QED·C

QUANTUM SENSING USE CASES

PROSPECTS AND PRIORITIES
FOR EMERGING QUANTUM SENSORS

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About the Quantum Economic Development Consortium

The Quantum Economic Development Consortium (QED-C) is an industry-driven consortium managed by SRI International. With a diverse membership and participation from across the quantum ecosystem, including industry, academia, government and other stakeholders, the consortium seeks to enable and grow the quantum industry and associated supply chain. For more about QED C, visit quantumconsortium.org.

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Executive summary

Quantum sensors are devices that leverage the quantum properties of a system to measure forces, fields, or time. In the late 20th century, the development and proliferation of clocks based on atomic vapors helped drive revolutionary advances in communications and absolute positioning systems such as GPS, among others. While atomic clocks continue to be a success story in the quantum sensing arena, sensors based on the quantum properties of atomic vapors, solid state defects, and superconducting circuits are now being used to make high performance measurements of inertial forces and electromagnetic fields. Though the performance of these quantum sensors is often compelling, they typically compete in crowded application spaces against mature, commercially available devices based on classical sensing principles. Given the considerable resources required to transition nascent quantum technologies from the prototype stage to designs that are both deployable and manufacturable in volume, there is a need to identify use cases for which these devices could provide revolutionary advances relative to current commercial offerings. This report identifies several such use cases and is based on briefs and discussion that occurred during a March 2022 workshop hosted by the Quantum Economic Development Consortium (QED-C) and attended by more than 300 representatives from industry, academia, and government.

The basic value proposition of emerging classes of quantum sensors can generally be divided into two categories. First, they may provide novel capabilities and/or performance levels not available with classical state of the art sensors. Second, they may provide comparable capabilities and performance to existing sensors but in a more compelling size, weight, power, or cost envelope. With both possibilities in mind, this report identifies high-priority use cases for quantum sensors in assured positioning, navigation, and timing (PNT), communications, and remote sensing (magnetometry).

To facilitate progress toward realizing robust, high-performance sensors to support the use cases above, this report also makes the following observations and recommendations for the joint community of quantum sensor developers and end users:

I. Deeper engagement is required between quantum sensor developers and targeted user communities to ensure that sensors meet or exceed user requirements and are robust against realistic environmental conditions in areas of greatest benefits.

II. Sensor developers and their financial backers should acknowledge that design paradigm shifts from "lab-in-a-box" approaches to robust, deployable architectures are often necessary, time-consuming, and costly.

III. Government-sponsored technology development pipelines generally do not promote cradle-to-grave maturation of technologies. Community-wide discussion of methods for making these pipelines more efficient to minimize the valley of death is worthwhile and needed.

IV. Government organizations should consider approaches for improving access to commercial-type testbeds and platforms to better support high-fidelity emulation of realistic operating conditions for promising quantum sensor variants. Such access would reduce financial burdens on small quantum sensor startups while ensuring that the government gains insight into sensor capabilities in real-world conditions.

V. Additional investment in the development of key enabling technologies is required. Advances in the performance and portability of lasers, vacuum components, photonic integrated chips, quantum transducers, and low noise electronics (among others) is required to benefit a range of quantum technologies in the sensing space and beyond.

1 Introduction

Quantum sensors exploit the quantum structure or properties of a system to measure quantities like forces, fields, and time.[1] To date, laboratory and portable atomic clocks arguably represent the most prominent success story in the quantum sensing arena, offering high-accuracy time and frequency references that support vast swaths of modern communication, financial, and absolute positioning systems. The same properties that make quantum systems accurate and stable timepieces can be leveraged to measure other physical quantities, however, and high-performance measurements of accelerations, rotations, gravity, magnetic fields, and electric fields have been reported (see, for example, [1] [2] [3]). While these developments are promising, as with other nascent technologies, significant hurdles often remain to graduate these capabilities from the laboratory into real-world environments.

In contrast to other proposed quantum technologies like fault-tolerant quantum computers and advanced quantum communication systems, in many cases quantum sensors do not explicitly enable capabilities that are otherwise challenging or impossible to achieve using existing classical approaches. For example, quantum inertial sensors compete directly against a vast array of mature, commercially available mechanical, micro-electro-mechanical (MEMS), and optical devices across a range of performance classes. Likewise, magnetometers based on quantum systems such as atomic vapors and defect centers in diamond are direct competitors with established technologies like fluxgate magnetometers, induction coils, and magneto-resistive sensors. Rydberg electric field sensors compete with an existing ecosystem of high-performance antennas and receiver systems. Given the crowded spaces in which many classes of quantum sensors are expected to compete, identifying development efforts that could yield revolutionary advances relative to the current state-of-the-art for key applications is of paramount importance.

This report provides a brief overview of promising quantum sensor classes and identifies use cases where they may provide transformative capabilities relative to the current state-of-the-art. In addition to identification of these priority use cases, this report also provides recommendations for quantum sensor developers, funding sources, and end users to expedite the maturation of these technologies from the laboratory or early prototype stages to robust, deployable designs. These use cases and recommendations were identified during a two-day

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[1]Throughout this document, colloquial wording is frequently used when referring to atomic clock and frequency systems as sensors that measure time. With apologies to those in the time and frequency metrology community who might prefer more precise wording, this intentional choice was guided by a desire to produce an accessible document for a potentially non-technical audience.

workshop co-organized by the Quantum Sensing sub-group of the Use Cases Technical Advisory Committee (TAC) and Quantum for National Security TAC of the Quantum Economic Development Consortium (QED-C). This workshop was held on March 30–31, 2022, and was attended by more than 300 participants representing industry, government, and academia. In addition to the findings summarized in this report, readers are also encouraged to review a recent document [4] by the National Science and Technology Council for perspectives on supporting the maturation of quantum sensors.

Quantum sensors that offer significant performance enhancements and/or reduction of size, weight, and power (SWaP) are expected to have the highest impact. The notional projected impacts of select quantum sensors for national security and commercial use cases are depicted in Figures 1 and 2, respectively. Sensors which have current or projected performance enhancements and/or SWaP specifications that are unmatched by classical sensors are characterized as moderate-to-high impact. High-SWaP sensors and/or those which have uncertain performance enhancements compared to classical sensors are characterized as having lower impact. It should also be noted that of the more advanced or commercially available sensors referenced in Figs. 1 and 2, many have newer versions undergoing early research and development (R&D) which may increase their potential impact.

Table 1 summarizes the sensor classes discussed in this report. Section 3 considers opportunities for next-generation atomic time and frequency devices, including emerging optical clock technology. Section 4 summarizes the current state of quantum inertial sensing devices and
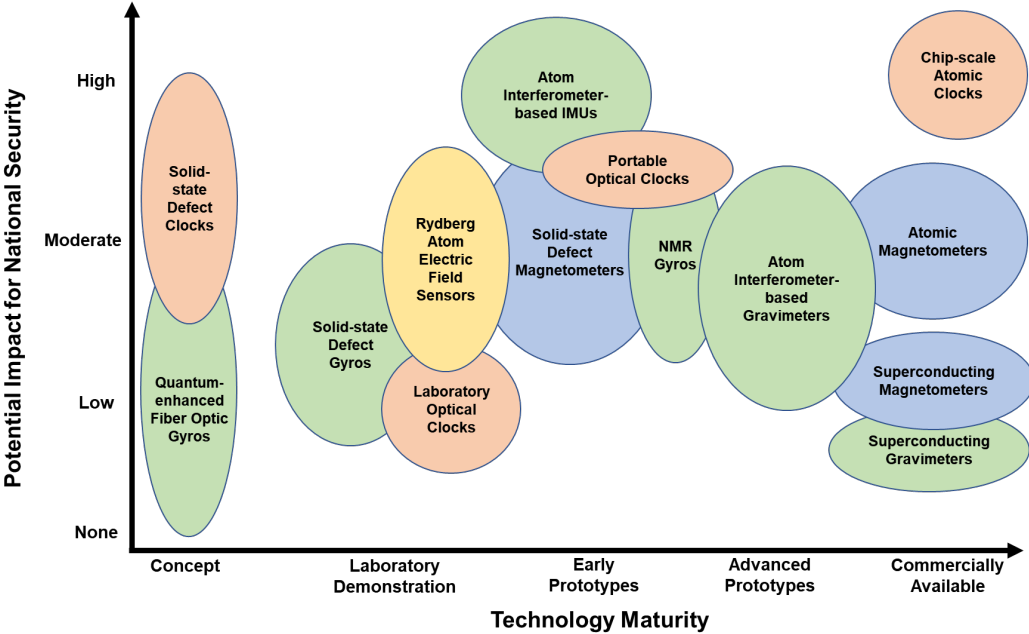

Fig. 1. Notional projected impacts for national security of select quantum sensors.
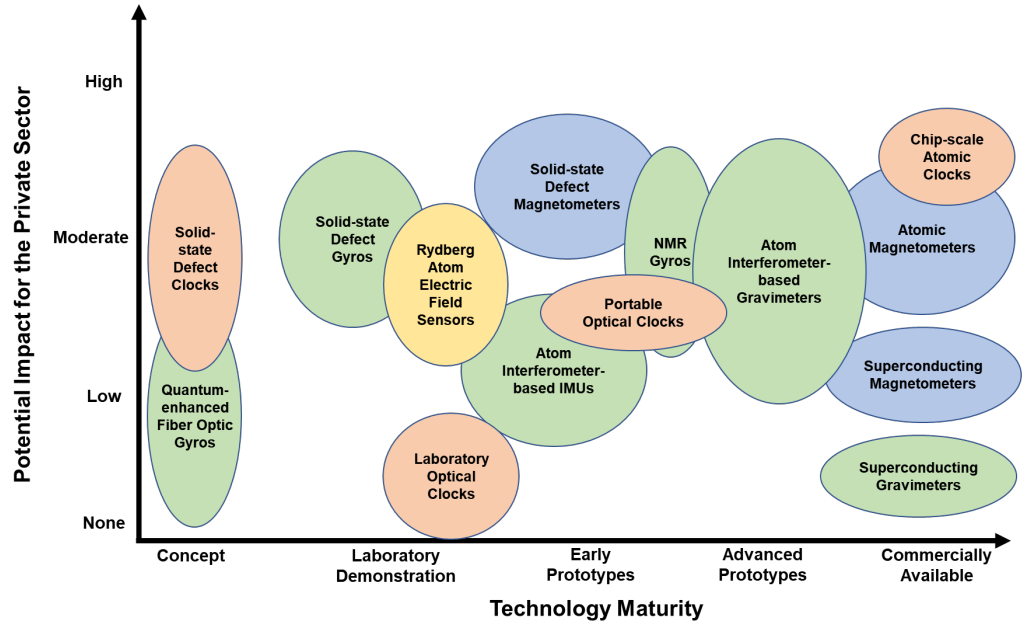

Fig. 2. Notional projected impacts for the private sector of select quantum sensors.

priority application spaces for their deployment. Section 5 addresses similar questions for quantum electric and magnetic field sensors. Section 6 concludes with a summary of findings and offers recommendations for stakeholders to expedite the development of the quantum sensing ecosystem.

Table 1: Quantum sensor classes, their current state of development, and relevant application spaces.

Category	Sensor type	Current maturity	Relevant applications
Timing	Microwave atomic clocks	Commercially available; broadly deployed	GPS-denied timing; Secure & resilient communications; Advanced sensing concepts (e.g., radar, reflectometry) requiring synchronized distributed sensor nodes
	Optical atomic clocks	Research grade, including both laboratory-scale and portable designs	
Inertial	Atom interferometer	Advanced prototypes, with limited commercial availability for gravimeters	High-end tactical grade and above inertial navigation
	Nuclear magnetic resonance	Advanced prototypes	High-end tactical grade and above rotation sensing
	Solid-state defect	Research grade	Space-constrained rotation and orientation sensing
Magnetic field	Atomic vapor	Commercially available	Resource exploration; underground infrastructure mapping; GPS-denied navigation; biomagnetics
	Solid-state defect	Primarily research grade; limited commercial availability of scanning microscope & bulk magnetometry devices	Magnetic microscopy; Widefield magnetometry; Geo-survey; GPS-denied navigation
	SQUID	Commercially available	Biomagnetics; resource exploration
Electric field	Rydberg sensor	Primarily research grade; custom sensors available for purchase from limited vendor base	Antenna calibration and other near-field spectrum sensing with mutual interference mitigation; wideband communications and sensing

	Solid-state defect	Primarily research grade	Electric field nano-microscopy; RF spectrum analysis

2 Atomic clocks

The history of increasingly accurate timekeeping [5] features a fascinating push-pull dynamic in which progress has sometimes arisen in response to an established need (e.g., the 1714 Longitude Act enacted by British Parliament to accurately determine longitude and thereby prevent loss of seagoing vessels) and sometimes due to technical progress that ultimately yielded unforeseen capabilities at the time of the innovation (e.g., meter-level position accuracy from the atomic-clock-backed GPS satellite constellation). While this dynamic presents challenges when trying to identify priority use cases for emerging atomic clock technologies, the increasing emphasis on developing portable variants of these devices suggests several priority development thrusts, as discussed later in this section.

The degree to which the emergence of atomic clocks has revolutionized precision timekeeping is perhaps best illustrated by observing that the very definition of the second has been based on atomic structure since 1967.[2] Atomic clocks probing microwave transitions (on the order of 10 GHz) in the ground state of alkali metal atoms dominate commercial atomic clock offerings and see widespread use in the communications, financial, utilities, and space sectors, among others.

Atomic clocks based on microwave frequency transitions account for the majority of atomic clocks in use globally. While these devices found widespread use throughout the late 20th century, it was not until the early 2000s that truly portable variants were developed. The DARPA Chip-Scale Atomic Clock (CSAC) program, initiated in 2001, sought to develop a portable, battery-powered atomic clock to support military needs for secure communications and jam-resistant GPS receivers [6]. A collaboration by

Fig. 3. Chip-scale atomic clock from Microchip. Image reproduced with permission from Microchip.

Symmetricom (now Microchip), Charles Stark Draper Laboratory, and Sandia National Laboratories developed a device that was brought to market by Symmetricom in 2011. Since that

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[2]Resolution 1 of the 13th Conférence Générale des Poids et Mesures established "The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the Caesium 133 atom." Modern atomic clocks based on optical transitions have uncertainties that are orders of magnitude better than microwave clocks, and it is expected that the second will be redefined in terms of an optical standard in the next decade (see, e.g., [47]).

time, more than 120,000 CSACs have been sold by Microchip [7], whose device is depicted in Fig. 3, and Teledyne Technologies has also brought a commercial offering to market [8].

The trend toward miniaturization and potential cost reduction for other, larger classes of microwave atomic clocks is also apparent. A notable mid-range microwave clock is the Deep-space Atomic Clock (DSAC) ion clock developed by NASA, which offers significant improvements in stability and drift compared to commercial offerings with comparable volumes. The DSAC is currently in orbit and expected to offer enhanced autonomy for deep-space navigation and radio astronomy [9].

The development of the optical frequency comb in the early 2000s has facilitated the development of higher performance atomic clocks based on optical transitions [10], though these devices are currently research-grade. Advanced laboratory optical clocks are currently producing systematic uncertainties on the order of 10^{-21}, which corresponds to a change in altitude of roughly one centimeter due to gravitational redshift [11]. While this development has been identified as a potential means of using networks of clocks for terrestrial geodesy [12], it presents a challenge for their use as timepieces since gravitational effects arising from, e.g., the change in the local terrestrial water table would impact the accuracy and apparent stability of the clock. As such, very high-performance optical clocks might be best hosted on satellites whose altitudes are sufficiently large to suppress these effects [13]. Other smaller, portable optical clocks currently under development are expected to offer improvements in stability compared to similar-size microwave clocks [14]. These devices are expected to offer support for longer holdover in GPS-denied environments and improved synchronization for networks of sensors [15, 16].

Section 3.1 elaborates on these developmental trends and identifies promising use cases for both microwave and optical atomic clocks.

2.1 Priority use cases

Table 2 summarizes current and future use cases for various atomic clocks. Commercially available atomic clocks are currently in use for applications including telecommunications, navigation (GPS), finance (time stamps for trading), GPS-denied (e.g., underwater) sensing, and distributed sensing. Advanced microwave clocks and emerging optical clocks are expected to enable improved stability compared to existing systems with comparable form factors. State-of-the-art optical clocks are expected to form the new basis for the SI definition of the second and enable new measurements for fundamental physics and geology.

Type of Clock	Priority use cases
Microwave chip-scale atomic clock	*Oil and gas exploration,* **Next-generation alternative GPS architectures**
Mid-range microwave atomic clock	*GPS/GNSS, Communications networks*
State-of-the-art microwave atomic clock	*International timekeeping, Very-long-baseline interferometry*
Portable, low-SWaP optical atomic clock	**GPS-denied navigation, Distributed sensing (e.g., synthetic aperture radar)**
State-of-the-art optical atomic clock	**International timekeeping, Geodesy, Fundamental physics**

3 Quantum inertial sensors & gravimeters

Originating in the pioneering work conducted by Steven Chu and Mark Kasevich at Stanford in the 1990s [17], high stability and sensitivity measurements of rotations, accelerations, and gravity using atom interferometers have been pursued using increasingly compact and portable instruments. In limited cases, instruments have reached the stage of commercial availability, as in the case of the MuQuans/iXblue Absolute Quantum Gravimeter. Section 4.1 provides a brief overview of these designs and reviews their current state of maturity. Sections 4.2 and 4.3 offer a similar discussion for inertial sensors based on solid state defects and optically pumped nuclear magnetic resonance (NMR) designs, respectively. Finally, Section 4.4 identifies priority use cases for this class of quantum sensor.

3.1 Atom interferometers

The advent of laser cooling and trapping of atomic vapors in high vacuum systems [18] has led to numerous basic and applied scientific developments. Among these is the use of cold atomic vapors and thermal atomic beams for the detection of accelerations and rotations (see review articles by Degen, et al [19], Kitching, et al [20], and Narducci, et al [21]). Inspired by successful university research lab demonstrations [17] [22] [23], a variety of organizations and commercial startups (AOSense, Muquans/iXblue, ColdQuanta, and Vector Atomic, among others) are now pursuing more portable variants of these designs, with particular focus on markets requiring high-end tactical through strategic grade performance.[3] The same technology base and methods are used in gravimeters and gravity gradiometers, and, as noted above, some of these devices are

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[3] These performance categories include: high-end tactical grade systems for use in platforms like smart munitions and unmanned aerial systems; navigation grade systems for commercial airliners, and strategic grade units for use in submarines and intercontinental ballistic missiles.

currently commercially available, with one example shown in Fig. 4.

While a detailed description of atom interferometry, which forms the basis of the inertial measurement in these systems, is beyond the scope of this report, it can be described in brief as a direct analog of optical interferometry in which atoms play the role of photons and carefully administered laser pulses function as beamsplitters and mirrors. In contrast to many other inertial sensor designs, the

Fig. 4. Quantum Gravimeter from iXblue. Image reproduced with permission from iXblue.

proof masses in an atom interferometer are atoms that are not tethered to the sensor case. As such, they are not subject to the nonlinearities and drift processes that are generally associated with restoring flexures and springs common to many other inertial sensor designs. While this isolation from the sensor case confers numerous benefits, it also introduces some complications. For instance, the measurement sequence in an atom interferometer is inherently sensitive to both accelerations and rotations, and cross-axis inertial inputs can become problematic for operation in dynamic environments.

3.2 Solid state defects

Nitrogen-vacancy (NV) centers in diamond have been proposed as a candidate system for applications including quantum computing, magnetic microscopy [24], and inertial sensing [25]. Diamond is a solid form of carbon with a well-defined crystalline structure. In NV center diamond, as in pure diamond, most lattice nodes are populated by carbon atoms. Unlike pure diamond, however, nitrogen impurities adjacent to unoccupied lattice sites are substituted for the carbon atoms that typically occupy those diamond lattice sites. These NV centers host a two-level quantum system that can be excited and measured optically. The solid-state nature and potentially small size of NV center systems make them good candidates for high resolution magnetic or electric field microscopy as well as for operation in challenging environments across a variety of sensing and measurement modalities. The use of NV centers in diamond for rotation sensing leverages the stability and isolation of the nuclear spin for the primary inertial measurement and the more readily accessible electron spin for system readout. These devices are being discussed as a potential competitor to MEMS-based sensors, though early proof of concept demonstrations have shown modest sensitivity (13 mHz/Hz$^{1/2}$) and bias stability (0.4 deg/s) [26].

3.3 NMR gyroscopes

While the investigation of gyroscopes relying on nuclear magnetic resonance (NMR) dates to the 1950's [27], there has been a renaissance of activity in this area due to more recent advances in key enabling technologies and miniaturization approaches. Much of this work has been driven by development efforts at Northrop Grumman [28], [29]. An example NMR gyro from Northrop Grumman is depicted in Fig. 5. Modern implementations of these systems rely on an optical pumping scheme in which spin polarization of an alkali metal vapor is transferred to a noble gas via collisional processes. Individual atoms in the polarized noble gas vapor have a

Fig. 5. NMR Gyro physics package from Northrop Grumman Corporation. Image reproduced with permission from Ref. [27].

magnetic dipole moment, causing them to precess about a bias magnetic field with a frequency proportional to the strength of the field. Provided the bias magnetic field remains constant, any apparent change in the precession frequency of the noble gas is then due to the rotation of the sensor case. Practical implementations of this design include precision magnetic field bias coils, magnetic shields to mitigate the impact of environmental magnetic field noise, and the use of multiple noble gas isotopes to suppress systematic drift effects.

3.4 Priority use cases for quantum inertial sensors

Target use cases for quantum inertial sensors are summarized in Table 3 below. Broadly-speaking, the performance of these sensors will encourage their use in navigation-grade or better application spaces for the defense and aerospace communities, though NV diamond gyroscopes are likely to compete with MEMS devices.

Table 3: Priority use cases for quantum inertial sensors

Type of Sensor	Priority use cases
Atom interferometer-based inertial measurement units	Navigation grade to Strategic+ grade performance for Department of Defense and Aerospace applications; Navigation grade performance for autonomous vehicles
NMR Gyroscopes	Munitions, missiles, and high performance (Strategic+) Department of Defense platforms
Atomic Gravimeters/Gravity Gradiometers	Mineral exploration, tunnel/bunker/object detection, ground water monitoring, city infrastructure monitoring and maintenance, gravity imaging/tomography, gravity map making & matching for navigation and complementary navigation methods; exquisite sensitivity for safety monitoring in geological/vulcanology studies
NV-defect gyros	Miniature gyro (possibly within 10 years) to support very small platform applications for which MEMS devices are inadequate

For many inertial sensing or gravimetry applications, the long-term stability of the sensor is a key driver of system performance. Atom interferometers (for both inertial sensing and gravimetry) as well as NMR gyroscopes leverage stable atomic structure to support their measurements. This atomic structure is both uniform for all atoms of the same species and isotope and does not change over time, in contrast to the physical proof masses used in many other sensor classes. As a result, these sensors are capable of extremely high performance and may have good long-term prospects for reduced unit cost, given their lack of moving and/or precision-machined parts. In general, however, these systems project to remain more complex and costly than sensor types (such as MEMS devices) that dominate more modest performance categories. Consequently, many of the priority use cases for these devices listed in Table 2 emphasize applications currently dominated by high performance mechanical devices, fiber optic gyroscopes, and ring laser gyroscopes. Whether quantum systems can take some market share from these established instrument classes will likely depend on their ability to provide comparable or better performance at a more desirable price point.

In the case of NV defects in diamond for use as gyroscopes, the long-term prospects are more challenging to predict. Considering form factor, zero g-sensitivity, and long-term stability, they would potentially be competitive with MEMS-based instruments especially in harsh environments, though significant additional work is needed to understand the performance bands in which they will compete.

4 Quantum magnetic and electric field sensors

A variety of quantum systems can exhibit net magnetic and electric dipole moments, allowing them to respond sensitively to external magnetic and electric fields. In contrast to many competing (non-quantum) sensor types, the performance of quantum sensors is often not principally dependent on the physical geometry of the sensing mechanism. As such, these sensors can offer unique advantages for size-constrained applications. The following subsections provide a summary of the state of the art for several classes of quantum sensor before summarizing use cases of interest in Section 5.5.

4.1 Atomic vapor magnetometers

Although the basic operating principles of magnetometers based on atomic vapors were known in the late 1950's [30] [31], the past several decades have seen a renaissance of interest in these systems, as the maturation of compact, spectroscopy-grade lasers and small vapor cells have enabled development of portable, high-sensitivity variants of these sensors. While the specific operating principles vary across devices, typical designs generally involve an alkali metal vapor (such as rubidium) housed in a glass vapor cell that is laser-pumped to an electronic state exhibiting a net magnetic dipole moment. The magnetic moments of the constituent atoms of the vapor then respond to ambient magnetic fields, and this response is generally tracked optically by monitoring changes in the index of refraction of the atomic vapor.

Fig. 6. Micro-fabricated Atomic Magnetometer from Geometrics. Image reproduced with permission from Geometrics.

These basic principles have been used to measure human brain and heart activity, low-frequency magnetic fields, and fields in the hundreds of megahertz for explosives detection. A number of commercial companies are now developing and/or selling these sensors, including Fieldline, Geometrics, QuSpin, and Twinleaf, with one example device from Geometrics shown in Fig. 6.

4.2 SQUIDs

Superconducting Quantum Interference Device (SQUID) sensors utilize loops of superconducting wire and Josephson junctions to detect changes in magnetic flux. These systems have been commercially available for many decades and have seen notable uptake in applications such as magnetoencephalography and resource exploration [cite]. While SQUID-based sensors are capable of outstanding sensitivity, their need to operate at cryogenic temperatures can limit their

use in portable applications. Relative to other sensor classes discussed in this report, SQUID magnetometers are generally mature, and identification of additional markets and applications is the primary limiting factor to further proliferation of these sensors.

4.3 NV centers

In addition to the inertial sensing capabilities discussed in Section 4.2, NV centers in diamond have also been used for detection and measurement of magnetic and electric fields. In this operating mode, the two-level quantum system formed by the nitrogen vacancy and adjacent empty lattice site exhibits changes in fluorescence following optical excitation in the presence of changing magnetic fields. well-localized nature of the crystalline defects and the ability to produce such defects close to the surface of

Fig. 7. Quantum scanning microscope from QZabre. Image

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bulk material enables short standoff distances from objects of interest for high spatial resolution magnetic microscopy [32], one example of which is depicted in Fig. 7. These sensors can also be used to generate full vector field information [33], which may have utility in applications such as navigation via magnetic anomalies [34]. In general, these systems are research-grade, though there are some preliminary commercial offerings of magnetic microscopy systems from Qnami (Muttenz, Switzerland) and QZabre (Zurich, Switzerland).

4.4 Rydberg atom electric field sensors

Rydberg atoms are atoms whose valence electron has been excited to a high-energy "Rydberg" state. These highly excited atoms behave as sensitive electric dipoles, and a collection of Rydberg atoms can be used as an electric field sensor which has been shown to be sensitive to a wide range of frequencies from near-DC [35] through THz [36]. This ultra-wideband frequency tuning is not attainable with a traditional antenna-based receiver, whose tunability is limited by impedance matching challenges. These sensors have also been shown to enable improved accuracy and precision for amplitude and phase measurements [37, 38], which could in turn improve the resolution of sensing applications such as radar.

Reproduced with permission from Rydberg Technologies, Inc.

In addition, because the sensor heads can be constructed entirely of non-conductive material, they are not susceptible to mutual inductive coupling with nearby antennas, and hence they may offer improved accuracy for near-field precision measurements, such as antenna characterization. There is one commercial offering of this sensor from Rydberg Technologies, Inc., whose product is depicted in Fig. 8.

4.5 Priority use cases

Quantum electric and magnetic field sensors may ultimately play a role in a wide range of fields, as indicated in the table below. Due to the early-stage nature of some of these devices, their maximum value propositions for some applications are anticipated to emerge with further development and refinement. For instance, better understanding of the achievable sensitivity, stability and bandwidth of NV diamond-based magnetometers will help guide future development toward favorable applications. Likewise, maturation of Rydberg atom electric field sensors will yield a better understanding of their frequency hopping agility as well as compatibility with existing communications protocols, which should inform their highest impact near-term use cases.

Table 4: *Priority use cases for electric and magnetic field quantum sensors*

Type of Sensor	Priority use cases
Atomic magnetometers	Detection of ships, submarines, and other magnetic anomalies; miniaturization would enable persistent monitoring of large perimeters/areas; geological surveys; complementary absolute navigation via crustal magnetic anomalies; biomagnetics (brain & heart)
SQUID magnetometers	Biomagnetics (brain & heart); best suited for static, shielded operating environments to leverage high sensitivity and manage cryogenic cooling requirements; low-frequency communications and sensing
Solid-state magnetometers and electric field sensors	Nanoscale MRI, microscopy for biological imaging, magnetoencephalography, material analysis, crystal structure mapping, and integrated circuit integrity analysis; Bulk devices could be used for RF spectroscopy, communications, navigation via magnetic anomalies, and geological surveys
Rydberg atom electric field sensors	Ultra-wideband spectrum sensing and communications; High-accuracy near-field sensing with mitigation of inductive coupling

Of the devices listed in 4, SQUID magnetometers are the most mature and appear to have found their target use case: stationary, magnetically shielded settings for high-sensitivity measurements, such as biomagnetics. Atomic magnetometers are the next most mature technology, and their combination of high sensitivity, good absolute accuracy, and small size make them favorable candidates for use on mobile platforms for tasks like resource mapping, anomaly detection, and navigation via the Earth's crustal magnetic anomalies. Solid state magnetometers offer unique

capabilities in terms of sensitivity, vector sensing capabilities, and very high spatial resolution for near-field measurements, which makes them well-suited for a variety of magnetic microscopy applications. Finally, the very broad tunability of Rydberg atom electric field sensors make those devices excellent candidates for a variety of demanding spectrum sensing and communications problems, and their metal-free sensor heads may enable higher resolution near-field measurements for certain applications, such as precision antenna characterization,

5 Discussion and recommendations

While much of this report is forward-looking in nature, it is worth taking a brief look back in search of lessons learned. To this end, particular focus is given to the efforts that led to the CSAC. While both a technological tour de force and a clear quantum sensing success story, the development and commercialization of the CSAC offers some cautionary notes that are relevant for other classes of quantum sensors. When it was first introduced, the unit cost of a CSAC was roughly $1,500 [39]. A subsequent Department of Defense Manufacturing Technology program sought to reduce these costs to roughly $300 per unit [40], and while many technologies do trend toward reduced unit cost as economies of scale are realized, in the intervening decade the unit price of a CSAC has *risen* to more than $5,000 with lead times on the order of three months [41].[4] The lengthy lead time suggests that CSAC production is at maximum capacity, a potential byproduct of a physics package design optimized for aggressive DARPA program goals rather than volume manufacturing [42]. Further, while the original intended applications were decidedly military in nature, a significant number of manufactured CSACs are currently seeing use in the oil and gas exploration industry [43]. While current research and engineering efforts to bring additional quantum sensors to market focus sensibly on maintaining the lofty performance from proof-of-concept laboratory demonstrations, it is worth considering that the arduous task of designing for manufacturability may be equally important to the long-term commercial success of the sensor. Likewise, even a thoughtful assessment of target markets might fail to identify both the highest impact use cases and the associated unit volumes manufacturers might expect to deliver to those markets.

With the above thoughts in mind, **key observations and recommendations** for the community of stakeholders funding, developing, and using quantum sensors are presented below:

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[4] Cost and lead time associated with direct purchase from Microchip, as of 06 April 2022. Similar costs and lead times were present prior to the COVID-19 pandemic, so we do not attribute these conditions to the widespread supply chain and labor availability constraints that have impacted other manufacturing pipelines in the 2020-2022 timeframe.

I. **Deeper engagement is required between quantum sensor developers and end users**. Developers should understand the existing solution space and barriers to market entry, including where current sensor offerings are lacking, as well as pain points and potential size, weight, power, or cost deal-breakers for end users. Developers should also note that most end users regard their sensors as black boxes whose contents are largely inconsequential, so long as they meet performance and cost requirements.

II. **Bridging the valley of death** [44] **is both difficult and expensive**. Funding for early-stage prototypes and demonstrations can be modest yet still yield high visibility outcomes. Conversely, costs associated with clearing the last several stages of the technology readiness level (TRL) ladder are generally much higher and the potential return on those more significant investments may be murkier. Company founders whose expertise resides in the physics and engineering arenas would benefit from tighter collaboration with more business-savvy colleagues, particularly as technologies approach commercial availability.

III. **Design paradigm shifts from "lab-in-a-box" approaches to more rugged, deployable designs may be necessary, time-consuming, and costly.** Maintaining the same basic design and merely shrinking component sizes may be an ineffective approach when moving from the prototype to commercialization stages of sensor development. In addition to the basic development challenges of novel sensing approaches, demonstrating that a device is rugged and deployable is difficult. Measuring short-term device sensitivity is often easy, but characterizing and refining long-term stability, a key selling point for many quantum sensor classes, is inevitably a time-consuming process. Moreover, the infrastructure needed to characterize some sensor classes (e.g., centrifuges, rate tables, and stable piers for inertial sensors) can be cost-prohibitive for smaller organizations. Specifications like mean time between failure and other robustness metrics are generally unknown for many quantum sensor classes and their constituent components.

IV. **Access to testbeds and platforms for high-fidelity emulation of realistic operating conditions is limited and frequently cost-prohibitive**. While it is often tempting to remain in the friendly confines of a laboratory environment when developing novel sensors, there is significant utility in getting early-stage prototypes into the field as rapidly as possible. Field tests naturally encourage efforts to miniaturize support equipment and can reveal design flaws or limitations that might not emerge under more benign testing conditions. Unfortunately, field tests can be costly, particularly when the target operating environments are airborne or ship-based platforms.

V. **Government-sponsored technology development pipelines generally do not promote cradle-to-grave maturation of technologies**. While exciting proof-of-concept

demonstrations are funded by organizations like DARPA and the Department of Defense-affiliated laboratories, the handoff of promising technology bases to other government or private funding sources for additional development and maturation is often inefficient, and more support is needed to transition basic research to viable commercial products. Another challenge to technology transition is ITAR and other export control restrictions which limit the market potential of quantum sensors and thus restricts private funding. Additional community-wide discussion of ways to make these development pipelines for both defense and commercial-oriented quantum sensors more effective, such as by expanding the NSIN Foundry effort [45] and close collaboration with the newly established Directorate for Technology, Innovation, and Partnerships (TIP) is worthwhile.

VI. **The state of enabling technology for quantum sensors is a mixed bag**. While there have been tremendous advances in portable, spectroscopy grade lasers in recent decades, the laser often remains a primary challenge in terms of developing compact, portable instruments. Other prominent enabling technology needs that would benefit multiple classes of quantum sensors include: vacuum components, photonic integrated chips, and low-noise electronics.

VII. **Much of the focus in quantum sensing remains on individual sensors, and the utility of quantum sensing networks remains unclear**. While the "killer application" has not been identified for many quantum sensor network concepts, modest levels of funding to continue to explore and develop networked quantum sensor concepts is worthwhile given the nascent nature of the field.

QED-C is well-positioned to support the community in overcoming many of these challenges. **Potential next steps for the QED-C** may include the following:

- The Q4NS & Enabling Technology TACs should plan additional workshops supporting a shift from "lab-in-a-box" systems to integrated, ruggedized designs for quantum sensors. Potential topic areas include photonic integrated chips and low-noise electronics.
- QED-C should facilitate business management workshops for members involved in private startup efforts to acquire baseline business skills and enable opportunities for networking with potential business partners who have experience in productization.
- QED-C Quantum Sensing subgroup of the Use Case TAC should collaborate with the Q4NS TAC as well as other stakeholders in government and private industry to generate target performance metrics for quantum sensors that would fill capability gaps.
- QED-C should work with government stakeholders to facilitate field test events which offer opportunities for quantum sensor developers to test their prototypes in non-benign

environments and for potential end users to learn about developing technologies and how they might impact their missions or market.

- QED-C should facilitate community-wide discussions of ways to make quantum sensor R&D pipelines more effective, possibly in collaboration with the NSIN Foundry and the NSF TIP Directive.
- QED-C should also expand its member participation to a greater community of companies, especially for those involved in the sensor marketplace.
- QED-C should participate in other societies and consortia with focus on sensing development and integration
- QED-C should review options for fundraising to establishing fund controlled by the QED-C members to prioritize financing and improve cradle to grave maturation of technologies

Despite the technical and policy challenges summarized above that must be overcome, historical developments in the quantum sensing space suggest that radical advances are possible, and perhaps even likely, with sustained funding. Consider that the first commercially available atomic clock from the late 1950s weighed 600 pounds, consumed 700 watts and occupied over 19 cubic feet [46]. The Microchip CSAC, by comparison, offers similar performance in a package that is roughly 32,000 times smaller by volume, 8,000 times less massive, and 6,000 times more power efficient. Critically, much of the technology development and miniaturization strategies that made CSAC possible can be applied to other quantum sensor classes as well. With targeted investment and tighter collaboration among developers and user communities, there is reason to be optimistic that the emerging crop of quantum sensors discussed in this report can have a real-world impact on a considerably faster timeframe.

6 Conclusions

Quantum sensors represent some of the most promising near-term opportunities to transition quantum technologies from laboratory demonstrations to real world applications. Some devices, such as microwave atomic clocks, have been essential backbone elements for civilian and military infrastructure for decades. Others, like quantum inertial, magnetic, and electric field sensors have demonstrated significant promise but have achieved more limited impact to date. In contrast to other technologies, like quantum computers and advanced quantum network concepts, quantum sensors generally compete against a wide range of established commercial devices. As such, their ultimate impact will be determined by the degree to which they can enable new capabilities and/or maintain existing ones in a more desirable size, weight, power, or cost envelope relative to the state of the art.

This report has identified promising use cases for quantum sensors in which the unique properties of the quantum design are expected to provide a compelling upgrade over existing classical approaches. In addition to the immediate and obvious benefits of more capably serving end users in the identified application spaces, the maturation and commercialization of these quantum sensors will yield dividends in other ways. For example, advances in key supporting or enabling technologies, such as compact spectroscopy-grade lasers and photonic integrated circuits, will benefit other quantum technology areas like computing and networks. Additionally, sensor research, development, and deployment will naturally promote quantum workforce development across industry and academia. As with any emerging technology, successfully bridging the valley of death for emerging quantum sensor classes will require the coordinated efforts of researchers, end users, and funding sources (both public and private). This report was written with the intention of identifying some of the most promising areas where these stakeholders might concentrate their resources and efforts.

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Appendix A: Workshop agenda

QED-C Quantum Sensing Workshop Agenda **March 30–31, 2022**	
Objectives: Bring together quantum sensing stakeholders to identify and address gaps related to sensing technology. Bridge emerging technologies with perceived challenges facing the public and private sectors. Co-organized by the QED-C Use Cases Technical Advisory Committee (TAC) sensing subgroup and the Quantum for National Security (Q4NS) TAC.	
March 30 (Day 1)	
1:00–1:05p *(all times EDT)*	**Introduction** Celia Merzbacher (QED-C) **Poll** Choice of breakout session
1:05–1:10p	**Updates from the quantum sensing subgroup** Yuri Lebedev
1:10–1:30p	**Keynote** Alex Cronin (NQCO): *On Bringing Quantum Sensors to Fruition*
  1:30–1:45p 1:45–2:00p 2:00–2:15p 2:15–2:30p	**Industry Session on Timing, Inertial sensing, and Gravimetry** **Focus Use Case: Assured PNT** (1) Evan Salim (ColdQuanta): *Building Blocks for Sensor Development* (2) Igor Teper (AOSense): *Quantum Sensors for Navigation and Gravimetry* (3) Jamil Abo-Shaeer (Vector Atomic): *Commercializing Atomic Clocks and Sensors* (4) Chad Hoyt (Honeywell): *Honeywell Sensing and Timing*
2:30-2:40p	**Q&A** *moderator: Mark f (MPW)*
2:40–2:50p 2:50–3:00p	**Venture Capital Perspectives on Investing in Quantum Sensing** Mark Danchak, Co-Founder (Quantum1 Group) Nardo Manaloto, Partner (Qubits Ventures): *A Natural Fit: Quantum Sensing & Healthcare*
3:00–3:05p	**Q&A** *moderator: Mark Wippich (MPW)*
  3:05–3:20p 3:20–3:35p 3:35–3:50p	**Government Perspectives on Capability Gaps and Open Challenges in Quantum Sensing** (1) Paul Baker (ARO): *Quantum Sensors for Army Applications* (2) Spencer Olson (AFRL) (3) Adam Black (NRL): *Cold Atom Interferometers for Dynamic Applications*
3:50–4:00p	**Q&A** *moderator: Joe Kinast (MITRE)*
4:00–4:50p	**Breakout Session #1:** Atomic Clocks **Breakout Session #2:** Quantum Accelerometers & Gyroscopes

	Moderator: Mark Wippich (MPW)	*Moderator: Mike Larsen (NGC)*
4:50–5:00p	**Breakout Sessions Summary**	

March 31 (Day 2)

1:00–1:05p	**Opening Remarks** Jonathan Felbinger (QED-C) **Poll** Choice of breakout session
1:05–1:25p	**Keynote** Peter Atherton (NSF)
	Industry Session on Electric and Magnetic Field Sensing **Example Use Cases: Communications, Precision Metrology, Magnetic Anomaly Detection, Biosensing**
1:25–1:35p 1:35–1:50p 1:50–2:05p	(1) Yuri Lebedev (Quantum Sensorix) (2) Fraser Dalgleish (L3Harris) (3) Mike Larsen (Northrop Grumman)
2:05–2:15p	**Q&A** *moderator: Mark Wippich (MPW)*
	Government and FFRDC Perspectives on Capability Gaps and Open Challenges in Quantum Sensing
2:15–2:30p 2:30–2:45p 2:45–3:00p 3:00–3:15p 3:15-3:30p	(1) John Kitching (NIST): *Quantum Sensing with Atomic Systems* *(2)* Paul Kunz (ARL): *Rydberg Atoms and Other Quantum Sensor Research within the Army Research Laboratory* (3) Charlie Fancher & Sean Oliver (MITRE): *Application-focused R&D of Rydberg electric field sensors and NV-diamond magnetometers* (4) Bethany Little (Sandia): *Pushing the Limits of Atom Interferometers at Sandia* (5) Malcolm Boshier (LANL): *Waveguide Atom Interferometers*
3:30–3:40p	**Q&A** *moderator: Celia Merzbacher (QED-C)*

3:40–4:30p	**Breakout Session #3:** National Security Use Cases for Quantum Electric and Magnetic Field Sensors *Moderator: Ronald Esman (Collins)*	**Breakout Session #4:** Commercial Use Cases for Quantum Electric and Magnetic Field Sensors *Moderator: Rima Oueid (DOE)*
4:30–4:45p	**Breakout Sessions Summary & Closing Statements**	

Appendix B: Workshop participants

Name	Organization	Type
Robert Bedford	AFRL	Government
Luke Bissell	AFRL	Government
Kurt Eyink	AFRL	Government
Michael Hayduk	AFRL	Government
Jamie Hoff	AFRL	Government
Brian Kasch	AFRL	Government
Sean Krzyzewski	AFRL	Government
Michael Newburger	AFRL	Government
Spencer Olson	AFRL	Government
Ryan Schultz	AFRL	Government
Michael Slocum	AFRL	Government
Matthew Squires	AFRL	Government
Ephraim Dobbins	Aliro Quantum	Corporate
Bruno Rijsman	Aliro Quantum	Corporate
Nadia Carlsten	Amazon	Corporate
Dan Pisano	American Physical Society	Non-profit
Jim Gable	Anametric	Corporate
Igor Teper	AOSense	Corporate
Brenton Young	AOSense	Corporate
Miao Zhu	AOSense	Corporate
Jayson Foster	Army	Government
Jenna Chan	Army Research Laboratory	Government
Fredrik Fatemi	Army Research Laboratory	Government
Paul Kunz	Army Research Laboratory	Government
Paul Baker	ARO	Government
Peter Reynolds	ARO	Government
Hany Fahmy	AT&T	Corporate
Benjamin Bloom	Atom Computing	Corporate
William Jeffrey	Atom Computing	Corporate
Luke Oeding	Auburn University	Academic
Marco Pravia	BAE Systems FAST Labs	Corporate
Marna Kagele	Boeing	Corporate
Melinda Andrews	Booz Allen Hamilton	Corporate
Patrick Becker	Booz Allen Hamilton	Corporate
Jessica Bianchi	Booz Allen Hamilton	Corporate
D. Scott Holmes	Booz Allen Hamilton	Corporate
Tyler LeBlond	Booz Allen Hamilton	Corporate
Robert Thompson	Booz Allen Hamilton	Corporate

Shawn Wilder	Booz Allen Hamilton	Corporate
Gabriella Carini	Brookhaven National Laboratory	Non-profit
Julian Martinez	Brookhaven National Laboratory	Non-profit
Christopher Lynberg	CDC	Government
Andrea Jett	Chicago Quantum Exchange	Academic
Stephen DiAdamo	Cisco	Corporate
Alireza Shabani	Cisco	Corporate
Brice Achkir	Cisco Systems	Corporate
Carl Williams	CJW Quantum Consulting	Corporate
Silvanus Udoka	Clark Atlanta University	Academic
Michael Williams	Clark Atlanta University	Academic
Dana Anderson	ColdQuanta	Corporate
Chester Kennedy	ColdQuanta	Corporate
Paul Lipman	ColdQuanta	Corporate
Max Perez	ColdQuanta	Corporate
Evan Salim	ColdQuanta	Corporate
Sarah Schupp	ColdQuanta	Corporate
Alexandra Tingle	ColdQuanta	Corporate
Christina Willis	ColdQuanta	Corporate
Ron Esman	Collins Aerospace	Corporate
Mike Shahine	Collins Aerospace	Corporate
Santanu Basu	Corning Research & Development Corporateoration	Corporate
Stuart Gray	Corning Research & Development Corporateoration	Corporate
Arifin Budihardjo	Cryomech	Corporate
Rich Dausman	Cryomech	Corporate
Evan Burnham	Deloitte	Corporate
Austin Choi	Deloitte	Corporate
Shannon Gray	Deloitte	Corporate
Dave Howard	Dept. of Energy	Government
Lindsay Rand	DHS	Government
Ann Cox	DHS S&T	Government
Jalal Mapar	DHS S&T	Government
Ali Ghassemian	DOE	Government
Carol Hawk	DOE	Government
Rima Oueid	DOE	Government
Lali Chatterjee	DOE SC ASCR	Government
Yuhua Duan	DOE-National Energy Technology Laboratory	Government
Ellen Winsor	EMW Consulting	Corporate
Tom Walsh	FBI	Government
Chris Wilson	FBI	Government

James Bray	GE	Corporate
Stephen Bush	GE	Corporate
Biju Jacob	GE	Corporate
Jonathan Owens	GE	Corporate
Stefan Bringuier	General Atomics	Corporate
William Clark	General Dynamics Mission Systems	Corporate
Pilgyu Kang	George Mason University	Academic
Jarrod McClean	Google Quantum AI	Corporate
Mus Chagal	Great Lakes Crystal Technologies	Corporate
Keith Evans	Great Lakes Crystal Technologies	Corporate
Bryan Gard	GTRI	Non-profit
Alexa Harter	GTRI	Non-profit
Robert Wyllie	GTRI	Non-profit
Zhao Sun	Hampton University	Academic
Robert Compton	Honeywell	Corporate
Chad Hoyt	Honeywell	Corporate
Neal Solmeyer	Honeywell	Corporate
Steven Tin	Honeywell	Corporate
Bob Sorensen	Hyperion Research	Corporate
Charles Chung	IBM	Corporate
Brian Eccles	IBM	Corporate
Paul Kassebaum	IBM	Corporate
Christopher Bishop	Improvising Careers	Corporate
Suresh Nair	INA Solutions	Corporate
Pablo Postigo	Institute of Optics	Academic
John Kaewell	InterDigital	Corporate
Pat Gearhart	IQT	Non-profit
Roger Stancliff	Keysight GEMS IST	Corporate
Gabe Lenetsky	Keysight Technologies	Corporate
David Savage	Keysight Technologies	Corporate
David Van Workum	Keysight Technologies	Corporate
Fraser Dalgleish	L3Harris	Corporate
James Drakes	L3Harris	Corporate
Chris Lowrie	L3Harris	Corporate
Randall Morse	L3Harris	Corporate
Sung Pak	L3Harris	Corporate
Haley Stumvoll	L3Harris	Corporate
Loucas Tsakalakos	L3Harris	Corporate
Alan Poon	Lawrence Berkeley National Laboratory	Non-profit
Dani Couger	Lockheed Martin	Corporate
Tom Loftus	Lockheed Martin	Corporate
Malcolm Boshier	Los Alamos National Laboratory	Non-profit

Michael Martin	Los Alamos National Laboratory	Non-profit
Anne Richards	LTS	Government
Robert Lutwak	Microchip Technology	Corporate
Peter Villano	Microsoft	Corporate
Tony Zhou	MIT	Academic
Cheryl Sorace-Agaskar	MIT Lincoln Laboratory	Non-profit
Kelly Backes	MITRE	Non-profit
Charlie Fancher	MITRE	Non-profit
Joseph Hagmann	MITRE	Non-profit
Joseph Kinast	MITRE	Non-profit
Neel Malvania	MITRE	Non-profit
Bonnie Marlow	MITRE	Non-profit
Dmitro Martynowych	MITRE	Non-profit
Sean Oliver	MITRE	Non-profit
John Qu	MITRE	Non-profit
Brandon Rodenburg	MITRE	Non-profit
David Scherer	MITRE	Non-profit
Josh Doherty	Montana Instruments	orate
Sheikh Mahtab	Morgan State University	Academic
Peker Milas	Morgan State University	Academic
Birol Ozturk	Morgan state university	Academic
Pranish Shrestha	Morgan State University	Academic
Joel Weymouth	Morgan State University	Academic
Mark Wippich	MPW	Corporate
Angela Hodge	NASA	Government
Jason Mitchell	NASA	Government
Alex Cronin	National Quantum Coordination Office	Government
Simin Feng	Navy	Government
Michael Bender	NC State University	Academic
Javad Shabani	New York University	Academic
John Haller	NIH	Government
Clare Allocca	NIST	Government
Scott Backhaus	NIST	Government
Christie Canaria	NIST	Government
Kristan Corwin	NIST	Government
Scott Diddams	NIST	Government
Elizabeth Donley	NIST	Government
Barbara Goldstein	NIST	Government
Jason Gorman	NIST	Government
Erich Grossman	NIST	Government
Jay Hendricks	NIST	Government

Chris Holloway	NIST	Government
Peter Hopkins	NIST	Government
Jason Horng	NIST	Government
David Howe	NIST	Government
Matthew Hummon	NIST	Government
John Kitching	NIST	Government
Thomas LeBrun	NIST	Government
Alan Migdall	NIST	Government
Carl Miller	NIST	Government
William Ratcliff	NIST	Government
Daniel Slichter	NIST	Government
Joel Ullom	NIST	Government
Andrew Wilson	NIST	Government
Neil Zimmerman	NIST	Government
Sean Crowe	NIWC	Government
Peter Curry	NIWC	Government
Robert Younts	NIWC	Government
Susan Berggren	NIWC Pacific	Government
Fernando Escobar	NIWC Pacific	Government
Anna Leese de Escobar	NIWC Pacific	Government
Joanna Ptasinski	NIWC Pacific	Government
Ramiro Rodriguez	NIWC Pacific	Government
Ryan Aguinaldo	Northrop Grumman	Corporate
Jonathan Green	Northrop Grumman	Corporate
Peter Kordell	Northrop Grumman	Corporate
Michael Larsen	Northrop Grumman	Corporate
Marc Sherwin	Northrop Grumman	Corporate
Peter Feldman	Novum Industria	Corporate
Adam Black	NRL	Government
Gerry Borsuk	NRL	Government
Craig Hoffman	NRL	Government
Peter Atherton	NSF	Government
Dominique Dagenais	NSF	Government
John Gillaspy	NSF	Government
Lawrence Goldberg	NSF	Government
Kiki Ikossi	NSF	Government
Pinaki Mazumder	NSF	Government
Bogdan Mihaila	NSF	Government
Nora Savage	NSF	Government
Nicholas Peters	Oak Ridge National Laboratory	Non-profit
Raphael Pooser	Oak Ridge National Laboratory	Non-profit
Robert Nelson	OCEA	Government

Roberto Diener	Office of Naval Research	Government
Tanner Crowder	OSTP	Government
Russ Renzas	Oxford Instruments Plasma Technology	Corporate
Christian Boutan	Pacific Northwest National Laboratory	Non-profit
Marvin Warner	Pacific Northwest National Laboratory	Non-profit
Joseph Williams	Pacific Northwest National Laboratory	Non-profit
Annie Xiang	Photodigm Inc.	Corporate
Justin Brown	Physical Sciences, Inc.	Corporate
Jennifer Carini	Pratt & Whitney	Corporate
John Berg	PSI Quantum	Corporate
Alexandra Boltasseva	Purdue	Academic
Yuri Lebedev	Q-Sensorix	Corporate
Tammie Borders	Quantinuum	Corporate
James Walker	Quantinuum	Corporate
Rebel Brown	Quantum Computing Inc.	Corporate
Mike Keymer	Quantum Computing Inc.	Corporate
Dave Morris	Quantum Computing Inc.	Corporate
Tim Rambo	Quantum Opus	Corporate
Carlos Augusto	Quantum Semiconductor	Corporate
Lynn Forester	Quantum Semiconductor	Corporate
Mark Mark	Quantum1 Group	Corporate
Corey McClelland	Qubitekk	Corporate
Scott Packard	Qubitekk	Corporate
Nardo Manaloto	Qubits Ventures	Corporate
Mael Flament	Qunnect	Corporate
Zac Dutton	Raytheon BBN	Corporate
Rodrigo Castillo-Gara	Raytheon Technologies Research Center	Corporate
Patrick Boswell	Rigetti Computing	Corporate
jackie kaweck	Rigetti Computing	Corporate
Dave Anderson	Rydberg Technologies	Corporate
Jim Carey	Rydberg Technologies	Corporate
Luca Basso	Sandia National Laboratories	Non-profit
Neil Claussen	Sandia National Laboratories	Non-profit
Roger Ding	Sandia National Laboratories	Non-profit
Aaron Katzenmeyer	Sandia National Laboratories	Non-profit
Pauli Kehayias	Sandia National Laboratories	Non-profit
Jongmin Lee	Sandia National Laboratories	Non-profit
David Lidsky	Sandia National Laboratories	Non-profit
Bethany Little	Sandia National Laboratories	Non-profit
Jesse Lutz	Sandia National Laboratories	Non-profit
Justin Schultz	Sandia National Laboratories	Non-profit

Peter Schwindt	Sandia National Laboratories	Non-profit
Dan Thrasher	Sandia National Laboratories	Non-profit
Paul Boieriu	Sivananthan Laboratories	Corporate
Krystal Bouverot	SRI International	Non-profit
Jasmine Cho	SRI International	Non-profit
Joseph Christesen	SRI International	Non-profit
Jonathan Felbinger	SRI International	Non-profit
Sunil Goda	SRI International	Non-profit
Barbara Heydorn	SRI International	Non-profit
Navin Lingaraju	SRI International	Non-profit
Sterling McBride	SRI International	Non-profit
Celia Merzbacher	SRI International	Non-profit
Kaitlin Moore	SRI International	Non-profit
David Morita	SRI International	Non-profit
Harris Rutbeck-Goldman	SRI International	Non-profit
Mary Scott	SRI International	Non-profit
David Zhang	SRI International	Non-profit
Daniel Jovinelli	Stable Laser Systems	Corporate
Mark Notcutt	Stable Laser Systems	Corporate
Jonathan Candelaria	Stanford	Academic
Joanna Peters	StratconGlobal	Corporate
Ekta Bhatia	SUNY Poly	Academic
Chen-Fu Chiang	SUNY Poly	Academic
Sarah Boen	Tektronix	Corporate
Senthil Thandapani	Tektronix	Corporate
Peter Heim	Thorlabs Quantum Electronics	Corporate
Siamak Dadras	TOPTICA Photonics	Corporate
Mark Tolbert	TOPTICA Photonics	Corporate
Yukihiro Tadokoro	Toyota Motor North America	Corporate
Chen Ling	Toyota Research Institute of North America	Corporate
James Harris	Treasury	Government
Jeffrey Boksiner	U.S. Army DEVCOM C5ISR Center	Government
Emily Parkhurst	U.S. Department of Commerce	Government
Lincoln Carr	U.S. Department of State	Government
Erick Jones	U.S. Department of State	Government
Astrid Lewis	U.S. Department of State	Government
Michael Bennett	UC Boulder	Academic
Longji Cui	UC Boulder	Academic
Henry Kapteyn	UC Boulder	Academic
James Thompson	UC Boulder	Academic
Clarice Aiello	UCLA	Academic

Mark Gyure	UCLA	Academic
Quntao Zhuang	University of Arizona	Academic
Preeti Chalsani	University of Chicago	Academic
Philip Makotyn	University of Colorado	Academic
Piotr Kulczakowicz	University of Maryland	Academic
Alberto Marino	University of Oklahoma	Academic
Zeeshawn Kazi	University of Wisconsin	Academic
David Coghlan	US Army / G2	Government
Stephen Badger	US Army DEVCOM C5ISR Center	Government
Daniel Wurmser	US Department of State	Government
Joseph Fraier	USAF	Government
Rex Kiziah	USAF Academy	Government
Dana Berkeland	USG	Government
Jamil Abo-Shaeer	Vector Atomic	Corporate
Matthew Cashen	Vector Atomic	Corporate
Matthew Turlington	Verizon	Corporate
Scott Davis	Vescent	Corporate
Michael Radunsky	Vescent	Corporate
Andrea Koslow	Virginia Tech	Academic
Troy Anderson	Wells Fargo	Corporate
Hunter Storm	Wells Fargo	Corporate
David Mitlyng	Xairos	Corporate
Nitish Kumar Panigrahy	Yale University	Academic