BRINGING QUANTUM SENSORS TO FRUITION

A Report by the

SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE

COMMITTEE ON SCIENCE

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

MARCH 2022

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The National Science and Technology Council (NSTC) Subcommittee on Quantum Information Science (SCQIS) was legislated by the National Quantum Initiative Act and coordinates Federal R&D in quantum information science and related technologies under the auspices of the NSTC Committee on Science. The aim of this R&D coordination is to maintain and expand U.S. leadership in quantum information science and its applications over the next decade. For more information see https://www.quantum.gov.

About this Document

This report augments the National Strategy for Quantum Information Science (QIS) by expanding upon policy topics outlined in the *National Strategic Overview for QIS.* Recommendations herein were developed by the SCQIS with input from its Quantum Sensors Interagency Working Group activity.

About the Cover

An artist's rendition of an electron in the Advanced Cold Molecule Electron-EDM (ACME) experiment. Quantum sensors, such as ACME, can serve as powerful probes for physics beyond the standard model of elementary particles, in this case by searching for a permanent electric dipole moment of the electron aligned with its spin axis.

Credit: *Nicolle R. Fuller, NSF* https://www.nsf.gov/news/news_images.jsp?cntn_id=296867&org=NSF

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Abbreviations and Acronyms

AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
ARL	Army Research Laboratory
ARO	Army Research Office
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOS	Department of State
DOT	Department of Transportation
EAR	Export Administration Regulation
ESIX	Subcommittee on Economic and Security Implications of Quantum Science
FBI	Federal Bureau of Investigation
IARPA	Intelligence Advanced Research Projects Activity
IC	Intelligence Community
IWG	Interagency Working Group
ITAR	International Traffic in Arms Regulation
LPS	National Security Agency's Laboratory for Physical Sciences
NASA	National Aeronautics and Space Administration
NDAA	National Defense Authorization Act
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NNSA	National Nuclear Security Administration
NOAA	National Oceanic and Atmospheric Administration
NQCO	National Quantum Coordination Office
NQI	National Quantum Initiative
NRL	Naval Research Laboratory
NSA	National Security Agency
NSC	National Security Council
NSF	National Science Foundation
NSTC	National Science and Technology Council
ODNI	Office of the Director of National Intelligence
OMB	Office of Management and Budget
ONR	Office of Naval Research
OSTP	Office of Science and Technology Policy
OUSD(R&E)	Office of the Undersecretary of Defense for Research and Engineering
QED-C	Quantum Economic Development Consortium
QIS	Quantum Information Science
QIST	Quantum Information Science and Technology
R&D	Research and Development
SCQIS	Subcommittee on Quantum Information Science
USDA	United States Department of Agriculture
USGS	United States Geological Survey
USPTO	United States Patent and Trademark Office

Executive Summary

Quantum sensors and measurement devices provide accuracy, stability, and new capabilities that offer advantages for commercial, government, and scientific applications. Examples such as atomic clocks for Global Positioning System (GPS) navigation, and nuclear spin control for magnetic resonance imaging (MRI) are widely used already, with transformative impacts for society. In the near future, Quantum Information Science and Technology (QIST) can enable a new generation of similarly transformative sensors. Furthermore, this process can be accelerated if concerted efforts are prioritized as a part of the National Quantum Initiative (NQI).

Several challenges must be overcome to transition QIST-based sensors from the lab to market and into various mission spaces. Cooperation among industry, academia, and U.S. departments and agencies (hereinafter agencies) can facilitate the requisite science and engineering, especially if a shared vision and mutually beneficial goals are identified. Appropriate partnerships can catalyze progress by linking researchers with potential end users to co-design and field-test prototypes. To this end, recommendations are presented here to coordinate research and development (R&D) and facilitate fruitful applications for quantum sensors. The National Science and Technology Council Subcommittee on Quantum Information Science should leverage its interagency working groups to facilitate the appropriate implementation of the following recommendations:

1. **Agencies leading QIST R&D should accelerate the development of new quantum sensing approaches and prioritize appropriate partnerships with end users to elevate the technology readiness of new quantum sensors.**
2. **Agencies that use sensors should conduct feasibility studies and jointly test quantum prototypes with QIST R&D leaders to identify promising technologies and to focus on quantum sensors that address their agency mission.**
3. **Agencies that support engineering R&D should develop broadly applicable components and subsystems, such as compact reliable lasers and integrated optics, to facilitate the development of quantum technologies and promote economies of scale.**
4. **Agencies should streamline technology transfer and acquisition practices to encourage the development and early adoption of quantum sensor technologies.**

These recommendations augment the U.S. strategy for QIST by building upon the *National Strategic Overview for Quantum Information Science* and the NQI Act. The long-term goal is to promote economic opportunities, security applications, and the progress of science through the development of quantum technologies. In the near- to mid-term, i.e., the next 1-8 years, acting on these recommendations will accelerate key developments needed to bring quantum sensors to fruition.

Collaborations between QIST R&D leaders (technology producers) and potential users will stimulate discussions and the field testing of devices. End users in agencies such as NIH, DHS, USDA, NOAA, NASA, DOD, and USGS can engage in appropriate efforts to apply QIST devices that were created with initial support from NIST, NSF, DOE, DOD, or NASA. Then, as value propositions and priorities evolve, coordination can spur R&D on key components, such as laser systems, integrated optics, and other cross-cutting and enabling technologies. Advances in quantum sensing components may also aid in the development of quantum computing and networking capabilities, for example, with chip-scale atomic processors. At the same time, translation of QIST research into marketable products and services can benefit from innovation-friendly practices and a robust technology transfer ecosystem.

I. Introduction

Due to their improved accuracy, stability, sensitivity, and precision, quantum sensors offer some advantages over traditional technologies. In addition, quantum measurement devices and modalities without classical counterparts enable some tasks that were previously unfeasible. For example, single atomic spins can map magnetic fields with nanometer resolution. Matter-wave interferometers can monitor gravitational fields with unprecedented accuracy. Entanglement and many-body quantum states may enable even more profound capabilities, such as non-invasive imaging or measurement precision beyond the standard quantum limit. However, realizing such new technology and deriving major benefits for society can take years or even decades of innovation. A goal of the National Quantum Initiative (NQI) is to accelerate this process and bring more quantum sensors to fruition.

Successful exemplars of quantum sensors include atomic clocks, which have many applications including GPS navigation, and also magnetic resonance imaging (MRI) scanners, which are widely used in medicine. Beyond these well-known cases, quantum sensors at various stages of development are on the horizon, and some will offer disruptive capabilities for industry, defense, and science. However, it is difficult to predict which platforms will become most useful, as translating research from the lab to market can take long and circuitous pathways.[1] To wit, the inventors of early atomic clocks probably never envisioned the advent of the ride hailing and food delivery apps that currently use atomic clocks to facilitate pick-up and drop-off via GPS navigation. In a similar spirit, tomorrow's enterprises may leverage novel quantum sensors for applications that are not yet foreseen.

Crossing the "valley of death," i.e., maturing proof-of-principle prototypes into economically viable devices, requires overcoming many hurdles.[2] Careful handoffs are needed between funding agencies, scientists, engineers, innovators, investors, manufacturers, and end users. Still, as with many emerging technologies, revolutionary innovations may fail to find a market for many reasons. Obstacles include competition with more familiar classical technologies, and the often incremental or iterative process of improving the size, weight, power and cost (SWaP-C), and functionality of devices. Cycles of development often require substantial and long-term efforts to reengineer key components. Even after business concepts are identified, supply chains require time to establish. Economies of scale can be elusive and may depend on other sectors. Navigating these challenges requires synergistic actions among academic, industrial, and government actors, which can be orchestrated with sound policy.

The policy recommendations presented here are designed to address gaps where coordination is needed and can substantially accelerate the discovery, development, and utilization of quantum sensors. For example, fostering joint ventures between QIST experts and potential consumers can stimulate use-inspired basic research and field testing. Joint efforts can pioneer applications and translate inventions towards commercial, mission-relevant technologies. The early adoption of new devices, even if it entails some risk or deviates from the status quo, can lead to discoveries and provide benefits such as expertise, intellectual property, and first-mover advantages. These actions can also grow the market for quantum sensors and supporting technologies, and galvanize the community.

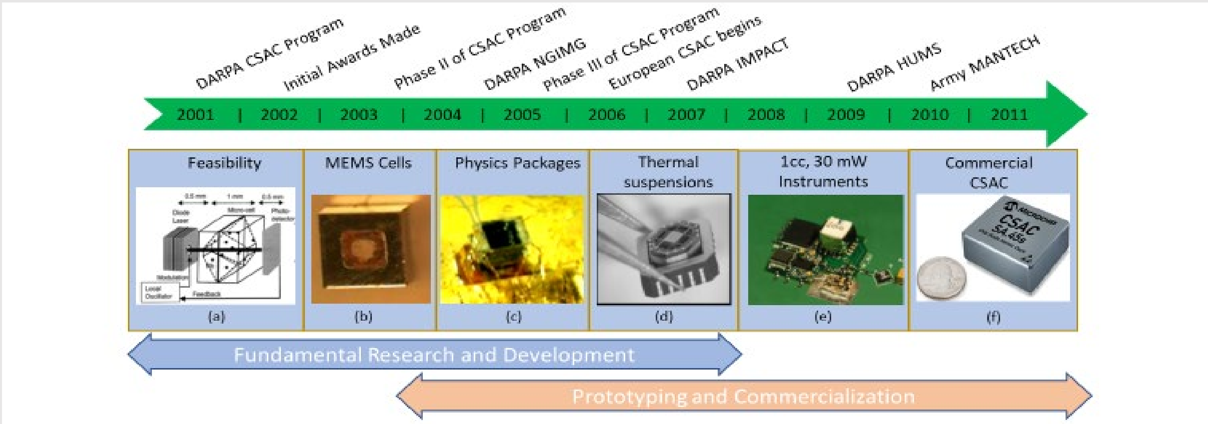
To mature a quantum sensing technology, a compelling vision with tangible goals can motivate the necessary theoretical, experimental, and engineering developments. For example, Box 1 highlights how the Chip Scale Atomic Clock (CSAC) incorporated key technologies – compact lasers, microfabrication, and the atomic physics of coherent population trapping – to deliver commercial devices for precision

[1] 'Return on Investment Initiative for Unleashing American Innovation,' doi:10.6028/NIST.SP.1234

[2] https://www.nist.gov/blogs/taking-measure/mind-gap-bridging-valley-death-us-biomanufacturing

time-keeping on a chip with a hundred-fold improvement over existing products of comparable scale. The CSAC development was motivated by clear use cases and leveraged synergistic efforts among industry researchers, agency program officers, and national laboratory teams. The goal was focused by a realistic vision for an attainable quantum sensor and fueled by a steadfast series of investments (roughly $100 million over ten years) from agencies and industry.

Box 1: Timeline of Development for 1st Generation Chip Scale Atomic Clocks



The Chip Scale Atomic Clock (CSAC) program, initiated by DARPA and catalyzed by a 2001 NIST workshop, built upon several advancements made in compact lasers, coherent population trapping, and microfabrication. From fundamental R&D (a-c),[3] to engineering and prototyping (d-e),[4,5] to an example of a commercialized product (f),[6] the CSAC effort took over a decade of sustained investments totaling almost $100 million, with coordination amongst academia, government, and industry. Multiple programs and industry partnerships contributed to CSAC development, resulting in key component technologies and commercialization, with over 100,000 sold.[7] CSACs are finding applications in the DOD, geophysical sensing, and cellular communication.

The NQI Act[8] provides for a coordinated federal program to accelerate quantum information science (QIS)[9] R&D for the economic and national security of the United States. It calls for cooperation across the civilian, defense, and intelligence sectors on QIST R&D. The NQI Act authorizes NIST, NSF, and DOE to strengthen QIS programs, centers, and consortia, and the National Defense Authorization Act (NDAA) authorizes related efforts in the defense sector. To guide these actions, the NQI Act legislates responsibilities for the National Science and Technology Council (NSTC) Subcommittee on QIS (SCQIS), and the FY 2022 NDAA legislates responsibilities for the NSTC Subcommittee on Economic and Security Implications of Quantum Science (ESIX).[10]

These subcommittees are augmenting the *National Strategic Overview for QIS*[11] with strategy documents containing recommendations, such as this one on quantum sensors, which can be found on www.quantum.gov.[12] The rest of this report is organized as follows: Section II provides background on quantum sensors, Section III presents recommendations, and Section IV proposes timelines for action.

[3] Images reproduced from 'Chip-scale atomic devices,' doi:10.1063/1.5026238
[4] Image reproduced with permission from 'The chip-scale atomic clock – low power physics package'
[5] Image reproduced with permission from 'The chip-scale atomic clock – prototype evaluation'
[6] Image reproduced with permission from Microchip Technology Incorporated
[7] https://www.nist.gov/noac/success-story-chip-scale-atomic-clock
[8] 15 USC §§ 8811-8815, 8831, 8841-8842, 8851; https://www.congress.gov/115/plaws/publ368/PLAW-115publ368.pdf
[9] As described in the NQI Act, ''quantum information science'' means the use of the laws of quantum physics for the storage, transmission, manipulation, computing, or measurement of information. QIST refers to technologies that leverage QIS.
[10] NDAA for FY 2022, Public Law 117-81; https://www.congress.gov/117/plaws/publ81/PLAW-117publ81.pdf
[11] https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf
[12] See www.quantum.gov

II. Quantum Sensor Exemplars

Quantum sensors are devices that use quantum mechanical properties, such as atomic energy levels, photonic states, or the spins of elementary particles, for metrology. They offer precision measurement techniques for science, technology, and industry. Several reports already discuss the impact of quantum sensors in various domains: positioning, navigation, and time keeping; local and remote sensing; biomedical, chemical, and materials science; and fundamental physics and cosmology.[13-21]

Box 2 lists a few quantum sensor technologies and anticipated applications. These exemplars are not intended to be comprehensive. They merely illustrate how quantum technologies are poised to provide benefits for health, security, commercial, industrial, and scientific uses. The discussion in this Section thus provides background and context for the recommendations presented in Section III.

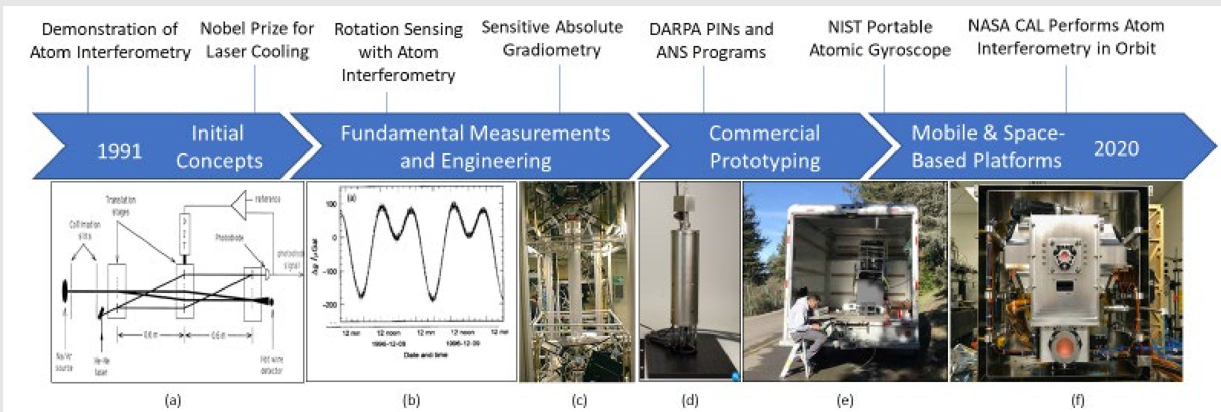
Box 2: Quantum Sensor Exemplars
1. **Atomic clocks** for positioning, navigation, networking, and metrology.
2. **Atom interferometers**, e.g., gravimeters for remote sensing and accelerometers for navigation.
3. **Optical magnetometers** for bioscience, geoscience, and navigation.
4. **Devices utilizing quantum optical effects** for local and remote sensing, networks, and fundamental science.
5. **Atomic electric field sensors**, e.g., Rydberg atoms for GHz-THz radiation detection.

Atomic clocks are key for GPS navigation. Access to auxiliary networks of atomic clocks and high-precision time-transfer protocols can provide resilience for navigation systems when standard GPS signals are unavailable. Atomic clocks currently enable internet and cell phone communication and are necessary for secure or high-bandwidth applications. Geology, seismology, oil exploration, power grid operations, and the financial services sector already benefit from CSACs discussed in Box 1. Radio telescopes use atomic clocks to support very-long-baseline interferometry. Dramatic improvements in state-of-the-art atomic clocks using cold atoms, optical transitions, and frequency combs are creating new opportunities. One example is geodesy using gravitational redshifts. Trace gas detection (e.g., for monitoring methane leaks) and enhanced spectrometer calibration (e.g., with "astro-combs") are additional applications of atomic-clock-enabling technologies like frequency combs. Advanced clocks also enable fundamental physics searches for dark matter and searches for variations of fundamental constants. Improved timekeeping in space will be needed for deep space navigation, while on Earth, space-based clocks can support time-transfer protocols and improved GPS accuracy, e.g., for monitoring changes in sea level. Like many quantum sensors, CSACs leverage technology such as compact lasers that were originally developed for other industries, with economies of scale.

[13] 'Quantum Sensors at the Intersections of Fundamental Science, Quantum Information Science & Computing,' doi:10.2172/1358078
[14] 'Quantum Science Concepts in Enhancing Sensing and Imaging Technologies: Applications for Biology: Proceedings of a Workshop,' doi:10.17226/26139
[15] 'Manipulating Quantum Systems,' doi:10.17226/25613
[16] 'Opportunities for Basic Research for Next-Generation Quantum Systems,' doi:10.2172/1616258
[17] 'Future directions of quantum information processing,' https://basicresearch.defense.gov/Portals/61/Documents/future-directions/Future_Directions_Quantum.pdf?ver=2017-09-20-003031-450
[18] 'Nuclear physics and Quantum Information Science,' https://science.osti.gov/-/media/np/pdf/Reports/NSAC_QIS_Report.pdf?la=en&hash=91703C70429F2B7D634CBC10573079858926141D
[19] 'Opportunities for Nuclear Physics & Quantum Information Science,' arXiv:1903.05453
[20] 'Assessment of the Future Economic Impact of Quantum Information Science,' https://www.ida.org/-/media/feature/publications/a/as/assessment-of-the-future-economic-impact-of-quantum-information-science/p-8567.ashx
[21] See additional reports on QIST posted on www.quantum.gov

Atom interferometers used as gravimeters and gravity gradiometers hold promise for geoscience studies of volcanology, groundwater, mineral deposits, tidal dynamics, and the cryosphere (i.e., the distribution of ice on the planet). Box 3 highlights some milestones for atom interferometers on the timeline from invention to commercial applications. These instruments may soon be able to map underground structures and voids, with potential uses for vehicle inspections and tunnel detection. Improved gravimeters offer the potential to reduce costs in civil engineering and geological surveys. Fundamental physics applications include measurements of the universal gravitational constant (big *G*), tests of the equivalence principle (the universality of free fall), measurements of gravity on the millimeter scale, searches for dark matter particles, and possible alternative approaches to gravitational-wave detection.[22] Atom interferometers also make competitive gyroscopes and accelerometers for inertial navigation, minimizing the need for sonar or GPS in certain situations, and potentially reducing long-term errors compared to traditional inertial measurement technologies. Applications to gyro-compassing, satellite pointing, guidance, gravity mapping for navigation, and undersea obstacle avoidance may be forthcoming.

Box 3: Atom Interferometry Timeline from Laboratory Studies to Commercial Applications

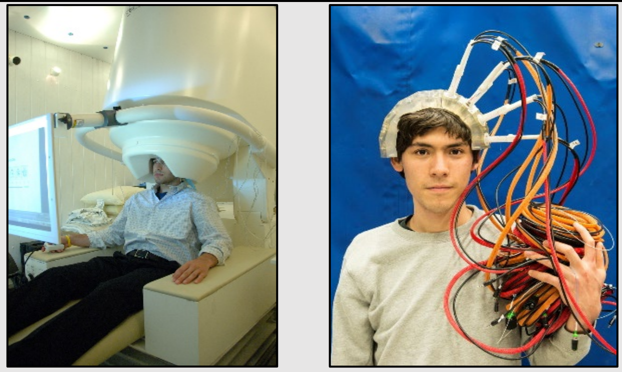


The field of matter-wave optics was launched by de Broglie's hypothesis that particles propagate like waves. Atom interferometry then benefited from key work on laser trapping and cooling of atoms, coherent momentum transfer from light to atoms, photonics, and nanotechnology. Modern demonstrations of atom interferometry were pioneered in 1991 (a),[23] and the field grew with support from multiple agencies including NSF, NIST, ARO, ONR, DARPA, NASA, and DOE. Atom interferometry has applications in gravimetry (b),[24] inertial navigation, civil engineering, geoscience, and the measurements of fundamental constants. Sustained investments over 30 years have taken atom interferometers from laboratory instruments (c)[25] to space based platforms, leading to new companies and commercial prototypes (d),[26] mobile units (e),[27] and atom interferometry experiments performed in orbit (f)[28] with NASA's Cold Atom Lab in 2020. Even with these advances, engineering challenges still need to be overcome to facilitate commercial uses of atom interferometry. For example, focused work is needed on laser systems, integrated optics, atomic sources, vacuum systems, and quantum control.

[22] https://news.fnal.gov/2019/09/magis-100-atoms-in-free-fall-to-probe-dark-matter-gravity-and-quantum-science/
[23] Image reproduced with permission from 'An interferometer for atoms,' doi:10.1103/PhysRevLett.66.2693
[24] Image reproduced with permission from 'High-precision gravity measurements using atom interferometry,' doi:10.1088/0026-1395/38/1/4
[25] Image reproduced with permission from 'Light-pulse atom interferometry,' arXiv:0806.3261
[26] Image reproduced with permission from https://aosense.com/product/gravimeter/
[27] Image reproduced with permission from 'Gravity surveys using a mobile atom interferometer,' doi:10.1126/sciadv.aax0800
[28] Image reproduced from https://science.nasa.gov/technology/technology-highlights/quantum-technologies-take-flight

Optical magnetometers based on atomic spins in vapors, Bose condensates, or solid-state systems such as nitrogen vacancy (NV) centers in diamond, can provide functionality for local and remote sensing, mapping, and navigation. Magnetometers enable biomedical studies of neurological function, for example, with magneto-encephalography (MEG) for understanding Alzheimer's disease, Parkinson's disease, and cognition. Technologies such as MEG (Box 4) are complementary to functional MRI, electroencephalography (EEG), and cryo-electron microscopy in biomedical sciences. NV centers also enable NMR spectroscopy (Box 5) of chemical shifts in micrometer scale samples, suitable to study protein dynamics in individual cells.[29] Quantum diamond microscopes based on NV centers can map magnetic fields with unprecedented spatial resolution for studies of geoscience, electronics, and biology. Optical magnetometers are also valuable for vector magnetometry and measurements of absolute magnetic field magnitudes. Optical magnetometers can also support non-invasive testing of biological samples and new tools for surface science.

Box 4: Vapor Cell Magnetoencephalography (MEG) Highlight



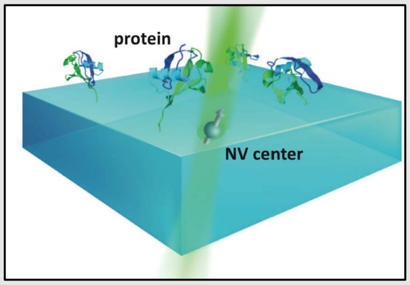
(a) (b)

Superconducting quantum interference device (SQUID) based MEG devices (a)[30] require cryogenic cooling, with large footprints and overhead. They are therefore confined to a few geographical locations, and while applicable to the field of medical research, they are unlikely to realize large-scale clinical use. Vapor cell-based MEG devices (b)[31] can approach and even exceed the sensitivity limits of SQUID MEGs, without the need for cryogenic cooling or the large footprint for operations. One application of these smaller, more transportable MEG devices, is the potential for diagnosing traumatic brain injuries in the field.

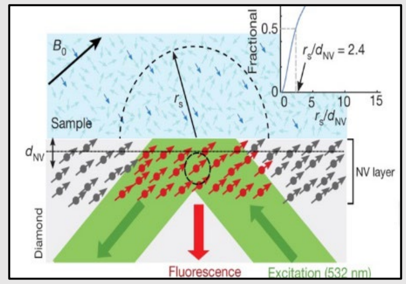
Fundamental physics applications of advanced quantum sensor technology include searches for a permanent electric dipole moment (EDM) of particles such as the neutron or electron. This leverages the *precision frontier*, as opposed to the energy frontier, to test theories that go beyond the Standard Model of elementary particle physics. One such project, the Advanced Cold Molecule Electron (ACME) EDM experiment is highlighted in the cover art for this report.[32] Approaches such as this are sometimes called "tabletop experiments with skyscraper reach,"[33] which present new opportunities at the intersection of high energy physics with atomic, molecular, and optical physics.[34]

[29] 'High-resolution magnetic resonance spectroscopy using a solid-state spin sensor,' doi:10.1038/nature25781
[30] Image reproduced from https://images.nimh.nih.gov/public_il/image_details.cfm?id=80
[31] Image reproduced from https://www.nist.gov/news-events/news/2016/07/detecting-brain-waves-atomic-vapor
[32] 'Advanced Cold Molecule Electron EDM Search,' https://www.nsf.gov/awardsearch/showAward?AWD_ID=1404146
[33] https://nsf.gov/awardsearch/showAward?AWD_ID=1707700; http://schmidta.scripts.mit.edu/tabletop_workshop/index.html
[34] NSF Dear Colleague Letter: Searching for New Physics Beyond the Standard Model of Particle Physics Using Precision Atomic, Molecular, and Optical Techniques, https://www.nsf.gov/pubs/2020/nsf20127/nsf20127.jsp

Box 5: Nitrogen Vacancy Center Magnetometry Highlight



(a)



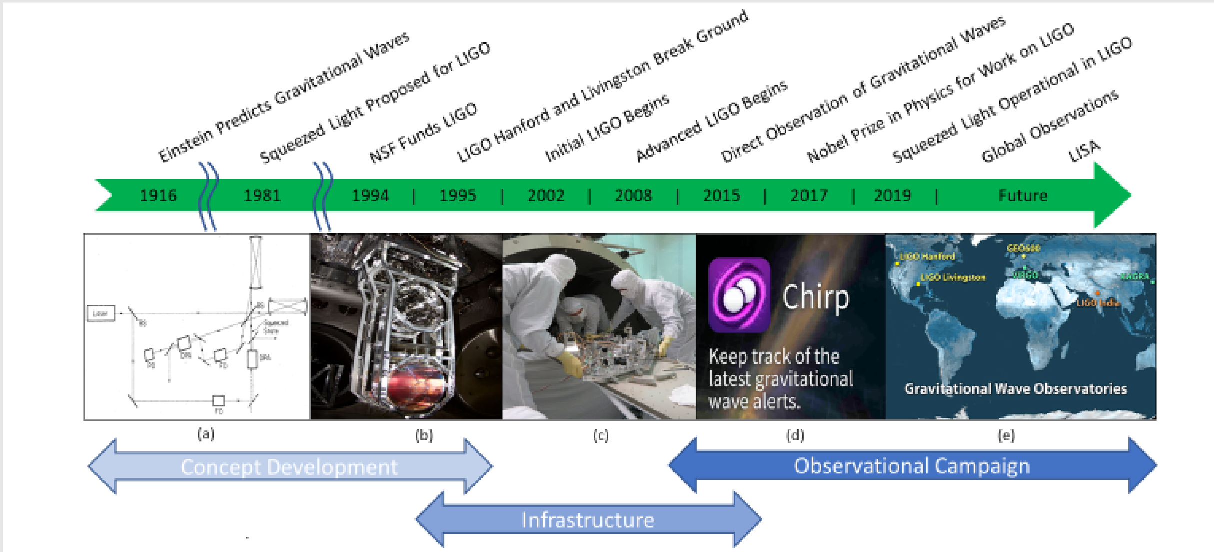
(b)

Nitrogen Vacancy (NV) centers in diamond allow for magnetometry and nuclear magnetic resonance (NMR) spectroscopy and imaging with spatial resolution approaching the nanometer scale. R&D on NV centers has spanned over two decades, with participation from NSF, NIST, DOE, DOD, and NIH. Notable achievements include the detection of multiple nuclear species within ubiquitin proteins, such as in (a),[35] NMR spectral resolution using NV centers, such as in (b),[36] the demonstration of scanning confocal microscopy with single NV centers, nanoscale magnetic field sensing, single cell imaging using quantum diamond microscope, and detection of single neuron excitations in live specimens. A possible near-term application for an NV diamond magnetic imager may be to detect changes in the conduction velocity of action potentials caused by diseases such as multiple sclerosis.

Devices utilizing quantum optical effects provide opportunities to understand, and in some cases beat, the standard quantum limit in microscopy, spectroscopy, and interferometry. Non-classical states of (N) photons enable measurements reaching towards the Heisenberg limit (characterized by uncertainty in phase that scales as $1/N$ as opposed to $1/\sqrt{N}$). As an exemplar, "squeezed light" allows NSF's Laser Interferometer Gravitational-Wave Observatory (LIGO) and its international counterparts, Virgo and KAGRA, to operate below the traditionally expected noise floor. Using squeezed light has significantly increased the detection rate for black hole collisions, effectively expanding the volume of the universe that can be studied with LIGO.[37] Quantum optical effects thus provide a valuable resource for multi-messenger astrophysics, recognizing that gravitational-wave signals can be precursors to gamma, visible, radio wave, and possibly neutrino events. The successful use of squeezed light to enhance cutting-edge instrumentation is a tribute to what can be achieved with sustained support of fundamental theory, experimental research, and targeted engineering. Advances in each were needed to achieve the results. A healthy tolerance for risk, substantial coordination, and a major focus on operational campaigns are hallmarks of what enabled quantum optics to be harnessed for enhanced LIGO functionality. Box 6 portrays the progress from initial conceptualization to the current state of LIGO.

[35] Image reproduced with permission from 'Nuclear magnetic resonance detection and spectroscopy of single proteins using quantum logic,' doi:10.1126/science.aad8022
[36] Image reproduced with permission from 'High-resolution magnetic resonance spectroscopy using a solid-state spin sensor,' doi:10.1038/nature25781
[37] https://www.ligo.org/

Box 6: A Timeline of LIGO Development from Theoretical Concepts to International Observation Campaigns



NSF's Laser Interferometer Gravitational-Wave Observatory (LIGO) is the result of over four decades of basic research and over $1 billion in investments. The existence of gravitational waves was predicted by Einstein a century before the first observation, and the use of squeezed light to beat the standard quantum limit was first proposed in 1981.[38] At the time of initial funding, LIGO accounted for the largest single award made by NSF. It took over 20 years from the initial investment to produce an observation of gravitational waves; a testament to the value of sustained and patient management. The 2017 Nobel Prize in Physics was awarded to three American physicists for the importance of the work done at LIGO and the observation of gravitational waves. To date, there have been over 90 detections of gravitational wave events resulting from black hole mergers, black hole-neutron star mergers, and a neutron star collision. There are international efforts underway to build additional terrestrially-based interferometers, and also a space-based interferometer called LISA. The thumbnails from left to right are pictures of an early schematic for using squeezed light in the detection of gravitational waves (a),[38] the quadruple pendulum suspension system in advanced LIGO (b),[39] the installation of optical circuitry for squeezed light in LIGO (c),[40] apps which can alert a mobile phone of gravitational wave detection events (d),[41] and a map of the current and in-development gravitational observatories across the world (e).[42]

The field of quantum optics also provides a basis for super-resolution and non-invasive, or less-invasive, imaging. These concepts may provide new types of microscopes for biomedical science. Single-photon and photon-number-state detectors can be applied to DNA sequencing, tracking of enzyme activity, particle physics, dark matter searches, quantum networking protocols, and remote sensing with low light levels, e.g., advanced LIDAR. Quantum sensors via quantum state tomography, quantum gate set tomography, and quantum process tomography may elucidate the behavior of quantum computer prototypes and components. These sophisticated probes for materials and devices may lead to a better understanding of superconducting qubits, trapped ion qubits, NV centers in diamond, and other designer impurities in solid state materials.

[38] Image reproduced with permission from 'Quantum-mechanical noise in an interferometer,' doi:10.1103/PhysRevD.23.1693
[39] Image reproduced from https://www.ligo.caltech.edu/image/ligo20091202a
[40] Image reproduced from https://news.mit.edu/2019/ligo-reach-quantum-noise-wave-1205, photo credit: Lisa Barsotti
[41] For example, app image reproduced with permission from Samuel Morell, University of Exeter
[42] Image reproduced from https://www.ligo.caltech.edu/image/ligo20160211c

Atomic electric field sensors can use Rydberg atomic states as a transducer or a quantum antenna to measure electromagnetic fields in a wide range of frequencies spanning DC (0 Hz) to THz (10^{12} Hz).[43] Detection, signal processing, and imaging of THz radiation can be accomplished with optical readout using coherent spectroscopy methods. This technology provides opportunities for remote sensing and new capabilities in electrometry, potentially expanding access to and enabling new applications in the THz regime. Additionally, atomic electric field sensors provide an opportunity to reduce the size of antennas and improve radio frequency filtering. Other applications include extending the range between cellular towers and the acquisition of signals with a wide dynamic range.

Discussion: Quantum sensing provides tools for precise metrology based on revolutionary approaches, as illustrated in this section. The broadly defined fields of quantum sensing, networking, and computing each contain important scientific frontiers - quantum frontiers[44] - on their own. Furthermore, R&D work in these domains can be mutually reinforcing and cross-connect with other fields. For example, support technology for quantum sensors, such as laser systems, integrated optics, cryogenics, and specialized materials, can have cross-functional uses in quantum computing and quantum networking. Quantum networks leveraging dark fiber and free-space optics may enable radically new quantum sensors such as long-baseline telescopes that could use entanglement as a resource. As another illustration, techniques first demonstrated in quantum computing experiments are enhancing the performance of atomic clocks using ion traps and quantum logic spectroscopy.[45] Thus, research on quantum sensors can benefit from, and also pave the way towards, more sophisticated systems for quantum information processing.

Workforce needs must be considered as part of the national strategy for quantum sensors, recognizing that progress relies on an adaptable, diverse, and talented workforce to explore quantum frontiers. Expanding the QIST workforce will take time, resources, and deliberate actions discussed in the recently released national strategic plan for QIST workforce development.[46] Fortunately, R&D on quantum sensors provides dynamic and rewarding training opportunities for the next generation of scientists and engineers, where people can gain a wide variety of skills.

Near-term opportunities for quantum sensors to benefit society are numerous. However, the vast space of possible applications and the broad range of quantum technologies illustrated in this Section causes challenges which will be discussed in the next Section. For example, quantum sensor R&D efforts are somewhat diffuse and unfocussed; many quantum sensor concepts are at low levels of technology readiness; and many sensor concepts still require substantial engineering with commensurately substantial funding for the development of key components. It is unlikely that all of these barriers can be overcome by any one agency acting in isolation, because the science and engineering problems are diverse and new.

A coherent strategy that motivates cooperative efforts on carefully chosen outcomes for research and development on quantum sensors is needed. Policy recommendations for that purpose are discussed next, in Section III.

[43] 'Waveguide-coupled Rydberg spectrum analyzer from 0 to 20 GHz,' doi: PhysRevApplied.15.014053
[44] https://www.quantum.gov/wp-content/uploads/2020/10/QuantumFrontiers.pdf
[45] 'Spectroscopy using quantum logic,' doi:10.1126/science.1114375
[46] https://www.quantum.gov/wp-content/uploads/2022/02/QIST-Natl-Workforce-Plan.pdf

III. Recommendations for Bringing Quantum Sensors to Fruition

Sensing is arguably the most mature subcategory of quantum technology. In comparison, quantum computing and quantum networking are at earlier, albeit dynamic, stages of development. Given the state of play, several quantum sensors appear poised to produce impacts for society in the near-term, provided that some key challenges can be overcome. Furthermore, R&D associated with the NQI can be instrumental for the realizing the full benefit of quantum sensors. The United States can spur development of quantum sensors with actions recommended in this Section.

Challenges to Address: Bringing new quantum sensors from proof-of-concept designs to fieldable products still requires overcoming many hurdles. Key challenges are briefly summarized here. For one, the vast application space and wide variety of potential user requirements makes it difficult to focus work on specific applications or requirements. Furthermore, the market drivers and commercial value of many quantum sensors are still being determined. Hence, R&D efforts are diffuse. Meanwhile, the long road from basic research to successful products requires substantial and sustained funding, often with several coordinated thrusts. Given the varied needs of different user communities, a long-term strategy should be developed to align multiple agencies and unite private sector stakeholders around the development of some particular applications and key supporting technologies. A cohesive, system-wide approach is especially important for R&D efforts that may be too costly for any single agency, university, or company to sustain on their own. Additional coordination with the private sector to efficiently mature quantum technologies across the valley of death may benefit from coordinated efforts to identify and disseminate effective practices for managing intellectual property, acquisitions, research security, and appropriate partnerships. Innovation-friendly practices can facilitate spin-off technologies and companies, and a robust ecosystem for technology transfer.

Four policy recommendations to address these challenges are presented in Box 7. To facilitate implementing these recommendations, the NSTC Subcommittee on QIS and its interagency working groups should help coordinate supporting actions discussed throughout this Section.

Box 7: Recommendations to Facilitate the Development and Utilization of Quantum Sensors

1. **Agencies leading QIST R&D should accelerate the development of new quantum sensing approaches and prioritize appropriate partnerships with end users to elevate the technology readiness of new quantum sensors.**
2. **Agencies that use sensors should conduct feasibility studies and jointly test quantum prototypes with QIST R&D leaders to identify promising technologies and to focus on quantum sensors that address their agency mission.**
3. **Agencies that support engineering R&D should develop broadly applicable components and subsystems, such as compact reliable lasers and integrated optics, to facilitate the development of quantum technologies and promote economies of scale.**
4. **Agencies should streamline technology transfer and acquisition practices to encourage the development and early adoption of quantum sensor technologies.**

Recommendation 1: Agencies leading QIST R&D should accelerate the development of new quantum sensing approaches and prioritize appropriate partnerships with end users to elevate the technology readiness of new quantum sensors.

Challenges Addressed: Many scientists conducting basic research lack expertise in vast domains where their work might eventually be applied. This includes familiarity with current (competing) technologies and the rigors of deploying sensors in operational environments. Finding experts and end users with that complementary knowledge can be challenging, and the payoff may require long durations with many cycles of development. These timeframes may not align neatly with criteria for promotion and tenure. The (perceived) lack of programmatic resources or agency support for new joint projects can slow progress. It is also difficult to forecast if or when experiments and demonstrations will lead to commercially or scientifically relevant devices or help agencies accomplish their missions.

Discussion of Recommendation: Agencies leading QIST R&D, such as NIST, NSF, DOE, DOD, NASA, and those within the intelligence community, should engage with potential end users for quantum sensor prototypes to jointly test, develop, and disseminate findings for end-user applications. The goal for this recommendation is to accelerate fundamental R&D, testing, and utilization of prototypes. These agencies should seek appropriate partnerships with end users in U.S. Government, industry, and academia who can apply quantum technologies to improve the way technology consumers accomplish their respective goals or missions. Field testing and early adoption of select relevant exemplars should stimulate developers to work on the most important specifications and functionality. At the same time, joint efforts should benefit the end users by providing new capabilities, first-mover advantages, and an increasing awareness of emerging technologies. Collaborations of this nature should also create opportunities to invest in use-inspired basic research and pioneer entirely new applications.

A first step for engaging end users is to share information, for example, at workshops, professional conferences, and through follow-up discussions and publications. Educating agency leadership, field scientists, and program officers about the capabilities of quantum sensors can be done with briefings, seminars, and working groups. Quantum 101 briefings can provide an overture or foothold for further discussions. While some agencies have engaged in the development of quantum sensors for decades, this knowledge can still be siloed within a few laboratories or divisions. Hence, sharing information about emerging quantum sensors with end users and agency leadership across the U.S. Government is an important step. This professional outreach can include staff at national laboratories, DOD laboratories, and a broad list of agencies that could utilize quantum sensors, including, e.g., NASA, NIH, DHS, NOAA, USGS, USDA, and DOT. Recognizing the ongoing and complementary work being done around the globe on quantum sensors and component technologies, international cooperation should be leveraged as appropriate. Memoranda of understanding (MOUs) and agreement (MOAs), or annexes to existing MOUs and MOAs, should be encouraged as a means to formalize collaborations and identify roles and responsibilities.

Overcoming barriers to these types of collaborations may require cultural shifts within agencies and academia. For example, promotion and tenure committees could acknowledge a wider variety of contributions to QIST development and not restrict professional reward solely to projects with neatly packaged milestones or publications. Instead, nurturing a culture of discovery that celebrates multidisciplinary efforts can help ensure that attention is not diverted from potentially transformative approaches. Agency program officers also need resources to explore new opportunities, work across boundaries, and support joint ventures. Cultural shifts of this nature require sustained efforts and leadership from multiple agencies and institutions to allocate resources and take appropriate risks.

Recommendation 2: Agencies that use sensors should conduct feasibility studies and jointly test quantum prototypes with QIST R&D leaders to identify promising technologies and to focus on quantum sensors that address their agency mission.

Challenges Addressed: Quantum technologies can sound exotic and be surrounded by exaggerated claims. Unrealistic expectations or misunderstandings about potential applications are unfortunately common consequences. There are also potential end users who are unaware of the existence of certain quantum sensors, leading to missed opportunities. Prior to developing economies of scale, it is difficult to project when or if lab demonstrations will become commercially viable or help agencies accomplish their missions. Comparisons with existing, classical alternatives and benchmarks are not straightforward, for example, because classical sensors may have decades of R&D. These challenges complicate seeing ahead to competitive devices that can be supported by procurement. Satisfying SWaP-C constraints for quantum sensors may depend on supporting technology that is still undergoing fundamental R&D, which may give the false impression that a given quantum sensor concept will never be viable. Furthermore, the practical value of a sensor depends on many factors, including performance in real-world environments. Specifications such as response to environmental noise, reliability, bandwidth, duty-cycle, and operational dead time are important, but often are not the first priority for scientists or inventors to optimize in early prototypes. Yet these factors are highly relevant for field deployment. Hence, potential end users should help to judge this trade-space.

Discussion of Recommendation: Agencies using sensors should identify a few relevant quantum technologies and investigate them with dedicated efforts, invoking partnerships, MOUs, and MOAs as appropriate. Potential end-user agencies (consumers) within the U.S. Government could include DHS, NIH, USDA, USGS, NOAA, as well as components of DOE, DOD, and NASA that might be initially outside of the QIST research ecosystem. National laboratories, federally funded R&D centers, and scientists in academia could be early adopters as well. Joint efforts among QIST R&D practitioners and these end users can be prioritized to field-test, co-design, and develop new quantum sensor prototypes and applications. Agencies can use the SCQIS and its working groups to help identify potential partnerships.

Time and resources should be allocated to encourage agency staff to collaborate with QIST R&D leaders in other government agencies, the private sector, and academic research institutions, both domestically and internationally. Attention should be given to potentially disruptive technologies. Establishing collaborations early in the R&D process will help to explore the value added from quantum modalities, recognizing that revolutionary approaches often take time to produce results. These efforts should assess the impact of quantum sensing to end-user agency missions, and prioritize use cases where quantum sensors address unsolved capability gaps or result in large-scale improvements.

Feasibility studies should result in reports with actionable plans and recommendations for developing quantum sensing technologies, along with descriptions of use cases with requirements or metrics that would need to be met for new sensors to impact an agency or research area. Producing and sharing these reports will inform realistic expectations and give QIST R&D leaders more clearly delineated goals, ultimately fostering future collaborative research undertakings.

These joint efforts should augment, not supplant, ongoing quantum sensor research. Importantly, coordination like this can provide a pull (complementary to a technology push) for early demonstrations of capabilities in realistic, mission-relevant environments. They can also leverage dual-uses of quantum technologies to develop robust markets. Users can bring fresh perspectives that may lead to entirely new applications or new approaches for using existing sensors.

Recommendation 3: Agencies that support engineering R&D should develop broadly applicable components and subsystems, such as compact reliable lasers and integrated optics, to facilitate the development of quantum technologies and promote economies of scale.

Challenges Addressed: Access to key supporting technologies is a challenge due to the demanding technical requirements and substantial cost of the engineering needed to control quantum systems. Migrating laboratory prototypes to field demonstrations often requires components or processes that are not yet available, such as specialized materials, fabrication facilities, integrated photonics, lasers, electronics, vacuum systems, interconnects, quantum control, and diagnostics. Unfortunately, many of these enabling technologies do not yet have a sufficiently large market to realize economies of scale. These obstacles delay the development of the required subsystems and create challenges to delivering functionality to end users without several iterations and subsequent refinements.

Discussion of Recommendation: Agencies that support engineering R&D should work with the SCQIS and its working groups to identify ways to facilitate the development of key components that are needed to make quantum sensors more compact, reliable, and cost-effective. Exploring joint efforts with industry and making targeted investments in infrastructure can produce cross-cutting, multi-functional components that enable several quantum devices, such as reliable lasers at applicable wavelengths and integrated optics circuits. Agencies should coordinate strategic R&D investments in these enabling technologies, to build joint ventures and talent that will foster a sustainable quantum industrial base.

A consortium or incubator that can manage small volume production runs (10 - 100 units) would fill a gap and provide infrastructure needed for rapid prototyping. There is also a demand for foundries that can produce integrated optics with new materials for chip-scale devices. A collaboration space for nanofabrication experts and non-experts to work together on designs would benefit this endeavor.

Compelling applications that justify dedicated engineering efforts can help to guide infrastructure development. In parallel, the QIST community can continue to leverage adaptable components that may be originally developed for other areas, e.g., photonics, microelectronics, or nanotechnology. Coordinating both of these approaches - versatile components for compelling applications - may present opportunities to seed QIST-related infrastructure in the broader marketplace, where economic motivations for maturing subsystem technologies can be stronger than what QIST applications alone might generate. Synergies among QIST and other technical sectors can provide mutual benefits.

Industry engagements can leverage appropriate partnerships through Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs, centers of excellence, the NSF Innovation Corps programs, academic liaisons with industry, industry/university cooperative research centers, and national laboratories. Procurement, technology transfer, and connections with consortia such as the Quantum Economic Development Consortium (QED-C) can also improve the supply chain for components and enabling technologies.

Overcoming certain technical hurdles may require multiple agencies to agree upon, and work towards, shared long-term visions. Agencies should use the SCQIS and its working groups as a vehicle for program officers to share information and help bring technologies across the valley of death. Interagency coordination can help ensure continuity and persistence of R&D programs, as has been crucial for most of the successful quantum sensor exemplars. Appropriate budgets to support key science and engineering efforts should be planned. MOUs and MOAs can clarify roles and responsibilities. Realistic, evidence-based predictions of development schedules are important too, because patience is needed in order follow the arc of technology development.

Recommendation 4: Agencies should streamline technology transfer and acquisition practices to encourage the development and early adoption of quantum sensor technologies.

Challenges Addressed: Some practices pertaining to intellectual property protection can impede or discourage cooperation, with these challenges becoming even greater for international engagements. Similarly, well-intended restrictions on procurement can delay acquisitions and slow development, in some cases reducing competitiveness. A balanced approach is therefore needed to ensure research security while maintaining the core values behind America's scientific leadership, including openness, transparency, honesty, equity, fair competition, objectivity, and democratic principles. While threats to research security are serious, there is also a risk that the overly broad implementation of protections could inhibit the flow of information that drives progress.

Discussion of Recommendation: Agencies should identify and implement helpful practices for resolving technology transfer issues such as source selection, purchasing authority, licensing agreements, and conflicts of interest. Efficient technology transfer and acquisition processes are vital for innovation. They can reduce administrative barriers for inventors to explore commercial viability, help end users access and co-develop products, and make public-private partnerships more straightforward. With public trust being paramount, ensuring that decisions are made in a manner that appropriately facilitates innovation and basic research, while reducing administrative burdens, can foster rapid innovation. To this end, agencies should thoughtfully consider their tolerance for technological or operational risks, while accounting for laws and norms, and maintaining research security best practices. As technology transfer depends on many people in different parts of government, the private sector, and academia, one approach is to engage the SCQIS, the NSTC Lab to Market Subcommittee, and their working groups to identify and share best practices.

Potential frameworks may include hybrid institutes and consortia that facilitate collaboration among entities, including those between government and private sector scientists. Start-ups and small businesses may benefit from standardized, possibly shared, government pre-approved mechanisms for handling a range of issues from intellectual property to immigration and investor relations. Advance market commitments for components or devices can incentivize early stage manufacturing of quantum technologies.[47] Other incentives may invoke government grants for user groups, shared infrastructure, or pre-competitive research to kick-start the development of enabling technologies. Agencies can engage with the SCQIS, consortia such as the QED-C, professional societies, and representative samples of institutions to identify best practices for facilitating technology transfer in these different venues.

International collaboration, which is important for growing the market and accelerating development, can be encouraged by relaxing barriers that discourage information sharing and preventing the creation of new barriers. Expediting international collaboration agreements, and improving guidance regarding the extent to which information sharing is permitted for items identified by the International Traffic and Arms Regulations (ITAR) and Export Administration Regulations (EAR) would facilitate work with international partners. Participation in international activities around standards, skills training, supply chains, and academic research can benefit all of the collaborating partners. These efforts must be balanced, though, to promote thriving innovation while protecting national security, intellectual property, and supply chains for critical and enabling technologies.

[47] 'Using advance market commitments for public purpose technology development,' https://www.belfercenter.org/sites/default/files/2021-06/UsingAdvanceMarketCommits.pdf

IV. Recommended Timelines and Metrics to Track Progress

To help implement these recommendations, some realistic expectations for the R&D community in the near-term (1-3 years) and medium term (3-8 years) are described. The SCQIS should create a venue to identify roles and responsibilities for agency participants in the following actions. It is incumbent upon the SCQIS, the agencies within the SCQIS, and the NQCO, in coordination with ESIX, to track progress, determine responsibilities, and create appropriate incentives to execute this timeline.

<u>1-3 Years</u>. In the next 1-3 years, community actions should include:

- Briefings and seminars on quantum sensors provided by QIST R&D leaders to various agencies. Surveys of available sensors and analysis of their impact on agency missions/needs should support these briefings. Ideally, these briefings will result in follow-up efforts to jointly test and demonstrate quantum sensors, as well as produce curated lists of existing and feasible performance metrics.
- Potential end users should engage with QIST-focused professional society meetings, workshops, and roundtables about their needs. End users could participate in proposers' day events to inform the R&D community about their interest in quantum technologies and desired performance metrics.
- Facilitate appropriate partnerships for new quantum sensor R&D on a rolling basis, to engage joint field tests and the evaluation of preliminary results. Acquisitions, demonstrations, and co-design of quantum sensors should help to pioneer and validate new applications. For tracking and assessment, it will be valuable to catalog existing and new joint R&D efforts on quantum sensors and their contributions toward maturing quantum sensing technologies.
- Identify specific, high-value applications for quantum sensors that can justify dedicated engineering and manufacturing efforts. One output would be prioritized lists of key components with specifications and plans for the associated engineering R&D.
- Identify and prioritize lists of engineering infrastructure and R&D activities that are needed to address gaps in enabling technologies and applications enabled by each activity. Estimate the time and investment required for each activity and its potential impact. Activities or infrastructure that will facilitate a broad set of quantum applications should be encouraged.
- Identify or establish bodies within agencies that can assist with the resolution of legal and policy issues in such a manner that facilitates quantum sensor technology development.
- Track engineering and scientific breakthroughs, as well as bibliometrics, participants, patents, licensing for quantum sensing technologies, and sales or revenue for quantum sensors, and track the key components or supporting technologies, both domestically and internationally.
- Project realistic resources required, including the supporting workforce, to implement the recommendations in this document.

<u>3-8 Years</u>. Once suitable technologies have been identified by coordinated activities, over the next 3-8 years, the R&D community and the agencies in the SCQIS should work to:

- Collaborate with end users to perform field tests and demonstrations that expedite early adoptions and transitions.
- Prioritize component miniaturization and subsystem integration.
- Develop and build R&D infrastructure through consortia and foundries.
- Develop standards for the identified quantum sensors and component technologies.

V. Summary

Quantum sensor development has a long and distinguished history within the United States and internationally. Quantum sensing technologies have already led to advances in fields such as: positioning, navigation, and timekeeping; remote sensing; biomedical, chemical, and materials sciences; and fundamental physics. Some successful examples required decades of careful investments, and a sometimes-circuitous series of theoretical and experimental developments, as well as sustained R&D efforts across multiple agencies and the private sector. The return on investment is evident from technologies, such as GPS and MRI, that are providing transformative impacts for society and advancing the frontiers of knowledge.

The realization of new quantum sensors is a tangible, near-term objective that should be catalyzed by agencies represented on the Subcommittee on QIS as part of the National Quantum Initiative program. Getting more quantum sensors to market is a goal that can lay a foundation for industries of the future and provide disruptive advantages for prosperity and security. Similar to the technological arcs described by the highlighted exemplars in Section II, these efforts will open new horizons and expand the reach of fundamental science and engineering.

An overarching strategy that engages several agencies, private sector entities, and academic leaders is important because there are potentially valuable quantum sensing technologies that are still vulnerable to failure. Opportunities can be missed for lack of communication between researchers and end users, underdeveloped supply chains, or insufficient engineering support for key components. Challenges also stem from barriers to technology transfer, tendencies to avoid risk, and the fact that timelines can be quite long to develop functional devices.

The four policy recommendations presented in Section III augment and expand upon the National Strategic Overview for QIS and provide specific approaches to overcome several of the main challenges facing quantum sensor developers. A concerted effort will help to identify mission-relevant quantum sensors, understand the performance requirements dictated by applications, anticipate fundamental limitations and failure modes for devices in realistic conditions, and take appropriate risks to explore truly revolutionary technologies. It will take leadership to facilitate collaborations between QIST R&D agencies and potential end users, and to identify appropriate budgets for these activities.

While there is much fundamental science to be done, and entirely new concepts and platforms for quantum sensors are likely to be discovered in the future, the strategy presented here has focused on joint efforts and field-testing of prototypes because these have been identified as gaps where coordination is needed and successes can bolster the entire field of QIST. Existing mechanisms that enable early-stage exploratory QIST research are an important source of new ideas and should not be supplanted by these recommendations. A national strategy to bring quantum sensors from lab to market must foster the long arc of technology development.

If this strategy is implemented successfully, joint efforts to develop, demonstrate, and utilize selected sensors should accelerate the dissemination of transformative products and services. First-mover advantages for early adopters and intellectual property for innovators and entrepreneurs will be gained along the way. Increased availability of quantum components and devices will benefit many users, including scientists in other fields, broadening the QIST R&D community. In sum, for the United States to realize the economic, security, and societal benefits of quantum technology, agencies should lead concerted efforts to bring the next wave of quantum sensors to fruition.