

Accelerating the Deployment of Space-Based Quantum Sensors

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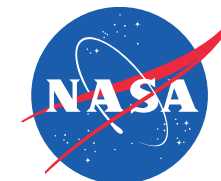
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Space S&T Partnership Forum

- **When:** Established in **2015** between NASA, NRO, and Department of Air Force (USSF in **2019**)
- **Why:** Identify and leverage synergistic efforts and technologies to influence science and technology portfolios at each agency in areas deemed pervasive and ready for collaboration
- **How:** Coordinate and facilitate dialog, collect data, and perform data analysis

Who: S&T Forum Participants

National Aeronautics and Space Administration (NASA)

A.C. Charania
Chief Technologist
Office of Technology, Policy, and Strategy

National Reconnaissance Office (NRO)

Dr. Byron Knight
Chief Engineer
Advanced Systems & Technology Directorate

United States Space Force (USSF)

Dr. Stacie Williams
Chief Science Officer
United States Space Force

What: S&T Forum Topics

2016	Small Satellite Technology Big Data Analytics
2017-2019	In-Space Assembly Cyber Resilient Space Systems
2019-2020	Space Trusted Autonomy
2020	Radiation-Hardened, High-Performance Electronics
2020+	Cyber Space Mission Assurance Experiment
2022+	Quantum Sensing



Study Objectives

S&T Forum effort to **accelerate the deployment of space-based quantum sensors** by:

- 1) Identifying **quantum sensors** with promising near-term potential for space science and operations, along with the required **infrastructure** and **supporting subsystems**.
- 2) Developing a plan for the three S&T Forum agencies to **collaborate** and **coordinate**.

Why present recommendations, findings, and next steps from this study to the AIAA SciTech community?

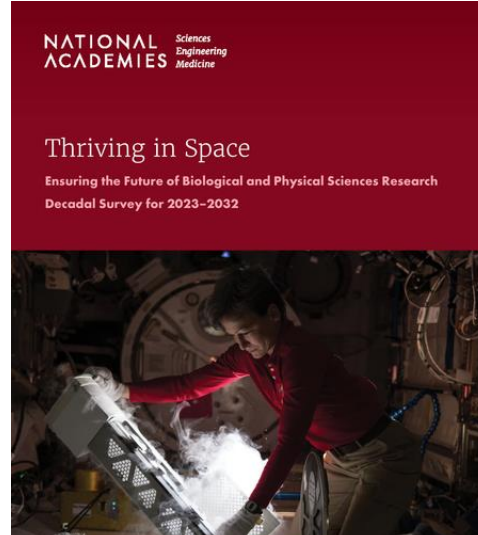
For technologists and researchers from industry and academia to understand potential areas for engagement with the S&T Forum agencies.



Background and State of Play: NASA

- **NASA quantum sensing expertise:**
 - Goddard Space Flight Center (GSFC)
 - Glenn Research Center (GRC)
 - Langley Research Center (LaRC)
 - Jet Propulsion Laboratory (JPL)
- **Existing collaborations** with industry, academia, international, and other government agencies
- **NASA strategic quantum sensing efforts:**
 - Reauthorization of the National Quantum Initiative Act
 - NASA Engineering and Safety Center (NESC)-sponsored quantum sensing technical capability assessment

Why quantum sensing at NASA?



Science

- Astrophysics
- Planetary Science
- Heliophysics
- Earth Science
- Biological and Physical Sciences



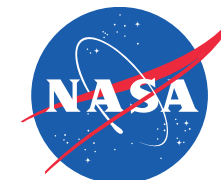
Climate

- Innovate
- Inform
- Inspire
- Partner



Artemis

- Science
- Infrastructure
- Transportation & Habitation
- Operations
- Recurring Tenets



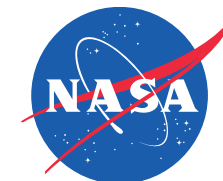
Background and State of Play: NRO

- **NRO Focus:**
 - Define which capabilities enable NRO Missions and are unique to our needs
 - Understanding actual vs theory for response and performance
- **Existing collaborations** with industry, academia, and other government agencies
- **NRO strategic quantum sensing efforts:**
 - Collaboration and Cooperation
 - Leveraging external resources and developments
 - Mix of early technology and demonstrations



Background and State of Play: USSF

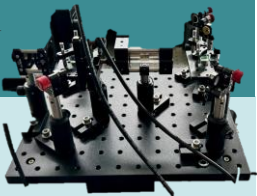
- **Vision for critical technology areas:**
 - USSF quantum sensing research efforts support the Department of Defense (DoD) vision for Quantum Science
- **USSF research efforts** focused on quantum sensing include atomic clocks, levitated optomechanics, photonic microcombs, ultracold atoms
- **Existing collaborations** and investments with industry, academia, and other government agencies to include:
 - Air Force Research Laboratory (AFRL)
 - Naval Research Laboratory (NRL)
 - Defense Innovation Unit (DIU)
 - Defense Advanced Research Projects Agency (DARPA)
 - Aerospace
 - MITRE



Technology Areas of Mutual Near-Term Interest

The following five areas of quantum sensing technology (listed in alphabetical order) were identified as being of near-term interest to all three S&T Forum agencies:

Atomic Clocks



Example

Optical Atomic Strontium Ion Clock (OASIC)

Image Credit:
NASA/Matthew Kaufman

Atom Interferometers

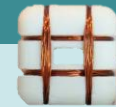


Example

Atom Interferometer Gravity Gradiometer (AIGG)

Image Credit:
NASA/Peter Brereton

Quantum Magnetometers



Example

Silicon Carbide Magnetometer (SiCMag)

Image Credit:
NASA/JPL-Caltech

Rydberg Sensors

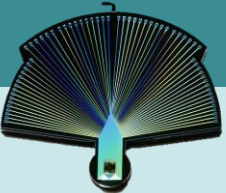


Example

Remote sensing of soil moisture using Rydberg atoms and satellite signals of opportunity

Image Credit:
NASA/JPL-Caltech/
Darmindra Arumugam

Single Photon Detectors



Example

Performance-Enhanced Array for Counting Optical Quanta (PEACQ) Detector

Image Credit:
NASA/JPL-Caltech

Recommendations

To arrive at recommendations for the Principals of the S&T Forum to accelerate the deployment of space-based quantum sensors, the interagency study team hosted and facilitated multiple interagency interactions to collect data, including an in-person Technical Exchange Meeting and working group meetings among quantum sensing subject matter experts.

Recommendation 1:

Leverage the **shared industrial and knowledge base** to develop **enabling component technologies** of mutual interest.

Recommendation 2:

Coordinate and collaborate on efforts **within and beyond the S&T Forum** to address shared transitions of quantum sensing technologies from the **laboratory to space**.



1.1. Common Enabling Component Technologies

Recommendation 1: Leverage the shared industrial and knowledge base to develop enabling component technologies of mutual interest.

Finding 1.1: Common enabling component technologies across the five quantum sensing technology areas of near-term interest to the S&T Forum agencies that require development include:

Enabling Technology	Atomic Clocks	Atom Interferometers	Quantum Magnetometers	Rydberg Sensors	Single Photon Detectors
Space-Qualified* Electronics	X	X	X	X	X
Laser Optical Systems	X	X	X	X	
Photonic Integrated Circuits (PICs)	X	X		X	
Vapor Cells	X		X	X	
Space-Qualified Photodetectors		X	X	X	
Cryogenic Systems			X		X

*(i.e., radiation-hardened, and temperature-resistant)



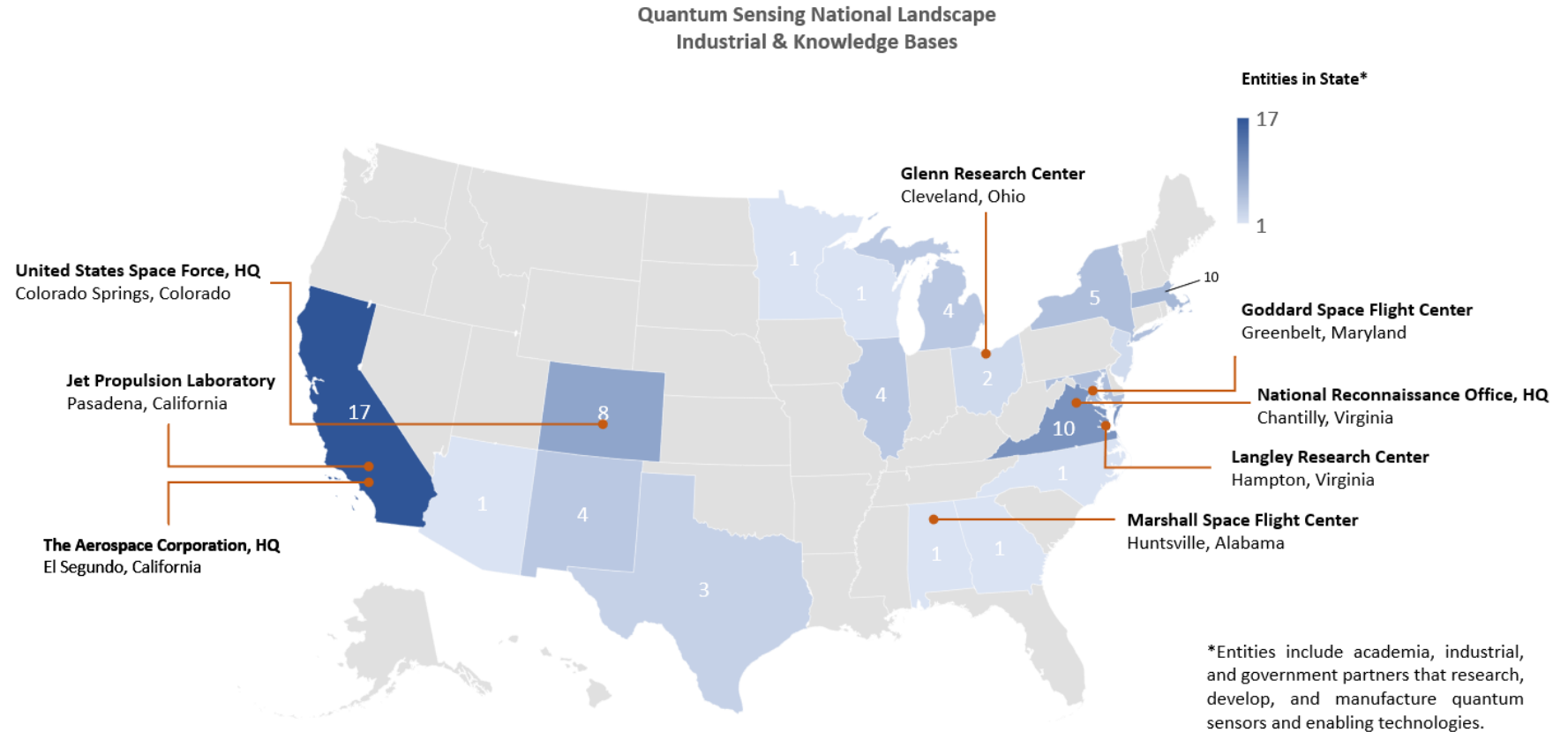
1.2. Quantum Sensing National Landscape

Recommendation 1:

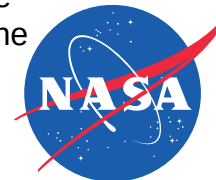
Leverage the shared industrial and knowledge base to develop enabling component technologies of mutual interest.

Finding 1.2:

A diverse community of industry, government, and academic organizations are developing enabling component technologies for quantum sensing.



This landscape is not comprehensive, rather it is a starting point to illustrate the geographical and institutional diversity of the quantum sensing players familiar to the SMEs of the S&T Forum agencies and to encourage future connections.



2. Moving from the Laboratory to Space

Recommendation 2: Coordinate and collaborate on efforts within and beyond the S&T Forum to address shared transitions of quantum sensing technologies from the laboratory to space.

Enabling Rapid Space Qualification of Quantum Sensors

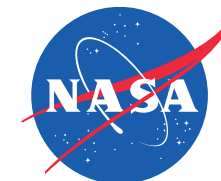
Finding 2.1: Given the small number of **spaceflight-proven components**, it is necessary to coordinate the development of technologies in the five quantum sensing technology areas of near-term interest to the S&T Forum agencies to enable faster space qualification and strengthened supply chain logistics.

Coordinating Small Business Support Efforts

Finding 2.2: Given the emergent state of space-based quantum sensors, many of the industrial partners pushing quantum sensing technology forward are smaller companies that rely on an academic base. Coordinating efforts could help sustain the **emerging markets**.

Sharing Lessons Learned

Finding 2.3: A challenge regarding many of the technologies is moving from ground-based development of large bench setups in a lab to an **integrated system that operates in space**. Overcoming this challenge will require strategic direction and coordination to ensure that lessons learned are shared.



Next Steps



Avenues for Increased Engagement with Industry and Academia

Explore the three S&T Forum agencies' models and mechanisms for engaging industry and academic institutions, to identify opportunities to develop enabling component technologies (e.g., leverage existing funding platforms to develop interagency needs).

Knowledge Sharing Among Developers

Ensure that subject matter experts in the S&T Forum have opportunities to share knowledge, convene as a community, and leverage industry breakthroughs.

Leveraging External Expertise

Leverage the quantum sensing expertise and investments of agencies outside of the S&T Forum, such as the National Science Foundation (**NSF**), the National Institute of Standards and Technology (**NIST**), and the Department of Energy (**DOE**).



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