Report for NSF Workshop on Quantum Information Science for the Geosciences

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Stony Brook University
June 2026

Quantum Information Science for the Geosciences

- NSF Workshop Summary, Stony Brook University • May 6–7, 2026
- Workshop Purpose
  - Convened experts from academia, national laboratories, industry, NASA, NSF, DOE, NOAA, and other federal agencies.
  - Examined how Quantum Information Science (QIS) can address major geoscience challenges.
- Focused on two technology areas:
  - Quantum Computing
  - Quantum Sensing
- Key Message
  - **Quantum technologies should augment—not replace—classical computing and observational systems, becoming specialized capabilities within hybrid scientific workflows**

Scientific Opportunities

- **Quantum Computing**
  - Earth system modeling, Uncertainty quantification, Optimization, Data assimilation, Inverse problems, Quantum chemistry, Machine learning, PDE solvers (long-term)
- **Quantum Sensing**
  - Gravity gradiometry, Atmospheric trace gas sensing, Quantum lidar, Quantum radar, Magnetometry, Atomic clocks, entangled observation
- **Near-Term Opportunity**
  - Participants agreed that **quantum sensing is significantly closer to operational deployment than fault-tolerant quantum computing**

Strategic Findings

1. **Hybrid Quantum-Classical Systems**
    - Quantum processors integrated with HPC
    - Quantum sensors integrated with existing observing systems
2. **Develop community benchmarks to evaluate:**
    - Scientific benefit, Accuracy, Uncertainty reduction, Cost-performance
3. **Validation Infrastructure need for:**
    - Testbeds, Field demonstrations, Calibration standards, Side-by-side comparison with classical instruments
4. **Strong collaboration** is essential for technology maturation and transition among:
    - Universities, National Laboratories, NASA, NSF, DOE, Industry

Workforce & Infrastructure Priorities

Develop a new generation of **"bilingual" researchers** who understand both:

  - Quantum Information Science
  - Geoscience applications

- **Recommended Activities**
  - Short courses, Summer schools, Graduate fellowships, Quantum playgrounds, Cloud-based quantum computing, Industry internships
- **Infrastructure Priorities**
  - Near-term
    - Benchmark datasets, Tutorials, Pilot projects
  - Mid-term
    - Hybrid HPC–QPU environments, Sensor testbeds, Validation campaigns
  - Long-term
    - National centers, Distributed sensing networks, Fault-tolerant quantum computing, Quantum communications infrastructure

Recommendations & Path Forward

- **Open competitive programs**
  - Quantum algorithms addressing geoscience challenges
  - Quantum sensor development
  - Cross-disciplinary collaborations
- **Establish shared national infrastructure**
  - Quantum computing access, Cloud resources , Benchmark repositories, Validation facilities, Shared testbeds
- **Build a coordinated national ecosystem to integrate**
  - Research, Technology development, Workforce, Infrastructure, Partnerships
- **Overall Conclusion**
  - Quantum Information Science represents a **long-term strategic opportunity** for geoscience. The greatest impact will come from **hybrid quantum-classical systems**, supported by sustained investments in **benchmarking, workforce development, shared infrastructure, and interdisciplinary collaboration coordinated with other government investments**

Quantum Advantage to Weather and Climate Sciences

Jason Hyon
Director, Quantum Space Innovation Center
Jet Propulsion Laboratory

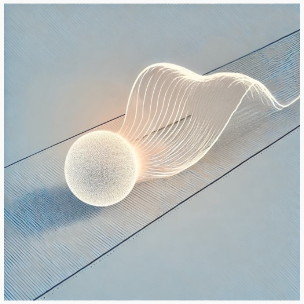
Quantum 101: What is Quantum?

Quantum physics is the science of small objects, such as atoms, molecules and subatomic particles.

The ability to isolate, manipulate and design quantum systems has brought quantum phenomena into the realm of engineering. The invention and availability of high power, high stability lasers have enabled the trapping of single atoms and cooling them down so that their quantum nature is preserved over long times.

Quantum systems exhibit non-classical behavior such as the **wave-like interference** of particles, the **superposition of individual systems** into different states, the **probabilistic nature of measurement**, and **entanglement**. Thus, we want to use these behavior to achieve disruptive measurement approaches.

When objects are cooled down these quantum effects dominate. ***By slowing atoms down in a vacuum chamber, we can engineer a system that exhibits quantum dominated effects.***



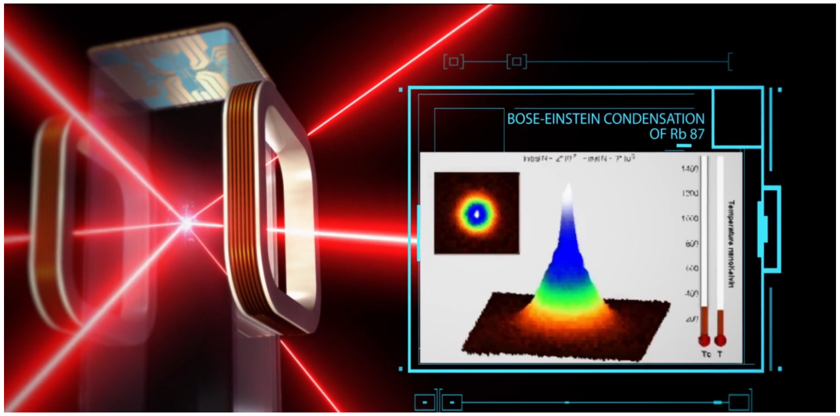
Quantum objects propagate as waves, but can act like particles, with a localized position, when you detect them

Quantum 101: What is a Quantum Sensor?

A quantum sensor takes advantage of this sensitivity by **utilizing quantum phenomena such as superposition or entanglement to measure a physical quantity,** such as acceleration, rotation and gravity with extraordinary precision.

Quantum atomic sensors are also **inherently stable** because the measurement depends on the **fundamental behavior of an atom,** unlike classical sensors that require calibration**.** Quantum sensors based on atoms can also be **orders of magnitude smaller** than classical systems because a **millimeter sized atom cloud can effectively be billions of "sensors."**

Quantum sensors hold great promise for space-based applications such as **gravity sensing, microwave sensing, navigation and time keeping**



Artist's concept of the heart of the Cold Atom Lab (CAL), which has demonstrated a variety of quantum sensors in space.
Inset: image of formation of Bose-Einstein Condensate of Rb

Why Space?

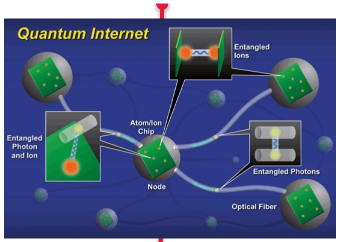
- **Space** can provide intercontinental quantum communications that is not possible with fiber optics linking quantum computers for exponential computation gain and enabling secure encrypted communications.
- In the **space environment** quantum metrology can perform with far greater precision over terrestrial settings.
- **Space** provides the long-baseline networks for far-distributed quantum sensing.

Little Deeper On Quantum Capabilities

Quantum Sensing Systems

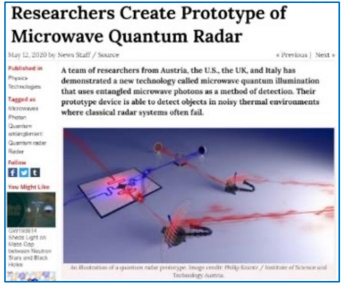
Quantum Computer- Not (yet) a Sensor

Future sensing technologies?



Space quantum communications

Quantum Optics→



Researchers Create Prototype of Microwave Quantum Radar

May 12, 2020 by News Staff / Source « Previous | Next »

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Physics
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Tagged as
Microwaves
Photon
Quantum entanglement
Quantum radar
Radar

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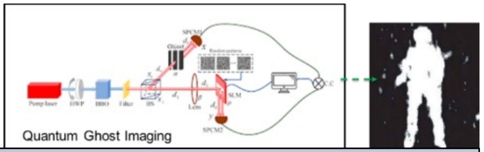
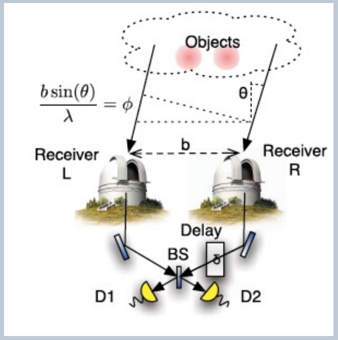
You Might Like

A team of researchers from Austria, the U.S., the UK, and Italy has demonstrated a new technology called microwave quantum illumination that uses entangled microwave photons as a method of detection. Their prototype device is able to detect objects in noisy thermal environments where classical radar systems often fail.

Photon Counting LIDAR



Quantum Ghost Imaging



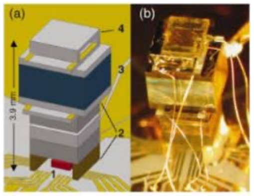
Quantum VLBI→

←Quantum Matter

Classical Matter→

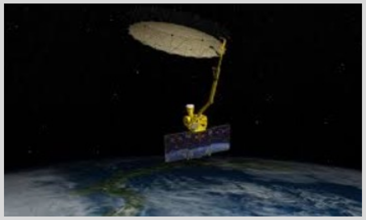
←Classical Optics

JPL Atomic Gravity Gradiometer



Chip-scale atomic magnetometer
tf.nist.gov

Atomic electrometers, gyroscopes, clocks, etc.



GOCE

Overview of Quantum Sensing Technologies

- **Beat the standard quantum limit** for useful measurements using squeezing, interference, or entanglement
  - **Squeezing:** LIGO *squeezed light* source for GW detection
  - **Interference:** *Atomic gravity gradiometry* for subsurface mapping
  - **Entanglement:** *Quantum optical VLBI* for imaging exoplanets
- Discover new **metrics for quantum advantages** in communication, computation, and measurement.
  - Determine how much information can be encoded in a **single photon**. – **Example:** 14 bit/photon demonstration
  - Push forward **tests of physical laws** using prototype quantum technology – **Proposal:** Direct probe of Dark Energy

QS uses quantum mechanical properties of light and/or matter to improve sensing capabilities

Mapping: Quantum Technologies to address Grand Challenges

The group then identified which of the selected *quantum sensing technologies* could be used to address which *measurement Grand Challenges*, and the maturity of applying the technology to that measurement challenge.

Annotation from session

	Quantum Sensing Technologies	Atom Interferometer	Atomic nuclear spin gyroscope	Atomic electric field sensor	Atomic clock	Atomic magnetometer	Squeezed laser interferometer	Quantum ghost imaging	Quantum radiometery calibrations	Single photon sourcing	Quantum radar	Quantum synchronization	Quantum network sensors	Collective entangled sensors	Single Photon Detection	Quantum Transducer
	Technology ID	1,2,3	4			7	8	9	10	11	12	13	14	15	16	17
	Technology Maturity Level	L	C			C	C	L	C	T	T	T	T			
Community	**Grand Challenge**															
Planetary	Lunar Volatiles			T												
	Life Detection														T	
	Seismology	D					T									
Astrophysics	Dark Matter Detector				T											
	Dark Energy Detector															
	Gravitational Wave Detector				D		M				M					
	Far IR Detection															D
	CMB Measurements								T							T
Earth	Ecosystem Structures				D						T					T
	Sea Level Rise	D	D		D						T					T
Telecom	Delay Tolerant Networks				D											
	Spectral Crowding						T	T							D	D
	Precision Nav & Timing	D											T			
DHS	Imaging in Low Light							T	T							
	Tunnel Detection	D	D		M	D										

Detection of water in-situ

UV laser, find individual photon returns

Help with space-based grav observatory; could enable single-S/C observatory with good enough clock

Used on LIGO

Reduce transmit power

Squeeze encoding

Detecting void from surface

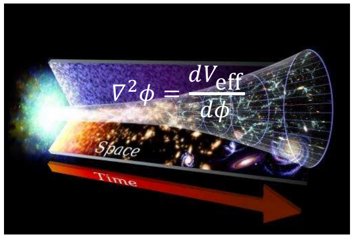
Mapping inside with drone

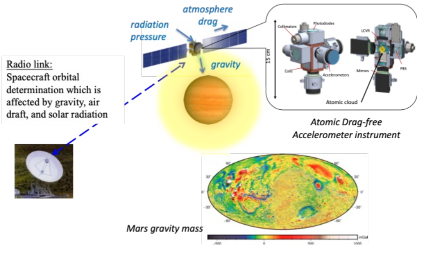
Technology Maturity Level Key
C = Commercial
L = Lab
T = Theory

Technology / Challenge mapping Maturity Key
M = Can already be used to make measurement
D = Requires development
T = Works in theory

QS-Enabled Science Mission Concept Study Summary

- Conducted trade studies to compare traditional vs quantum approaches for selected science mission concepts
  - QS for Earth Science – David Wiese, Jason Hyon, Duane Waliser
    - Mass Change by measuring gravitational change over time.
  - QS for Astrophysics – Jason Rhodes, Charles Lawrence, Margaret Frerking
    - Direct Dark Energy Detection in the Solar System
  - QS for Planetary Science – (Bruce Bills, Mark Panning, Sami Asmar)
    - Planetary gravity measurements and seismometry
- Developed Science Traceability Matrix for each mission concept
  - Science goals, science objectives, science requirements, measurement requirements, instrument requirements, and mission requirements
- Key findings:
  - QS for Earth Science - Leading to new and more capable Mass Change measurement configurations, improving 3x from GRACE-FO in short-term, potentially single spacecraft configuration in long-term.
  - QS for Astrophysics - Enable Direct Dark Energy Detection in the Solar System, constraining certain dark energy models by > 50 sigma in 1 year.
  - QS for Planetary Science - Unlock the full potential of radio tracking capability for planetary gravity studies and provide new capabilities for orbiter and terrestrial gravity survey and mapping for science and exploration.





Radio link:
Spacecraft orbital determination which is affected by gravity, air draft, and solar radiation

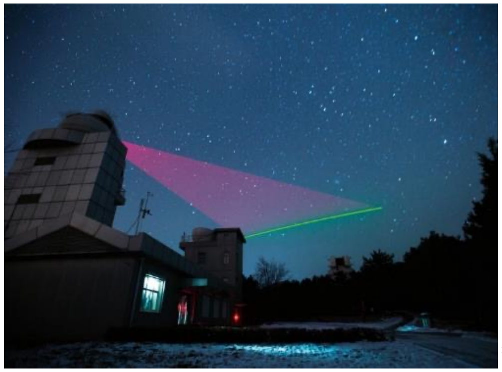
Atomic Drag-free Accelerometer instrument

Mars gravity mass

Investments and WF for Quantum

Quantum Investment

- September 2017, China demonstrated secured Quantum Key Distribution (QKD) using the Chinese Micius Satellite
  - “A Twenty-First-Century Sputnik” event*
- September 2018, The White House published “National Strategic Overview for Quantum Information Science”***
  - Science-first approach to identify and solve Grand Challenges.
  - Provide key infrastructure for scientific and technological opportunities
  - Maintain national security and develop international collaboration
- December 2018, Congress passed the National Quantum Initiative (NQI) Act
  - Ten-years plan with $1.25B over the first 5 years
- The proposed $100B Endless Frontier Act with strong bipartisan support
  - Quantum Computing and Information Science is identified as one of the technology areas with global strategic significance
- President’s FY2021 budget request proposed to double the R&D budget for Quantum Information Science (QIS) to $860M by 2022
- NQI Reauthorization Bill has a strong bipartisan support for FY27 investment consideration
  - NQI has expired 2025



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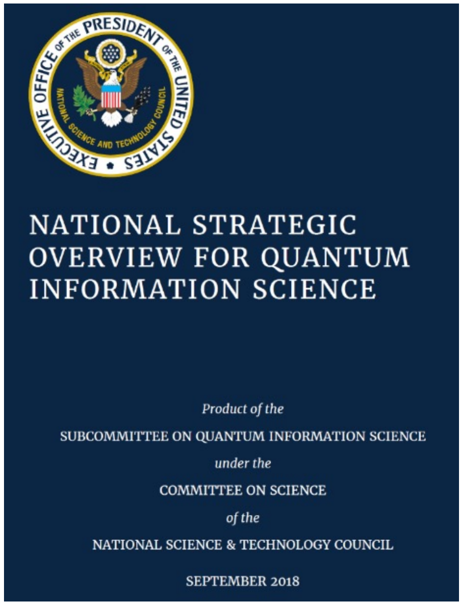

EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES

NATIONAL STRATEGIC OVERVIEW FOR QUANTUM INFORMATION SCIENCE

Product of the
SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE
under the
COMMITTEE ON SCIENCE
of the
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

SEPTEMBER 2018

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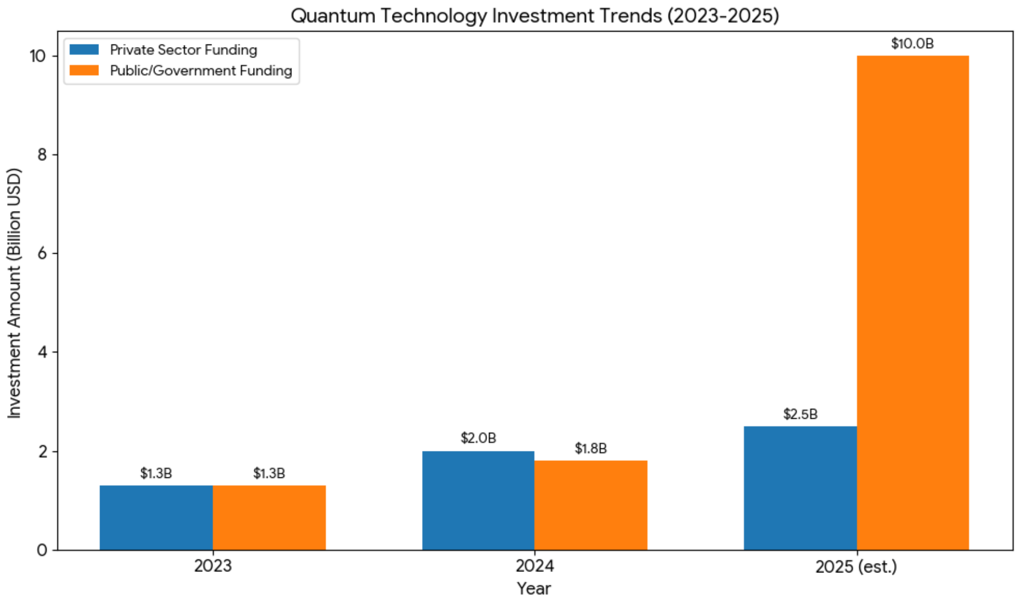
* https://www.nippon.com/en/japan-topics/c06501/a-twenty-first-century-sputnik-moment-china%E2%80%99s-mozi-satellite.html
** https://cosmosmagazine.com/technology/the-quantum-internet-is-already-being-built
*** https://www.whitehouse.gov/wp-content/uploads/2018/09/National-Strategic-Overview-for-Quantum-Information-Science.pdf

NQI Reauthorization Act & EO (2029)

- https://www.commerce.senate.gov/2026/1/cantwell-young-colleagues-introduce-bipartisan-national-quantum-initiative-reauthorization-act
  - Maria Cantwell (D-Wash.), Ranking Member of the Senate Committee on Commerce, Science and Transportation, Todd Young (R-Ind.), Dick Durbin (D-Ill.), Steve Daines (R-Mont.), Ben Ray Luján (D-N.M.), Marsha Blackburn (R-Tenn.), Tammy Baldwin (D-Wisc.), Ted Budd (R-N.C.), Chuck Schumer (D-N.Y.) and Mike Rounds (R-S.D.)
- On June 22, 2026, President Trump signed two executive orders to advance U.S. quantum research and protect critical infrastructure. The first directs the development of an advanced, scientifically relevant quantum computer and accelerates the National Quantum Strategy. The second mandates that federal agencies transition to post-quantum cryptography (PQC) by 2031
  - Department of War (DoW): Tasked with identifying specific quantum sensing projects within the military infrastructure and deploying them into active operations by 2028.
  - Department of Energy (DOE), NASA, and NSA: Directed to combine processing capabilities and align hardware specifications to build the Quantum Computer for Application Development and Discovery Science (QC-ADDS).
  - Commerce, NSF, and NASA: Ordered to draft comprehensive 5-year tactical plans specifically detailing the commercialization and deployment of advanced quantum timing, sensing, space applications, and networking.
  - National Science Foundation (NSF): Mandated to establish dedicated National QIST Workforce Development Institutes and expand open-access federal QIST user facilities.

Opportunities

- Agencies Involved in Quantum Information Science
  - OSTP
    - National Quantum Coordination Office
  - Civil Agencies
    - Department of Energy
    - National Science Foundation
    - National Institute of Standards Technology
    - National Aeronautics and Space Administration
  - DoD
    - Office of the Secretary of Defense
      - Principal Director for Quantum Science
    - DARPA
    - Army Research Lab
    - Navel Research Lab
    - Air Force Research Lab
  - Intelligence Community
    - National Security Agency
    - Laboratory for Physical Sciences
    - Intelligence Advanced Research Projects Activity
    - National Reconnaissance Office



State of the Quantum Industry

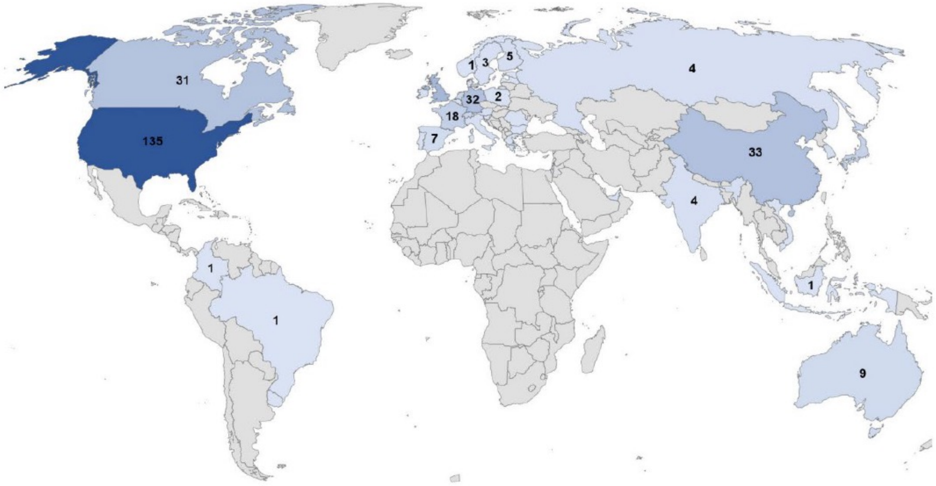


FIGURE 2. **Geographical distribution analysis of quantum start-up: Examining global patterns and dispersion over the research data timeframe. The geographical investment map of quantum start-ups provides valuable insights into the current investment status and global dynamics of the quantum technology landscape, as well as illuminating the collaborative and competitive factors influencing the future of quantum innovation globally.**

From: D. S. C. Putranto, R. W. Wardhani, J. Ji and H. Kim, "A Deep Inside Quantum Technology Industry Trends and Future Implications," in IEEE Access, vol. 12, pp. 115776-115801, 2024

Quantum industry needs technical skills that engineers don't have, and a set of soft skills that physicists don't have

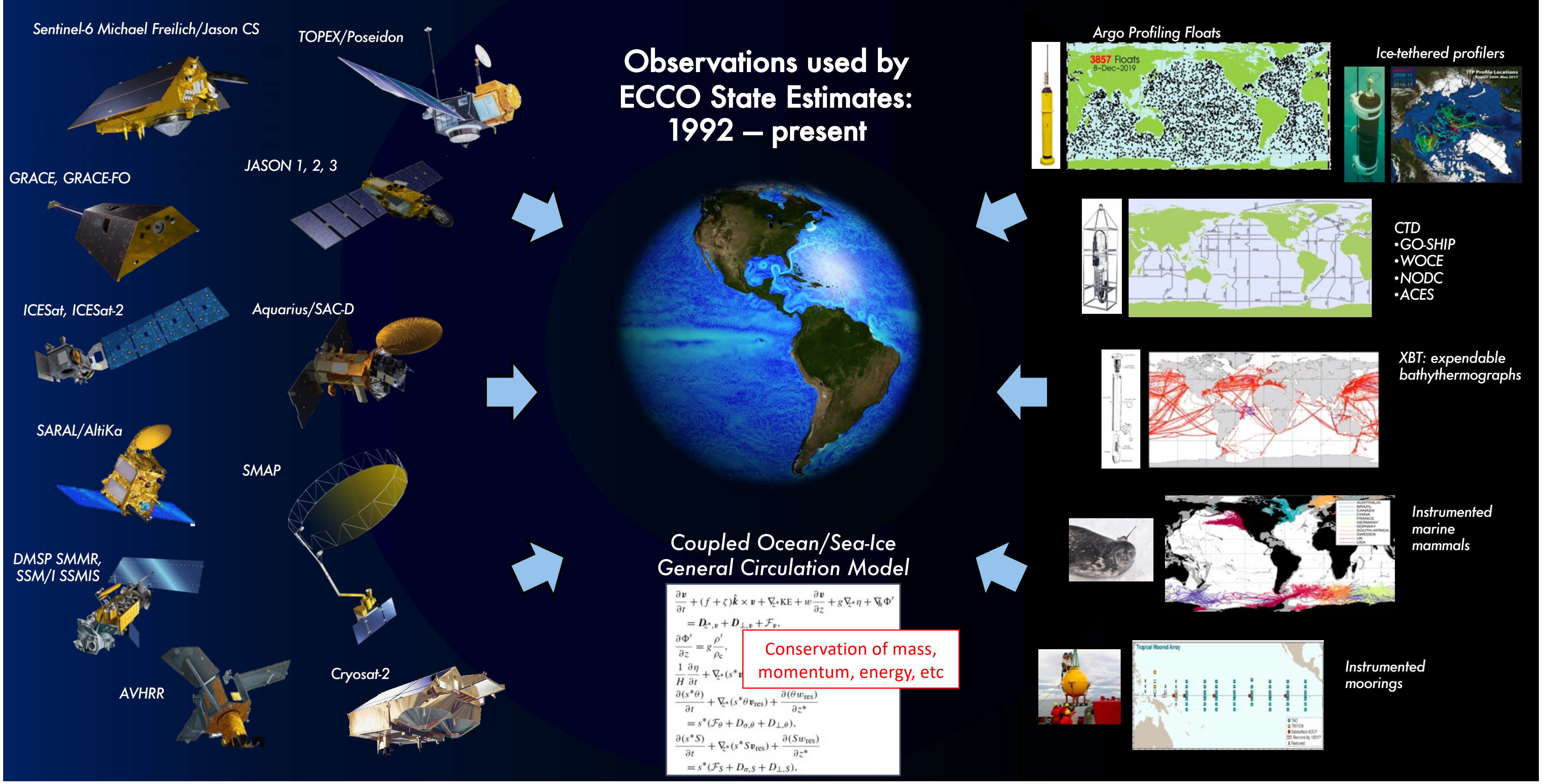
FIGURE 10. **Pie chart of percentage distribution across quantum technology industry fields. We classified the data into primary (level-1) categories, such as quantum computing, quantum communication, quantum sensing, quantum software, and quantum hardware, along with their corresponding subcategories (level-2), to capture the dominant areas within the field. According to the dataset and research timeframe, the analysis shows that 38 companies (8.8%) operate in the quantum sensing sector, 146 companies (34%) are involved in quantum software, 71 companies (16.5%) are focused on quantum computing, 83 companies (19.3%) are engaged in quantum communication, and 92 companies (21.4%) are dedicated to quantum hardware.**

Quantum and Climate Science: Approaches

Approach

- Understand the current science measurement challenges
  - NASA Decadal Survey
  - Applications from boundary organizations
  - Uncertainty quantification form models
- Build an affordable mission concept
  - Low SWaP
  - Good enough measurements
  - Complement existing missions and commercial data buy
  - Identify key technology gaps
- Assess how quantum sensing enhance or enable technology gaps
  - Lowering the cost – QGG, Rydberg MW sensor
  - Improve sensitivity to reduce UQ – Constellation, 3D topography, concurrent
  - Enable measurements where classical approach can't – entangled sensors, GPS denied env

Observation-Informed Earth System Modeling



Observations used by ECCO State Estimates: 1992 – present

Sentinel-6 Michael Freilich/Jason CS

TOPEX/Poseidon

GRACE, GRACE-FO

JASON 1, 2, 3

ICESat, ICESat-2

Aquarius/SAC-D

SARAL/AltiKa

SMAP

DMSP SMMR,
SSM/I SSMIS

AVHRR

Cryosat-2

Argo Profiling Floats

Ice-tethered profilers

CTD
- *GO-SHIP*
- *WOCE*
- *NODC*
- *ACES*

XBT: expendable bathythermographs

Instrumented marine mammals

Instrumented moorings

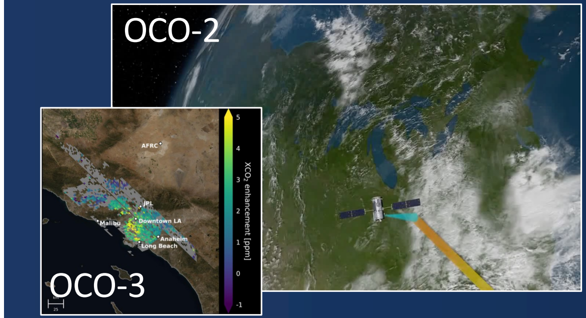
Coupled Ocean/Sea-Ice General Circulation Model

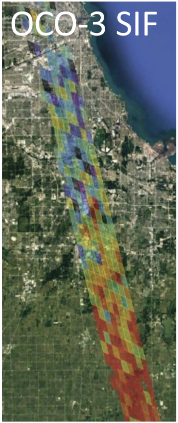
$$\frac{\partial \boldsymbol{v}}{\partial t} + (f+\zeta)\hat{\boldsymbol{k}} \times \boldsymbol{v} + \nabla_{z^*}\mathrm{KE} + w\frac{\partial \boldsymbol{v}}{\partial z} + g\nabla_{z^*}\eta + \nabla_h \Phi'$$
$$= \boldsymbol{D}_{z^*,\boldsymbol{v}} + \boldsymbol{D}_{\perp,\boldsymbol{v}} + \mathcal{F}_{\boldsymbol{v}},$$
$$\frac{\partial \Phi'}{\partial z} = g\frac{\rho'}{\rho_c},$$
$$\frac{1}{H}\frac{\partial \eta}{\partial t} + \nabla_{z^*}(s^*\boldsymbol{v}$$
$$\frac{\partial (s^*\theta)}{\partial t} + \nabla_{z^*}(s^*\theta\boldsymbol{v}_{\mathrm{res}}) + \frac{\partial(\theta w_{\mathrm{res}})}{\partial z^*}$$
$$= s^*(\mathcal{F}_\theta + D_{\sigma,\theta} + D_{\perp,\theta}),$$
$$\frac{\partial (s^*S)}{\partial t} + \nabla_{z^*}(s^*S\boldsymbol{v}_{\mathrm{res}}) + \frac{\partial(S w_{\mathrm{res}})}{\partial z^*}$$
$$= s^*(\mathcal{F}_S + D_{\sigma,S} + D_{\perp,S}),$$

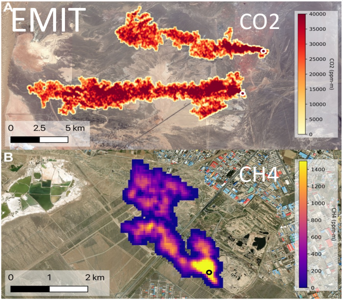
Conservation of mass, momentum, energy, etc

Contributing Global to Facility Scale Information for GHG Mitigation

Observations



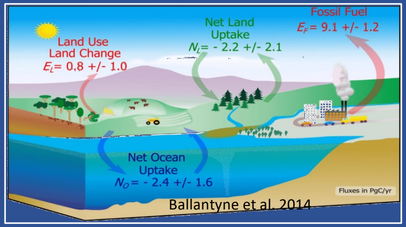




Other Critical Measurements

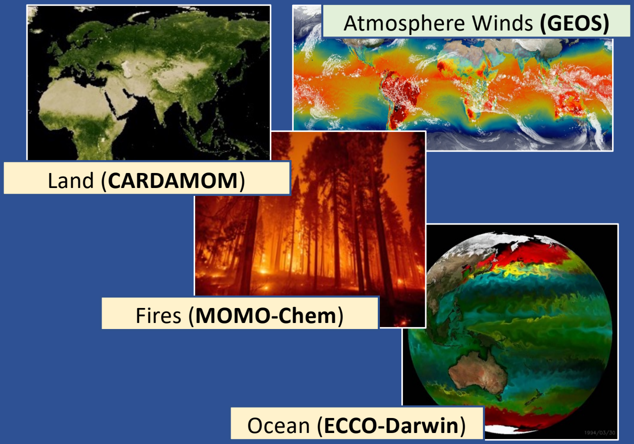
- AIRS Carbon Monoxide
- NISAR Biomass
- SMAP/Aquarius Salinity
- More….

Science & Modeling



Ballantyne et al. 2014

GHG Fluxes (**CMS-Flux**)



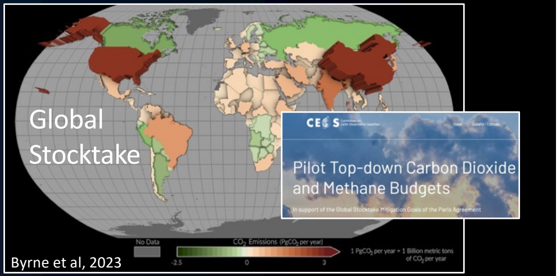
Atmosphere Winds **(GEOS)**

Land (**CARDAMOM**)

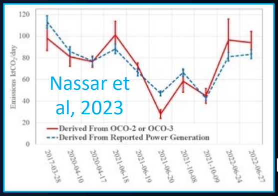
Fires (**MOMO-Chem**)

Ocean (**ECCO-Darwin**)

Decision Support



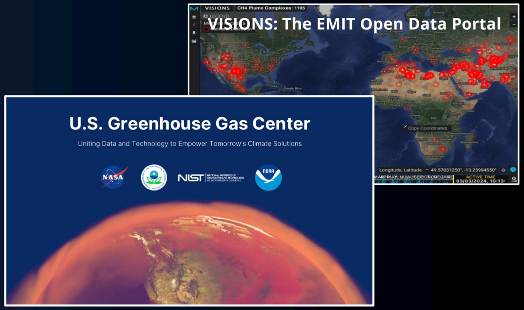
Byrne et al, 2023



Nassar et al, 2023

CO2 Emissions

Bełchatów Power Station, Poland



VISIONS: The EMIT Open Data Portal

U.S. Greenhouse Gas Center

Uniting Data and Technology to Empower Tomorrow's Climate Solutions

Science Traceability Matrix for Earth System Mass Change via Quantum Gravity Gradiometer

2017 Earth Science Decadal Survey

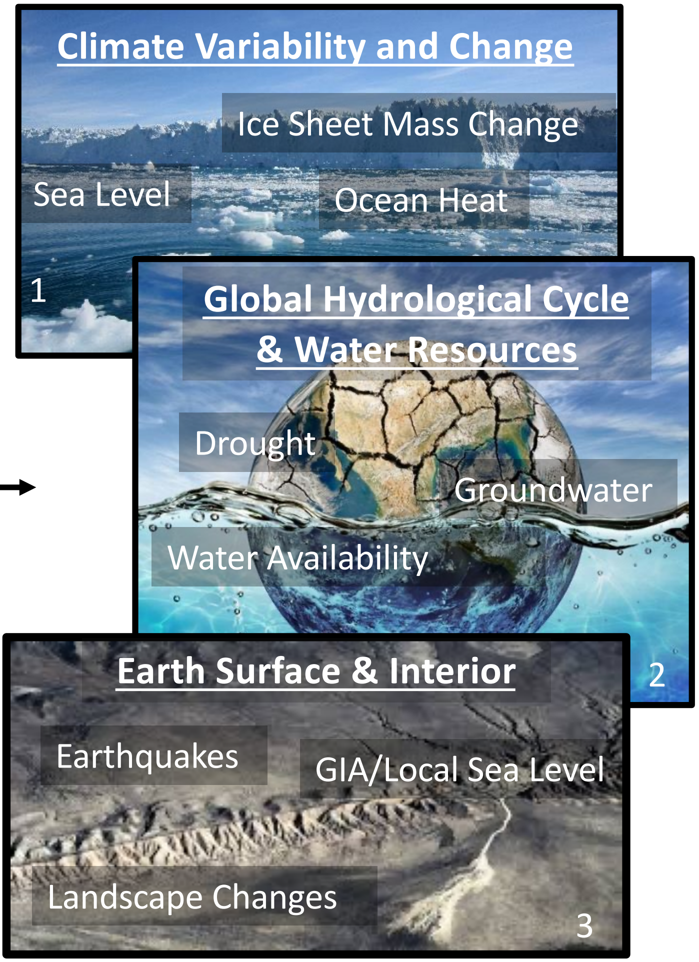
CONSENSUS STUDY REPORT

THRIVING ON OUR CHANGING PLANET

A Decadal Strategy for Earth Observation from Space

Mass Change as a Designated Observable

Science Objectives



Climate Variability and Change

Ice Sheet Mass Change

Sea Level

Ocean Heat

Global Hydrological Cycle & Water Resources

Drought

Groundwater

Water Availability

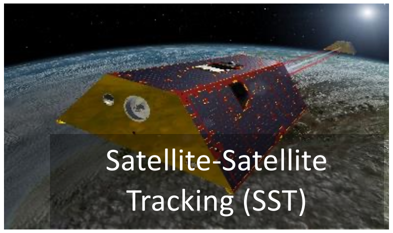
Earth Surface & Interior

Earthquakes

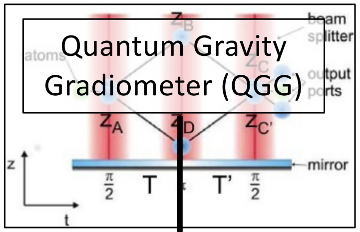
GIA/Local Sea Level

Landscape Changes

Measurement Approaches



Satellite-Satellite Tracking (SST)



Quantum Gravity Gradiometer (QGG)

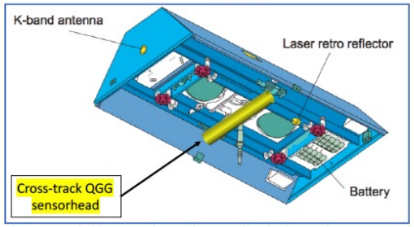
QGG: High Science Value; Low TRL

Single Satellite Implementation rivals that of 4-satellite SST

Instrument Requirements: 10-100 $\mu E/Hz^{1/2}$

Implementation Approaches

Single Satellite



Secondary Payload

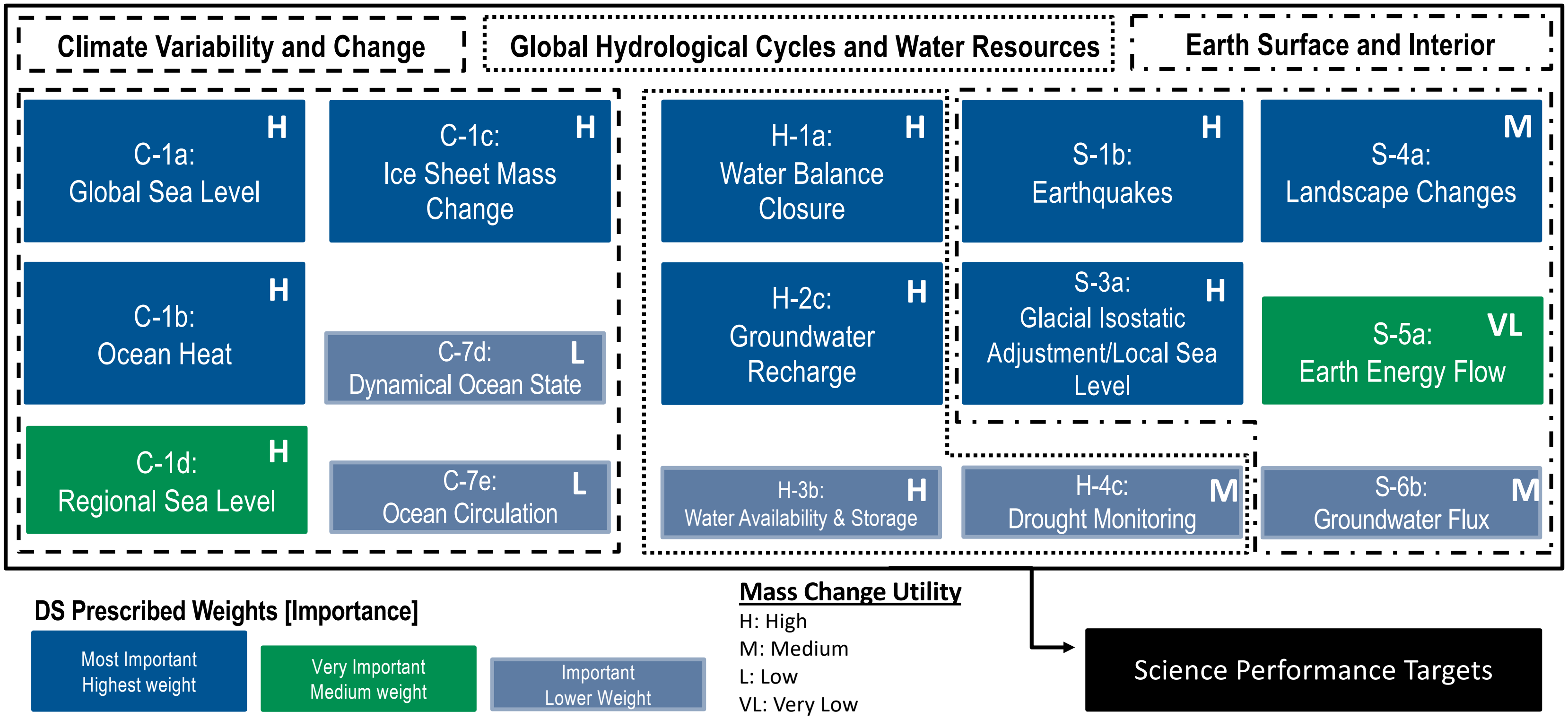
1 Credit: Eric Rignot, JPL

2 Credit: GettyImages/iStockphoto/Alexandrum79

3 Credit: Cultura RM Exclusive/Chris Sattlberger/Getty images

Decadal Survey Science and Application Objectives for Mass Change

A Diverse Set of Objectives Spanning Three Panels



Climate Variability and Change

- C-1a: Global Sea Level — H
- C-1c: Ice Sheet Mass Change — H
- C-1b: Ocean Heat — H
- C-7d: Dynamical Ocean State — L
- C-1d: Regional Sea Level — H
- C-7e: Ocean Circulation — L

Global Hydrological Cycles and Water Resources

- H-1a: Water Balance Closure — H
- H-2c: Groundwater Recharge — H
- H-3b: Water Availability & Storage — H
- H-4c: Drought Monitoring — M

Earth Surface and Interior

- S-1b: Earthquakes — H
- S-4a: Landscape Changes — M
- S-3a: Glacial Isostatic Adjustment/Local Sea Level — H
- S-5a: Earth Energy Flow — VL
- S-6b: Groundwater Flux — M

DS Prescribed Weights [Importance]

- Most Important
Highest weight
- Very Important
Medium weight
- Important
Lower Weight

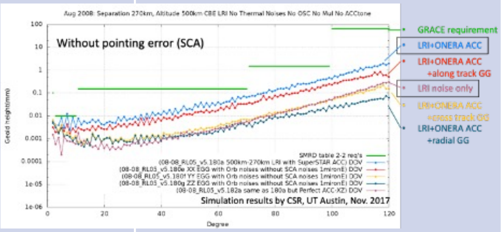
Mass Change Utility

H: High
M: Medium
L: Low
VL: Very Low

Science Performance Targets

Science Traceability Matrix for Quantum Gravity Gradiometer for Earth Sciences (6/7/2020)

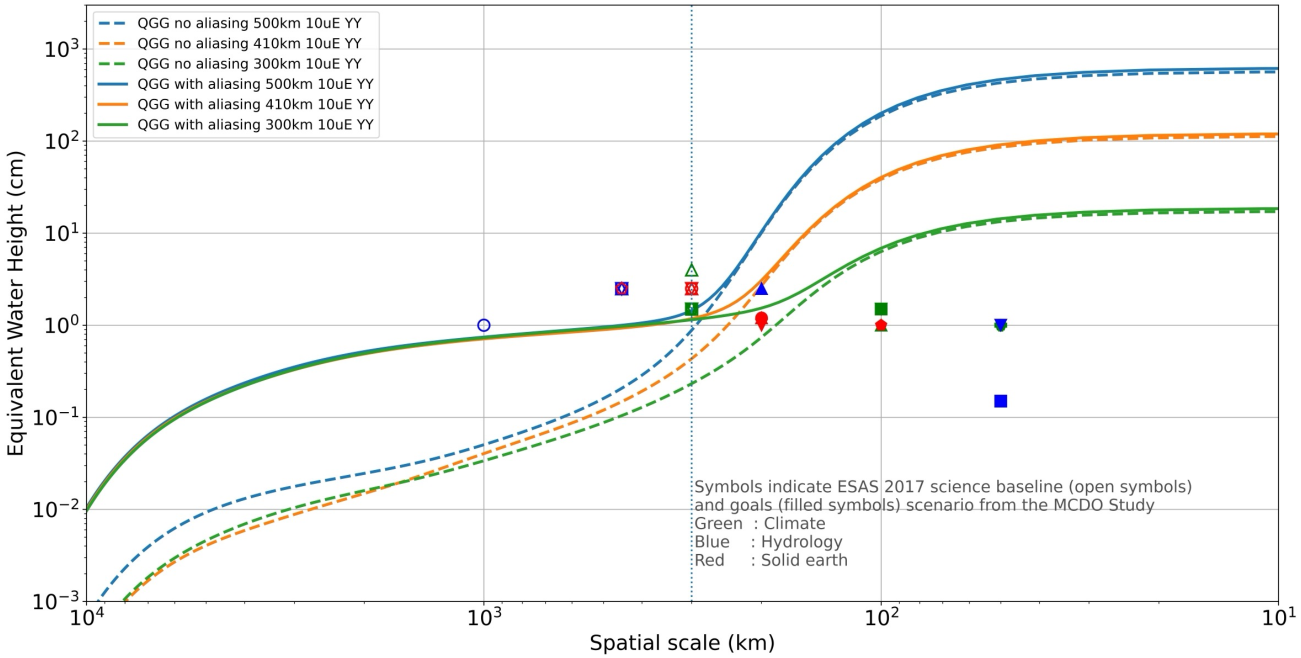
Science goals	Science objectives	Science requirements	Measurement requirements	Instrument requirements	Mission requirements
2017 Earth Science Decadal: Mass Change (MC) as one of the five Designated Observables (MC determined by measuring gravitational changes over time)	Understand climate variability and change Monitor global hydrology cycles and water resources Study solid earth and interior	Global sea level, ocean heat, ice sheet mass change: 15 mm equiv. water height at (300 km)^2, monthly. Water balance and ground water recharge: 25 mm equiv. water height at (450 km)^2, monthly Earthquake, glacial isostatic adjustments: 25 mm equiv. water height at (300 km)^2, monthly.	Improve over the current GRACE-FO performances by a factor of 2x to 10x. Measurement architecture: Spacecraft-spacecraft-tracking by laser +cross track gradiometer (Alternative, single spacecraft 3-axis gradiometer or constellation) Geoid height at spherical harmonic degrees (spatial resolution): 0.005 mm at 2—10 degree 0.005 mm at 10 – 70 degree 0.05 mm at 70 – 100 degree 0.1 mm at 100 – 120 degree	GRACE-FO instruments and their performances plus cross-track gradiometer with $1\mathrm{x}10^{-5}$ E/Hz$^{1/2}$ in the frequency range of 1 nH to 1 Hz. (E = 10^{-9} m/s^2 per meter) Quantum gravity gradiometer, accelerometer sensitivity $1\mathrm{x}10^{-13}$ m/s^2/Hz$^{1/2}$ with sensor separation ~ 1 m. Atom interferometer accelerometer: interrogation time > 10 s, participating atom number > $1\mathrm{x}10^8$, high-order Bragg diffraction splitter of order > 5. [In the single spacecraft gravity gradiometer configuration (Goddard AIGG), $1\mathrm{x}10^{-5}$ E/Hz$^{1/2}$ in the frequency range of 1 nH to 1 Hz in three axes (?). interrogation time > 10 s, participating atom number > 1e8, high-order Bragg diffraction as matter wave splitter of order > 5.	two spacecraft in tandem SST + Gradiometer hybrid measurement architecture Mission lifetime > 5 years Post-processing of combined SST and gradiometer data



Simulation results by CSR, UT Austin, Nov. 2017

The promise of the SGI

QGG simulation anticipates 10 μE performance is accessible in the future with Quantum Sensing



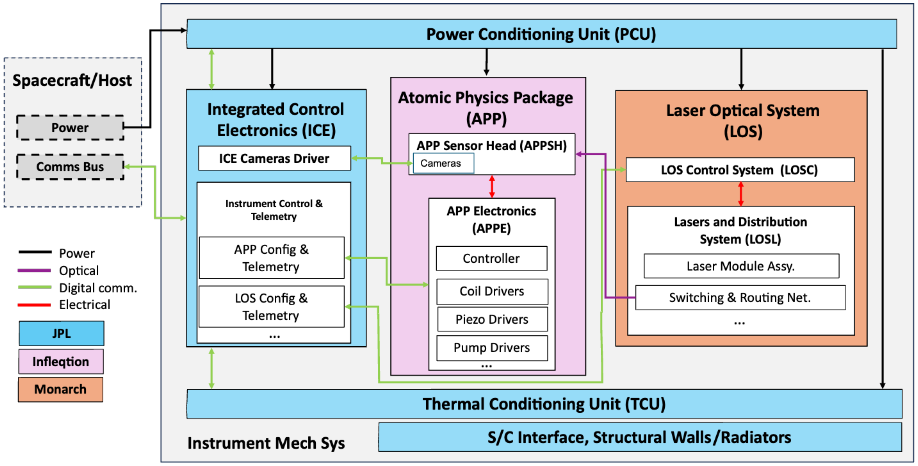
Symbols indicate ESAS 2017 science baseline (open symbols) and goals (filled symbols) scenario from the MCDO Study
Green : Climate
Blue : Hydrology
Red : Solid earth

For this level of aliasing error or noise, the QGG flight configuration change does mitigate the effects of aliasing error.

NB: These are global aggregated error statistics, and do not provide information on signal-to-noise ratio.

QGGPf Instrument Implementation Overview

- QGGPf is a technology demonstration Project requiring flight demonstration of a new quantum sensor system capable of measuring Earth's gravity gradient from a free-flying spacecraft in LEO by 2030.
- JPL is the lead Center and implementer of the Integrated Control Electronics (ICE) S/S, Power Control Unit (PCU) S/S and Instrument Mechanical System (IMS) S/S and responsible for instrument microgravity testing, system testbed and system I&T.
- Project is working with Inflegtion, Inc. as the implementer of the Atomic Physics Package (APP) S/S, with the Laser Optical System (LOS) S/S being developed by Monarch Quantum, Inc. as a subcontractor to Inflegtion.



Spacecraft/Host
Power
Comms Bus

Power Conditioning Unit (PCU)

Integrated Control Electronics (ICE)
ICE Cameras Driver
Instrument Control & Telemetry
APP Config & Telemetry
LOS Config & Telemetry
...

Atomic Physics Package (APP)
APP Sensor Head (APPSH)
Cameras
APP Electronics (APPE)
Controller
Coil Drivers
Piezo Drivers
Pump Drivers
...

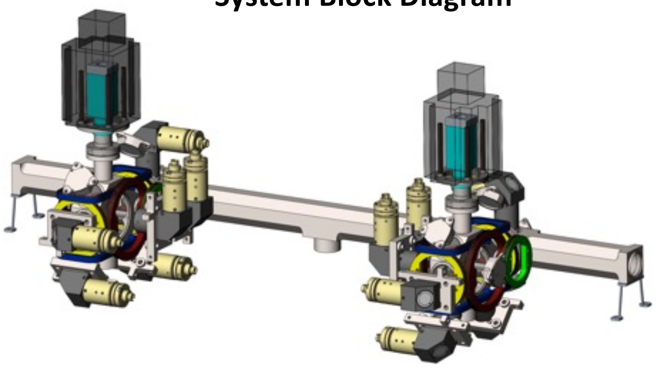
Laser Optical System (LOS)
LOS Control System (LOSC)
Lasers and Distribution System (LOSL)
Laser Module Assy.
Switching & Routing Net.
...

Thermal Conditioning Unit (TCU)
Instrument Mech Sys
S/C Interface, Structural Walls/Radiators

Power
Optical
Digital comm.
Electrical

JPL
Inflegtion
Monarch

System Block Diagram

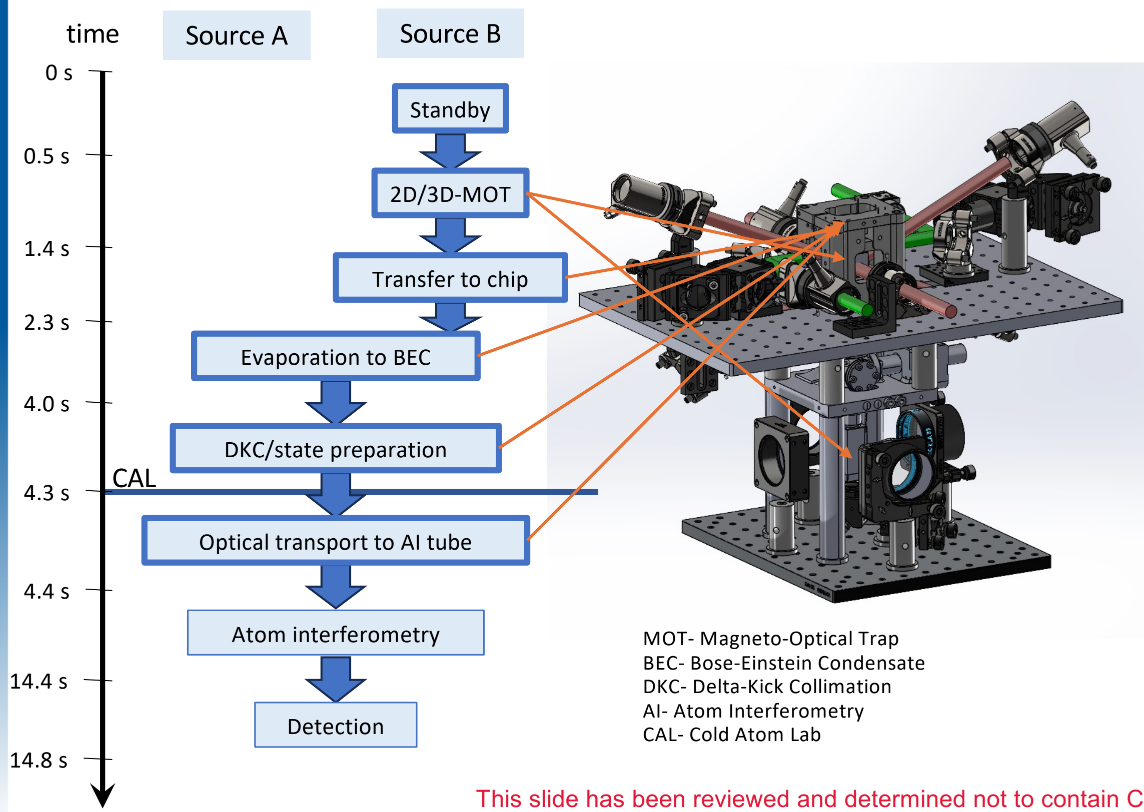


Two source Rb QGG using super cooled Bose Einstein Condensate

JPL Testbed: Risk Reduction, Current Status, Microgravity Campaigns

Physics Protocol demonstration and modeling

Current Status



time

Source A

Source B

0 s

0.5 s

1.4 s

2.3 s

4.0 s

4.3 s

4.4 s

14.4 s

14.8 s

CAL

Standby

2D/3D-MOT

Transfer to chip

Evaporation to BEC

DKC/state preparation

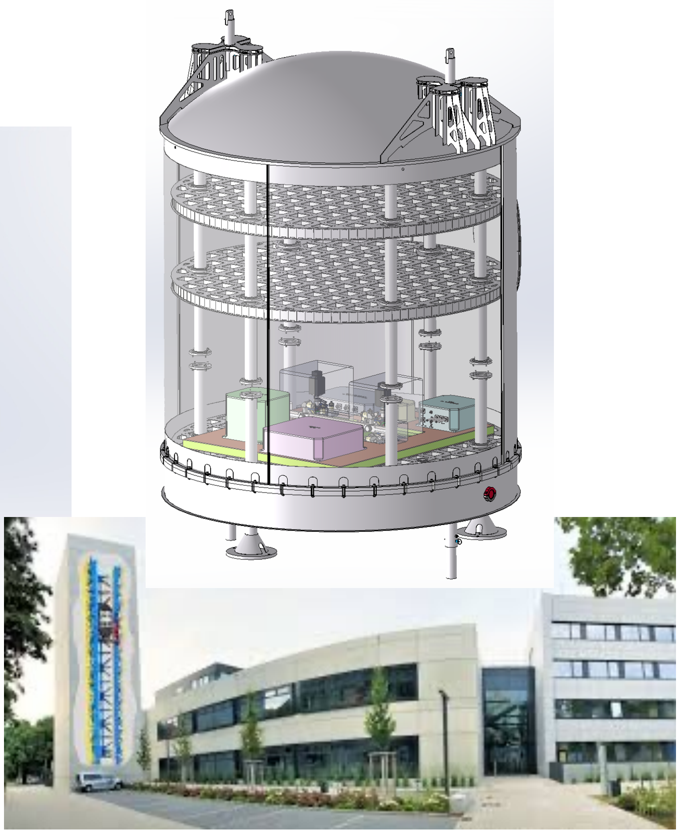
Optical transport to AI tube

Atom interferometry

Detection

MOT- Magneto-Optical Trap
BEC- Bose-Einstein Condensate
DKC- Delta-Kick Collimation
AI- Atom Interferometry
CAL- Cold Atom Lab

Microgravity testing before going to space

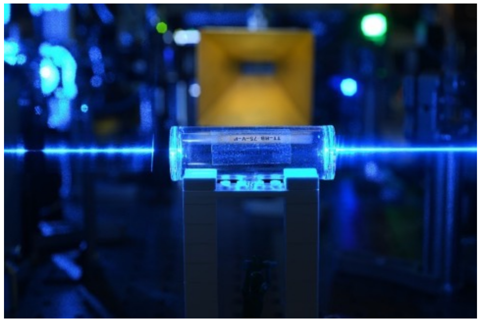


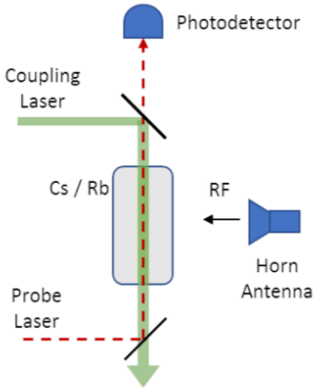
The Einstein Elevator Facility, Hannover, Germany
4 seconds of microgravity time, 100 shots a day

This slide has been reviewed and determined not to contain CUI.

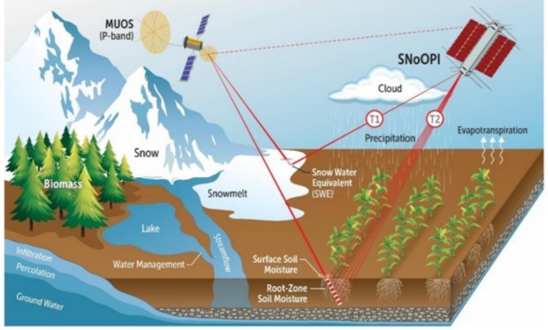
Rydberg Ultra-Broadband Radar Receivers for SoOP

- Based on room-temperature Rydberg atoms - Alkali atoms placed in a vapor cell excited optically to Rydberg states and the applied radio frequency (RF) field alters the resonant state of the atoms
    - Excited to a very high principal quantum number, n. These Rydberg atoms have large dipole moments (scale as n^2).
- This approach exploits the sensitivity of the high-lying Rydberg states to RF radiation.
- It is possible to excite the atom to a wide range of atomic states. As such, with one vapor cell, accurate measurements of a RF -field strength over a frequency range from 100 MHz to >500 GHz are possible
- **Near term:** The sensitivity and ultra-broadband nature make these promising for signal of opportunity (SoOP) radars
- **Long term:** A major advance in tunable broadband radar receiver architectures

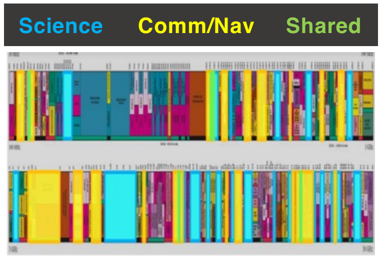




Rydberg receiver setup



Example: Root zone soil moisture

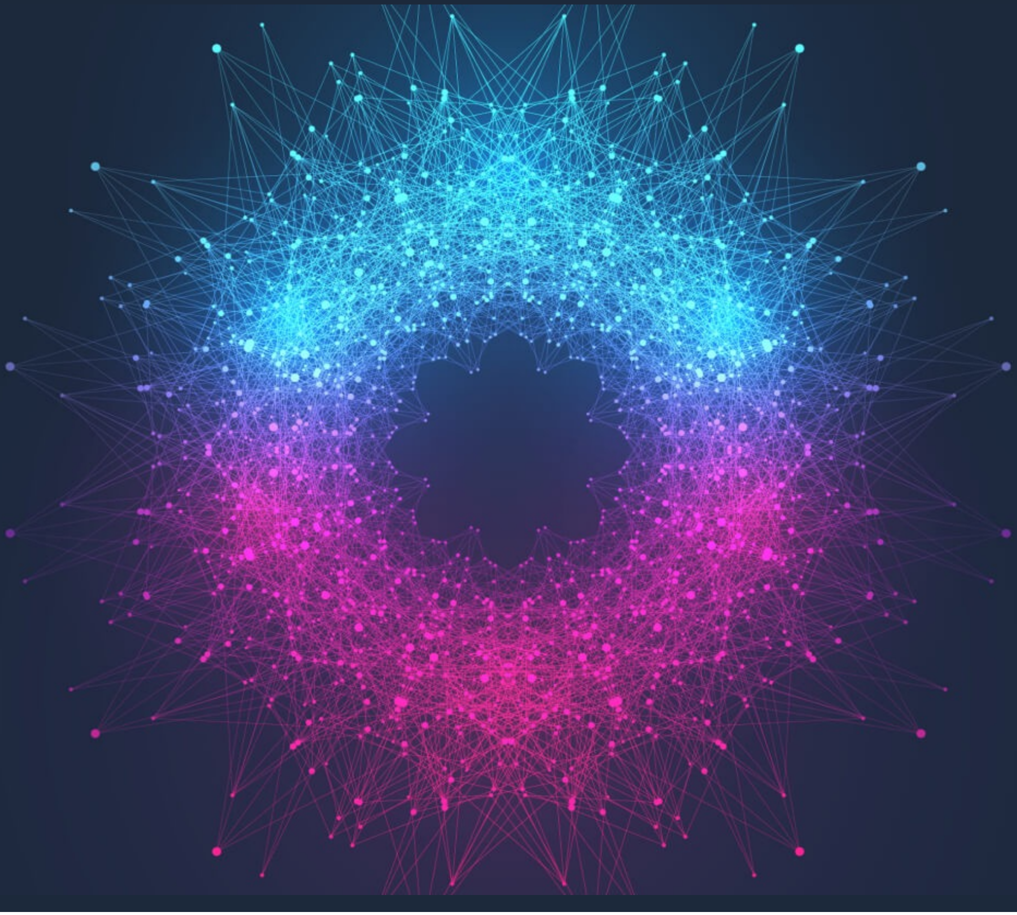


NTIA spectrum allocations = valuable signals of opportunity for remote sensing

Waveguide-Coupled Rydberg Spectrum Analyzer from 0 to 20 GHz, in *Physical Review Applied*, 2021.

JPL Efforts

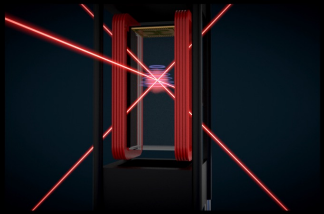
Establish a Center to harness and leverage breakthrough quantum technologies that enable new science and a Hub to build connections with industry and universities to develop a pipeline of talent



JPL is the only NASA center to operate quantum sensors in space.

2009

Transportable ug-compatible gravity gradiometer with SOA performance

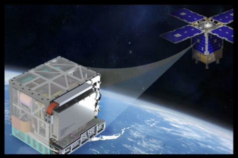


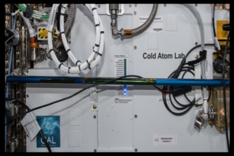
CAL-First Quantum Gas in orbiting space platform

2018

2019

Deep Space Atomic Clock

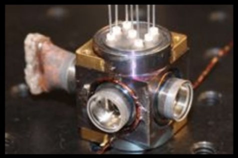




CAL-First atom interferometer demo in space

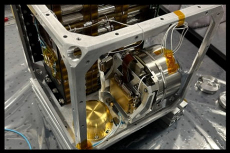
2021

Micro Mercury Ion Clock with Enhanced Stability



2023

Lunar Atomic Seismometer (under development)

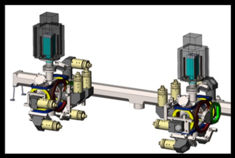


Bose Einstein Condensates and Cold Atom Lab (with DLR)

2027

2029

Quantum Gravity Gradiometer QGG



FIBERTEK, INC.

L3HARRIS

FIRST MODE

CONTROL DYNAMICS INC. CDI

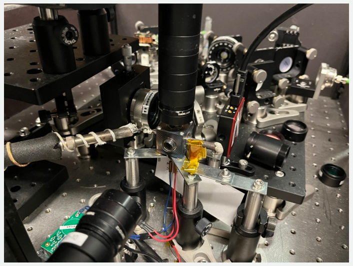
LGS INNOVATIONS

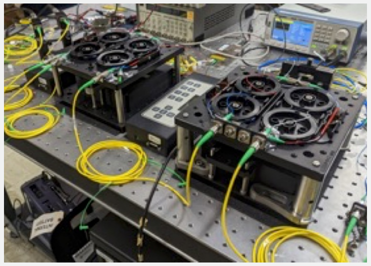
JPL

An Existing Set of Testbeds - 12

Cold Atom Lab/
Atom
Interferometer

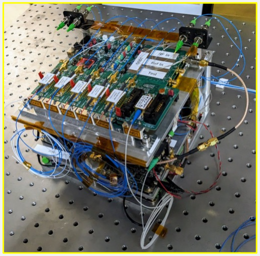
Clock Testbed

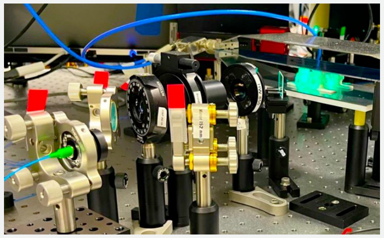




Quantum Entanglement

Laser for Cs





Rydberg MW Sensor

Quantum Hub Members

JPL
Jet Propulsion Laboratory
California Institute of Technology

NASA

Caltech

USC

UCLA

UC Berkeley

UC Irvine

UC Riverside*

UCSB

UCSD

Chapman U.

ASU

U Az

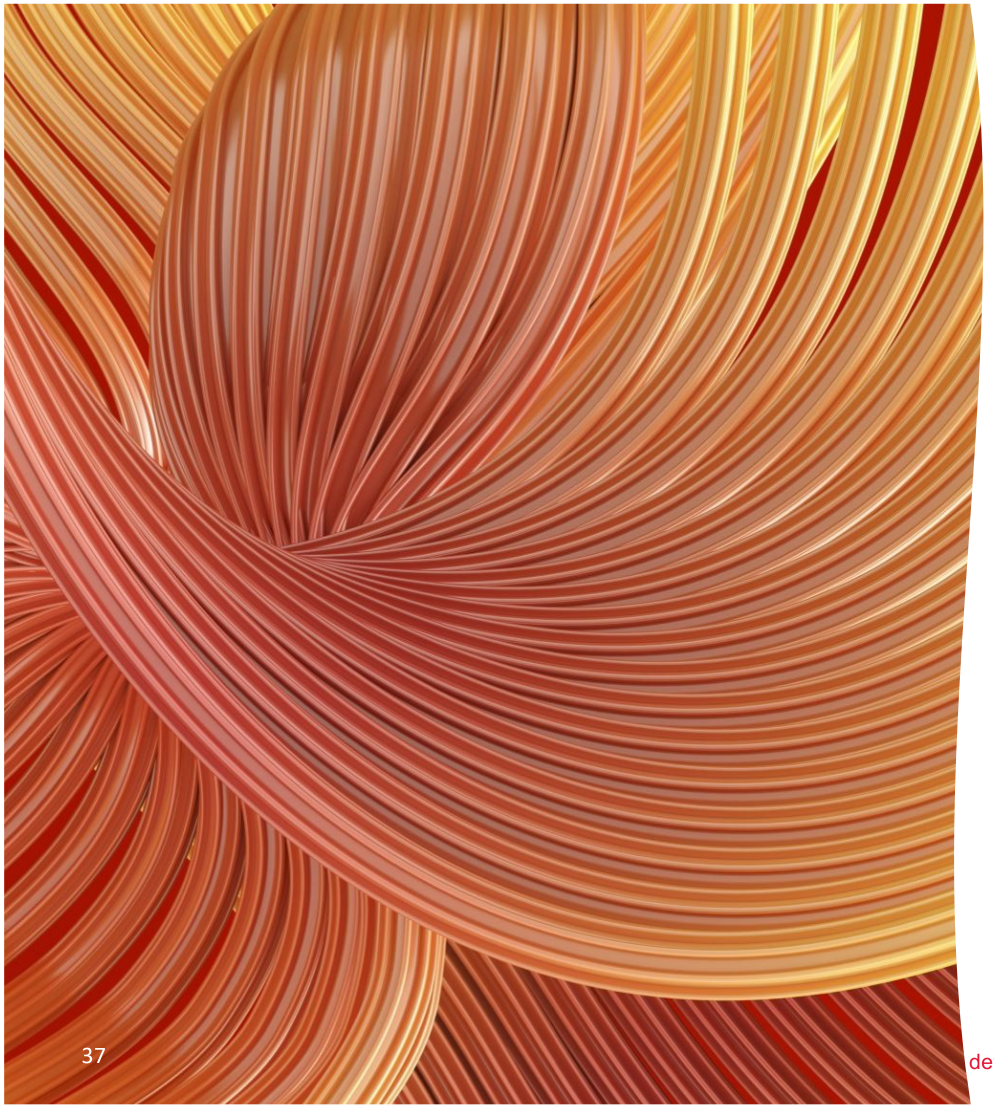
UCol Boulder

UNLV*

Notre Dame*

Industry Partners: Infleqtion, IonQ, Monarch Quantum, D-Wave, Microsoft, many startups

* Recently added



How To Reach Us

Center Director: Jason Hyon, 818-354-0730

Deputy: John Callas, 818-354-9088

Types of interactions

Opportunity capture
Capability assessment
Partnership
A joint workshop or studies
Curriculum development
Internship opportunities
Speaker engagements
Roadmaps

Motivation and Focus Areas

- Remote sensing or detection that is enhanced by using intrinsic quantum properties of light or quantum processing coupled with active interrogation and signaling
- Goal is to enhance sensitivity and surpass performance of classical active remote sensing strategies

- ○ **Entangled photon remote sensing**
  - *Quantum LIDAR using entangled photon pairs*
  - *Quantum RADAR using entangled microwave photon pairs*
  - Weak or cluttered background sensing applications
  - Ghost imaging
- ○ **Quantum Illumination**
  - *Quantum LIDAR in lossy environment*
  - *Quantum RADAR in lossy environment*
  - High background noise rejection
  - Ultra-sensitive microscopy
- ○ **Quantum Receivers**
  - Squeezed channel receiver
  - Entangled microwave-photonic receiver array
  - Entangled long-baseline receiver array
  - Adaptive single-photon detection
  - Ultra-wide spectrum Rydberg receiver
- **Quantum inspired sensing and imaging**
  - Ghost imaging with correlated signals
  - Intensity correlation imager
  - Turbulence-free imaging
  - Compressive sensing
  - Coordinated classical-to-quantum phenomena (coherence, quantized energy levels) advances