).
- Allow researchers to retrieve the parameters of the local lattice describing stratocumulus clouds and its relationship to large-scale moisture evolution.
- Rare example of a problem that can be solved using quantum technology as it exists today.

PI: Alex Guillaume , JPL

Sunlight Denoising for Spaceborne Lidar



- This project aims to develop an innovative quantum computing technique to mitigate the effects of sunlight noise in spaceborne lidar data analysis.
- While lidar systems excel at capturing high-quality measurements at night, their effectiveness during the day is hindered by solar interference.
- This research will investigate three distinct quantum approaches to subtract sunlight noise from lidar images by solving constrained minimization problems using the state-of-the-art Dirac-3 quantum computer.
- The performance of these quantum methods will be evaluated against classical computing techniques in terms of both noise reduction efficacy and computational efficiency.

PI: Yongxiang Hu, NASA LaRC

For more information please visit www.esto.nasa.gov

Latest news Articles:

ESTO supports critical investments in quantum sensing

ESTO's quantum technology portfolio empowers universities and private companies to create novel quantum sensors, which are essential assets for superior science missions and national security.

Physics-Aware Quantum Neural Network Modeling

- Focused on ocean dynamics as a test case, this project aims to develop innovative methods for solving complex partial differential equations (PDEs) using classical and quantum machine learning.

- By harnessing quantum computing's potential for efficient PDE solutions, this research will compare quantum and classical learning-based approaches, integrating PDE structures into neural networks to enhance trainability and accuracy.

- The project will demonstrate feasibility while providing a framework extensible to a wide range of interconnected Earth system models.

PI: Eleanor Rieffel, NASA ARC

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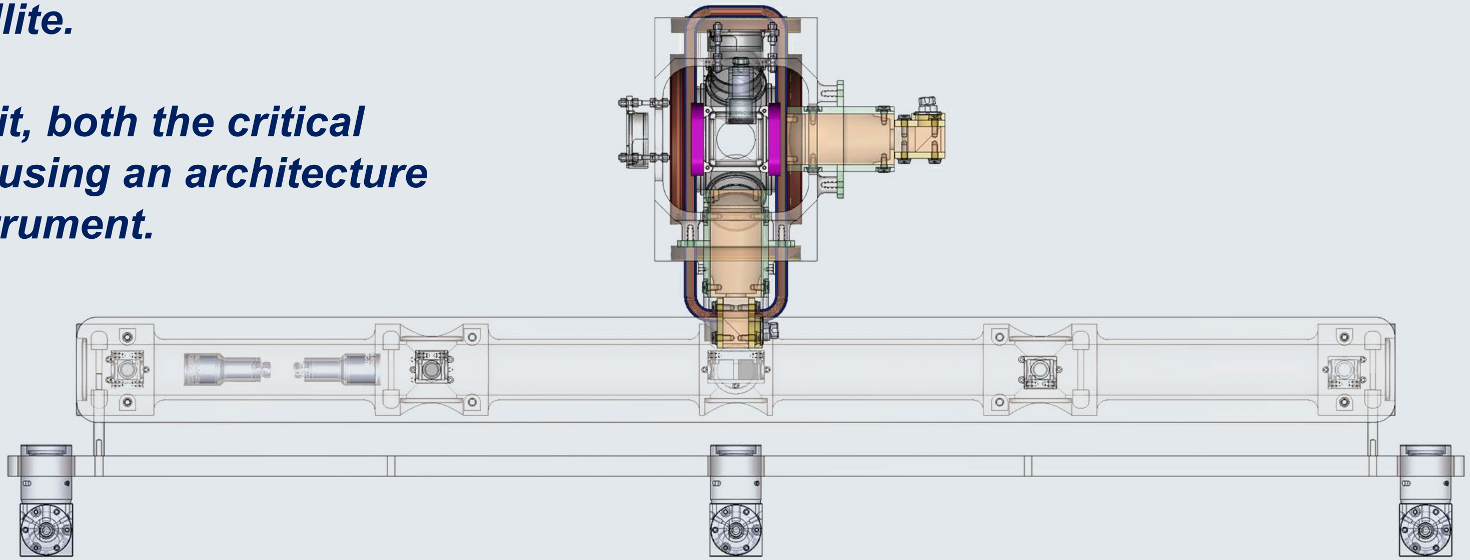
Toward a Quantum Gravity Gradiometer

As a future capability, quantum technology has the potential to be revolutionary in advancing the accuracy and precision of Earth science measurements, such as aquifers, ice sheets, geodesy, and ocean levels and currents. Technology investments in quantum also serve the national goal to establish U.S. leadership in this field.

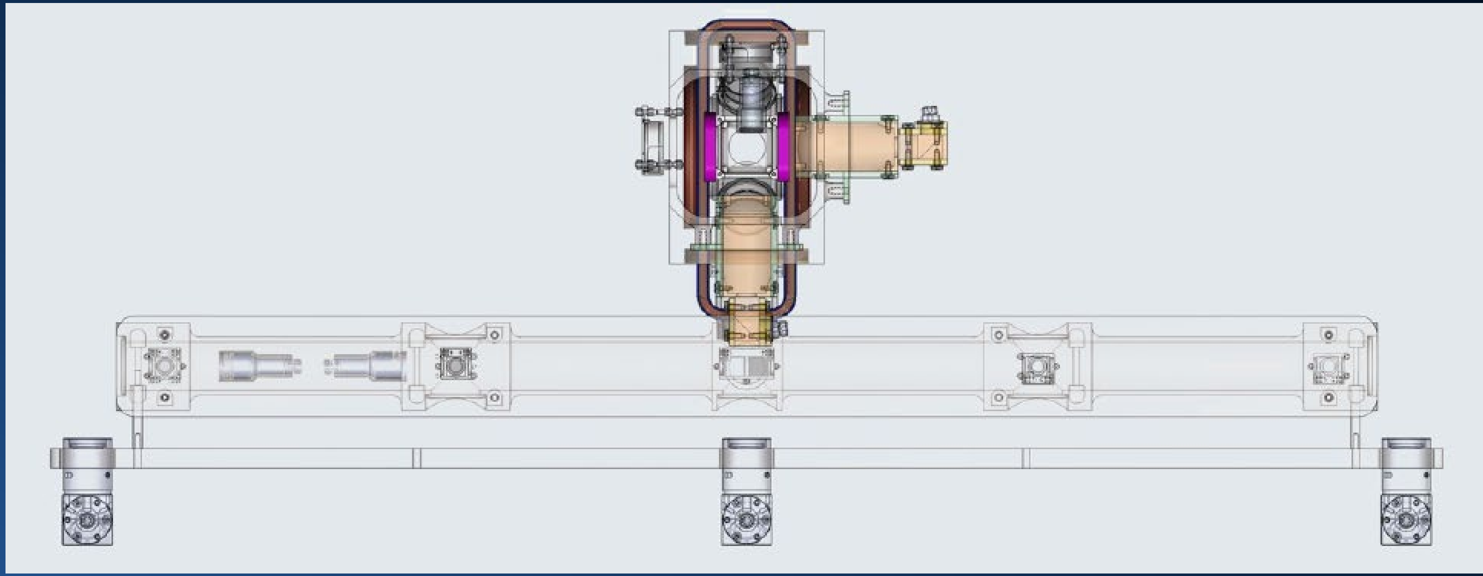
A QGG has the potential to collect more precise measurements of Earth's gravitational field than existing methods – such as the Satellite-to-Satellite Tracking (SST) utilized by NASA's GRACE-FO mission – and could do so from a single satellite.

The QGG Pathfinder will demonstrate, on orbit, both the critical technologies and the observation technique, using an architecture that could be scalable to a science-grade instrument.



Single source design of the pathfinder payload based on a Rubidium source. (Credit: NASA JPL)

QGGPf: Quantum Gravity Gradiometer Pathfinder



QGGPf is a critical first step for developing a science-grade quantum sensor for recovering geophysical features of a planet's surface in high resolution, globally.

- The Quantum Gravity Gradiometer Pathfinder (QGGPf) Project will use atom interferometry – a single sensor using laser-cooled atoms as proof-masses – to measure nuances in Earth's gravitational field with unprecedented accuracy.

- Objectives include long-interrogation time atom interferometry and validating a novel laser optical system, as well as testing control algorithms and electronics.

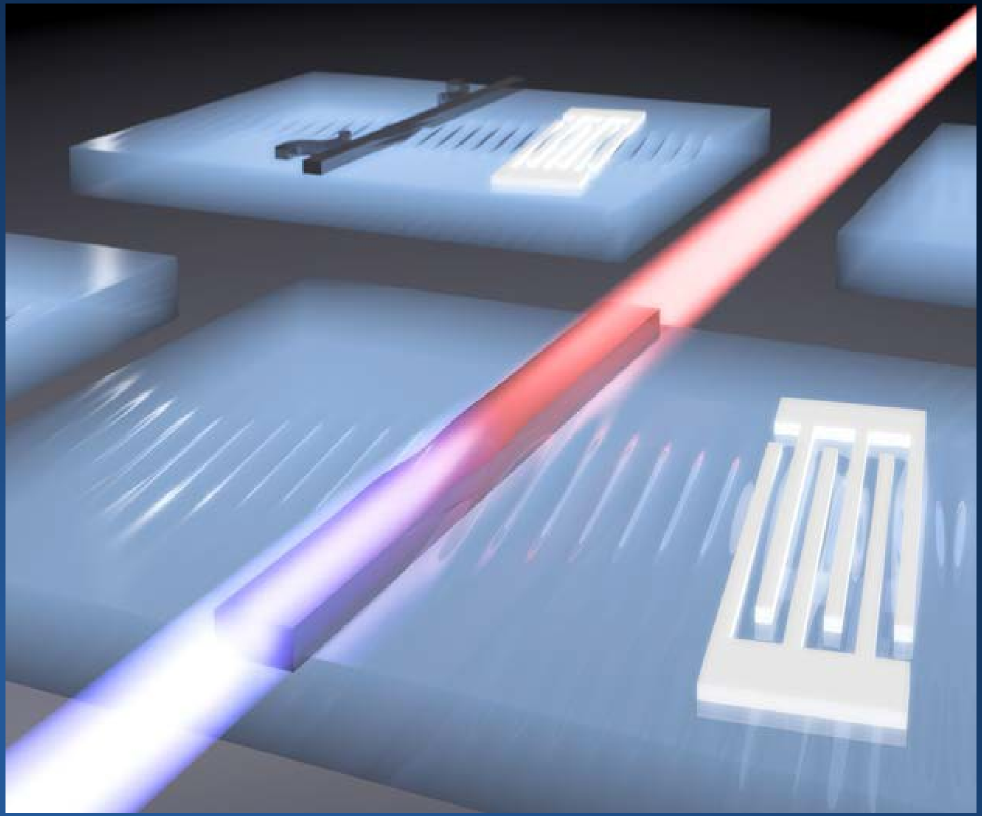
PI: Sheng-wey Chiow, JPL
(JPL serves as the project lead, with significant contributions from NASA GSFC, University of Texas Austin, and U.S. industry partners)

DECALS: Development of a Cold Atom Laser System

- DeCALS is a robust, space-compatible laser system that will enable a space-based Quantum Gravity Gradiometer (QGG) that can measure Earth's gravitational field at high resolution globally.
- This 780 nm, rubidium-based cold atom laser system will leverage robust telecom components to support a rapid and low-cost route to deploying atomic sensors in space, enabling pathfinder missions and future ultra-high-performance devices.

PI: Matthew Cashen, Vector Atomic

Low-power Integrated Acousto-Optics for Atomic Quantum Sensors



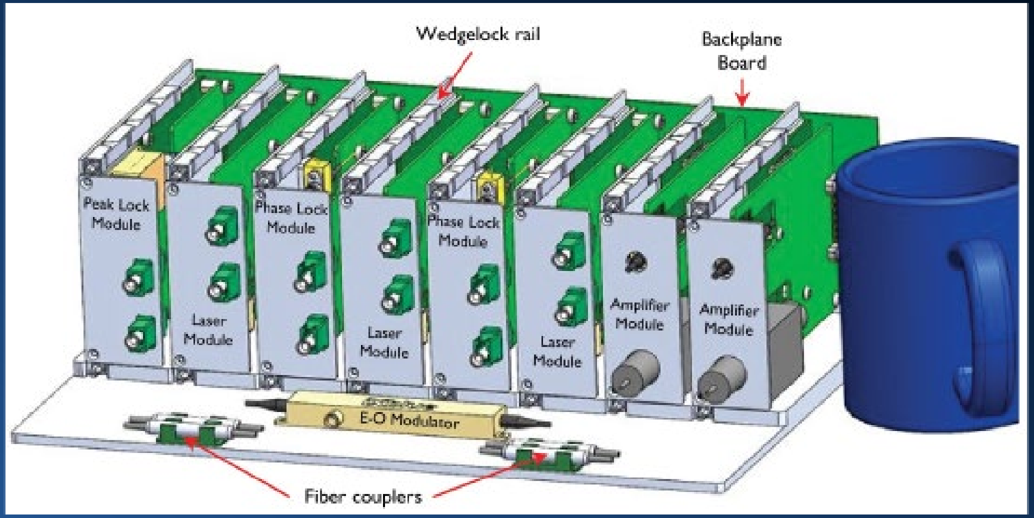
- This project will develop an integrated photonic acousto-optic modulator (AOM) that will lower power requirements from satellite-based quantum sensors from ~300 W to < 50 W.

- AOMs are a key component technology for spaceborne cold-atom quantum sensors, such as atom interferometer gravity gradiometers or Rydberg-atom radars.

- Currently, there is no compact integrated alternative to free-space acousto-optic frequency shifters, which are used to precisely control laser spectra for atom manipulation.

PI: Peter Rakich, Yale University

Modular Laser Architecture for Laser-Cooled Quantum Sensors and Atomic Clocks



Notional CAD model of the proposed modular laser system that will generate the requisite frequency-agile light for a Cs-based atom interferometer. (Optical fiber interconnects between the modules are not modeled.) The coffee cup illustrates the small scale of the proposed system (30 cm x 22 cm x 10 cm).

- This project will develop a high-performance laser system with low size, weight, power, and cost for cesium-based atom interferometry used in quantum remote sensing.
- Currently, spaceborne quantum gravity gradiometry (QGG) is limited by the lack of suitable frequency-stabilized lasers that can withstand the rigors of space flight while meeting the high-performance requirements for light-pulse atom interferometry (LPAI).
- This laser system will be able to support a wide variety of cold-atom-based quantum sensors and atomic clocks.

PI: Kurt Vogel, Vescent Photonics