Accelerating the Deployment of Space-Based Quantum Sensors

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**The Space Science and Technology Partnership Forum (S&T Forum), comprised of an interagency team from the National Aeronautics and Space Administration, the National Reconnaissance Office, and the United States Space Force, presents findings and recommendations from a study on the state of quantum sensors for space applications, enabling component technologies, facilities, and developers across government, industry, and academia. 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, atom interferometers, quantum magnetometers, Rydberg sensors, and single photon detectors. This paper focuses on two recommendations: 1) increased collaboration between the S&T Forum, industry, and academia on the development of enabling components for the five quantum sensing technology areas, and 2) challenges and future opportunities to take quantum sensors from the laboratory to space. Through this study, the S&T Forum found a diverse and broad community of quantum sensing developers in the United States that are leading efforts in research, testing, manufacturing, and qualification of quantum sensors and their enabling component technologies. There are common needs across quantum sensing technology areas. To address the common needs, the S&T Forum agencies are encouraged to utilize existing models and mechanisms to enable co-development of enabling component technologies and to explore new avenues for engagement with the quantum sensing community.**

# Background

The Space Science and Technology Partnership Forum (S&T Forum) was established in 2015 to bring together representatives from the National Aeronautics and Space Administration (NASA), the National Reconnaissance Office (NRO), and the Department of the Air Force in order to encourage coordination and collaboration across the government aerospace research, development, test, and evaluation community. The United States Space Force (USSF) took over as the primary representative for the Department of the Air Force in 2019. The technological maturity of quantum sensing is rapidly advancing and is expected to cross the threshold of laboratory-based demonstrations to fieldable, space-based instrumentation in the 2030s. From a physics perspective, quantum sensors offer advantages over traditional sensors; these advantages include higher signal-to-noise ratios, better measurement resolution and sensitivity, and accuracies that can be tied to fundamental constants. Though the mission scopes of the three S&T Forum agencies are distinct, quantum sensors relate to overlapping areas such as precision timing and attitude control, gravimetry, electromagnetic field sensing, and communications. The S&T Forum is well positioned to implement the recommendations of the National Science and Technology Council Subcommittee on Quantum Information Science for “bringing quantum sensors into fruition”: prioritizing partnerships with end users, conducting feasibility studies, developing broadly applicable components, and streamlining technology transfer [1].

To prepare for the opportunities of quantum sensing, the S&T Forum initiated a study in March 2023 to accelerate the deployment of space-based quantum sensors. The goals of the study were to 1) identify quantum sensors with promising near-term potential for space science and operations and identify the required infrastructure and supporting subsystems, and 2) develop a plan for the three S&T Forum agencies to collaborate and coordinate to accelerate the deployment of space-based quantum sensors. To accomplish these goals, the interagency study team sought to answer multiple questions:

1. Which quantum sensors are ideal for collaboration, providing benefits to all three S&T Forum agencies’ missions? What are the potential use cases and value propositions for quantum sensors, and how do these use cases and value propositions compare to those of traditional sensing technologies?
2. What component technology and infrastructure are required to enable the identified quantum sensors of interest?
3. Who are the points of contact in quantum sensors, enabling component technology, and infrastructure from the three S&T Forum agencies, their accompanying Federally Funded Research and Development Centers (FFRDCs), other U.S. government agencies, U.S. industry organizations, and U.S. academic institutions?

This paper discusses findings from the S&T Forum's exploration of space-based quantum sensing technologies during the study, as well as two recommendations for how the S&T Forum agencies can strategize on quantum technology development. The recommendations highlight: 1) increased collaboration between the S&T Forum, industry, and academia on the development of enabling components for quantum technologies in space, and 2) challenges and future opportunities to take quantum sensors from the laboratory to space.

Overall, the aim of these recommendations is to facilitate the development and advancement of quantum sensing capabilities for space and to increase collaboration amongst the S&T Forum agencies. The findings, recommendations, and next steps of the study are directed at the S&T Forum Principals: The Agency Chief Technologist in the Office of Technology, Policy, and Strategy (OTPS) at NASA; the Chief Engineer in the Advanced Systems and Technology Directorate at NRO; and the Director of Science, Technology, and Research at USSF. The purpose of sharing the study findings, recommendations, and next steps in this paper is to give the broader quantum sensing community insight into the S&T Forum perspective on accelerating the deployment of space-based quantum sensors. It is pertinent to elaborate on this topic so that the intended audience of this paper, technologists and researchers from industry and academia, understand potential areas for engagement with the S&T Forum agencies.

1. **Methods**

To arrive at recommendations, the interagency study team hosted and facilitated multiple interagency interactions to collect data, including an in-person Technical Exchange Meeting (TEM) and working group meetings among quantum sensing subject matter experts (SMEs). In preparation for the TEM, the interagency study team created a value proposition model based on the primary study goals of the three S&T Forum Principals. The model consisted of ten figures of merit that the interagency study team used to evaluate the data collected about quantum sensor projects across the agencies. The recommendations produced from the study were supported by findings derived from conversations with the SMEs and by analysis of the data collected for the value proposition model. In addition, each recommendation is accompanied by next steps for the three S&T Forum agencies to implement to achieve the recommendation’s objectives.

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, atom interferometers, quantum magnetometers, Rydberg sensors, and single photon detectors. Each agency has recently worked on, or is currently working on, development in some, or all, of the five areas. Atom-based sensing technologies are clearly of near-term interest. Additional areas of interest that were discussed at the TEM include solid-state sensors and entanglement-enhanced sensing. Each of the three S&T Forum agencies is driven by specific applications and requirements, but there is overlap in the research and development of quantum sensing technology. It should be noted that assessing the true benefits of quantum sensors in comparison to classical sensors is complicated and nuanced and comes with trade-offs in precision; flight heritage; and size, weight, and power (SWaP). The S&T Forum acknowledges that applications of quantum sensing technologies must be targeted and judicious to meet mission needs.

1. **Recommendation 1**

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

Several enabling component technologies were identified as cross-cutting for the five quantum sensing technology areas of near-term interest to all three S&T Forum agencies (see section A below). Further, a diverse community of industry, government, and academic organizations are developing enabling component technologies for quantum sensing. Given the common needs regarding enabling component technologies and the shared U.S. industrial and knowledge base, it is recommended that the three S&T Forum agencies share knowledge and coordinate efforts with industry and academic institutions, using the available engagement mechanisms (e.g., university institutes, small business programs). The next step in implementing this recommendation is to further explore the three S&T Forum agencies’ models and mechanisms for engaging industry and academic institutions to identify opportunities to co-develop enabling component technologies.

## Common Enabling Component Technologies

**Finding:** 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 space-qualified (i.e., radiation-hardened and temperature-resistant) electronics, laser optical systems, Photonic Integrated Circuits (PICs), vapor cells, space-qualified photodetectors, and cryogenic systems.

To raise awareness of the S&T Forum’s quantum sensing technology needs and increase engagement with industry and academia, the interagency team and the working groups identified several component technologies that can enable development in the five quantum sensing technology areas of near-term interest to the S&T Forum agencies as shown in Table 1.

Table 1. Common Enabling Component Technologies.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Enabling Technology | Quantum Sensing Technology Area Working Group | | | | |
| 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 |  |
| PICs | X | X |  | X |  |
| Vapor Cells | X |  | X | X |  |
| Space-Qualified Photodetectors |  | X | X | X |  |
| Cryogenic Systems |  |  | X |  | X |

In all the quantum sensing technology areas, development, manufacturing, and qualification are required to ensure the sensor systems can operate in the space environment and have a SWaP suitable for launch. The need for space-qualified electronics crosscuts the five areas of quantum sensing technology, as shown in Table 1. The sensor systems require radiation-hardening and temperature resistance. All three S&T Forum agencies require space-rated lasers that are stable, compact, power efficient, and radiation tolerant at all relevant wavelengths. Initial quantum sensors could be developed using space-qualified laser systems based on current technologies while the S&T Forum agencies focus on integration. Follow-on work could involve evaluating the development of mission-specific laser systems to replace the existing technologies. A key need is also to develop technology to repeatably and reliably create nitrogen vacancy (NV) centers in diamond to enable consistent performance in the relevant sensors. SWaP and packaging could be improved by coordinating the development of components not specific to quantum sensors, such as PICs. Additionally, for vapor cells to be readily available for quantum systems, there is a need to develop space-qualified vapor cell technology. Cryocooling requirements for single photon detectors have a large system-level impact on quantum sensors in space. Detectors are small, but the cryocooling system composes a large portion of the overall SWaP requirement for spacecraft. A possible path forward to address this challenge is to evaluate and analyze improved cryogenic systems and the performance of high-temperature superconductors. NASA is developing higher critical-temperature materials for single photon detectors. Another area for development is space qualification of peripheral electronics and photonics associated with cryogenic quantum sensors.

Enabling technologies specific to a single area of quantum sensing technology were also noted. Oscillators, transferring light off a chip, and frequency combs would specifically support flight-qualified atomic clocks. Quantum magnetometers would require isotopically purified semiconductors, bias magnetic field and coils, and microwave radio frequency (RF) systems. Rydberg sensors would require resonators and microwave dressing fields. Multiplex imaging arrays and time taggers would specifically support flight-qualified single photon detectors, namely superconducting nanowire single photon detectors (SNSPDs).

## Quantum Sensing National Landscape

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

Members of the working groups identified more than eighty-two entities in twenty-two states as being part of the United States industrial and knowledge bases of quantum sensing, as shown in Figure 1. These entities include NASA Centers, Department of Defense (DoD) organizations, FFRDCs, universities, and private companies in which quantum sensors or enabling components are researched, developed, and manufactured. In some cases, these entities are actively working on more than one type of sensor or enabling technology. 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.

**Map

Description automatically generated**

**Figure 1. Heat map of entities working on quantum sensing and enabling technologies in the United States.**

## Avenues for Increased Engagement with Industry and Academia

**Next Step:** 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, such as Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs, to develop interagency needs).

Multiple enabling technologies need to advance for all S&T Forum agencies to succeed. The S&T Forum agencies should collaborate to stimulate the industrial and academic knowledge bases and strategic investments in which all partners contribute. Key enabling technologies that need further development are space-qualified lasers, NV centers in diamond, and vapor cells. Determining how to modify existing laser technologies for space qualification is a key early step for quantum systems. Technologies that can reliably and accurately create NV centers in diamond with repeatable properties will enable a broad application of quantum sensors.

It was identified that there could be benefit from greater coordination with industry and academia as there is mutual benefit. A coordinated approach could help to speed up the innovation curve for some technologies. Projects should be presented to the S&T Forum for a shared understanding of technology maturation and communication of future technology hurdles.

1. **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.**

The three S&T Forum agencies should coordinate and collaborate to address the gaps in using quantum sensing to achieve each agency’s goals regarding space. Three barriers to closing these gaps were identified: the developing supply chain, the emerging commercial market, and funding for integrated spaceflight demonstrations. The next steps in implementing this recommendation are to increase connections and coordination among SMEs in the S&T Forum and to expand the agencies that the S&T Forum engages with to include other parts of the federal government that are involved in quantum sensing development.

## Enabling Rapid Space Qualification of Quantum Sensors

**Finding:** 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.

Almost every key component of quantum sensors (e.g., vapor cells, laser systems, and frequency combs) is in limited supply, does not meet application needs and requirements, or does not exist outside the lab environment. Although the specifics for each of the three S&T Forum agencies differ, the agencies do need some of the same enabling sources, electronics, and photonics. Further, all three S&T Forum agencies require space qualification at the subsystem and component levels.

Here again, size, weight, and power (SWaP) is a major factor. A challenge for optical atomic clocks is the SWaP needed for a space-based system. Reducing optical clock performance could allow for a much smaller system with performance equivalent to a microwave clock. This miniaturization of atomic clocks can be helpful in some applications, even with performance reduction. Regarding integrated photonics, it is challenging to reduce the size without decreasing system performance. Rydberg sensors will also require improvements in SWaP. SNSPDs require very cold operating temperatures often in the mK range. Raising their operating temperatures to 20-25K range would improve the SWaP.

## Coordinating Small Business Support Efforts

**Finding:** 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. The S&T Forum coordinating efforts with these small companies could help sustain the emerging markets.

Small businesses are providing many of the enabling component technologies for quantum sensors. Production of components and systems has not yet scaled to routine large production lines especially for space-qualified parts. There are several supply chain challenges in developing enabling components of quantum often from the low production volume and not having an industrial base due to lab-based development. In an existing demonstration, NASA’s Cold Atom Lab has flown commercial diode lasers, which are shielded from radiation inside the International Space Station [2]. Currently, there are only a handful of government labs and academic institutions focused on developing SNSPDs, with no industrial base.

## Sharing Lessons Learned

**Finding:** 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.

While some subsystems may be robust against vibrations, thermal cycles, and radiation; the supporting subsystems require significant attention to the reduction of SWaP and to ensure they can meet the unique environment of space.

## Knowledge Sharing Among Developers

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

Knowledge-sharing activities that would benefit the S&T Forum’s members include compiling a comprehensive database of space-qualified flight components, transferring personnel between agencies in the short term or long term, and routinely exchanging knowledge through working groups. The three S&T Forum agencies should leverage shared knowledge. For example, knowledge about verification and validation techniques can be leveraged across the agencies to build more mature models for system validation and to build a common framework in which agency-specific modules can be tested. An annual TEM for S&T Forum participants could keep the interagency community engaged beyond the completion of this study. Relationships between subject matter experts could be maintained by participation in existing groups such as NASA’s Quantum Sensing Community of Practice run by the NASA Engineering and Safety Center, the informal NASA PIC working group, and the NRO’s Forum for Innovative Research in Science and Technology (FIRST).

## Leveraging External Expertise

**Next Step:** When implementing these recommendations, the S&T Forum should also 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).

The three S&T Forum agencies recognize their place in the whole-of-government picture. More work is needed for the three S&T Forum agencies to better understand their roles and how inputs from other organizations can be leveraged, keeping in mind that those organizations may have different and unique needs, objectives, and investments for quantum sensing technology. The three S&T Forum agencies should explore opportunities to partner with and collaborate on initiatives with other funded organizations. Opportunities may be available through the CHIPS and Science Act [3] and with other U.S. government agencies such as NSF, DOE [4, 5], and NIST. Furthermore, the S&T Forum may look to engage further in the Quantum Economic Development Consortium (QED-C), established by NIST in response to the National Quantum Initiative Act, which includes stakeholders across industry, academia, and government to enable and grow the quantum industry [6].

1. **Conclusion**

Quantum sensing has the potential to revolutionize missions for the three S&T Forum agencies. There is a need to stimulate research and development of quantum sensing technologies in industry and academia. The recommendations resulting from the S&T Forum study lay a strong foundation for interagency collaboration and coordination, identifying areas of technology development with the highest near-term potential to accelerate deployment of space-based quantum sensors. Between the ongoing efforts of the diverse community of quantum technology developers in industry and academia and the quantum sensing needs of the S&T Forum agencies, there is an opportunity and interest in the co-development and space qualification of enabling quantum component technologies. Many of the existing groups, funding programs, and facilities mentioned in this paper could be leveraged to support this effort. The quantum sensing interests of S&T Forum agencies highlighted in this paper should serve as a foothold for future industry and academic partners looking to initiate collaborations with the U.S. government space agencies.

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