DEPARTMENT OF DEFENSE

# DEFENSE SCIENCE BOARD


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Department of Defense
OFFICE OF PREPUBLICATION AND SECURITY REVIEW

# applications of quantum technologies

**October 2019**

## Executive Summary

OFFICE OF THE UNDER SECRETARY OF DEFENSE FOR RESEARCH AND ENGINEERING

This report is a product of the Defense Science Board (DSB). The DSB is a Federal Advisory Committee established to provide independent advice to the Secretary of Defense. Statements, opinions, conclusions, and recommendations in this report do not necessarily represent the official position of the Department of Defense. The DSB Study on Applications of Quantum Technologies completed its information-gathering in May 2019. The Executive Summary is unclassified and was cleared for open publication by the DoD Office of Prepublication and Security Review on December 18, 2019.

OFFICE OF THE SECRETARY OF DEFENSE
3140 DEFENSE PENTAGON
WASHINGTON, DC 20301–3140

DEFENSE SCIENCE BOARD

MEMORANDUM FOR UNDER SECRETARY OF DEFENSE FOR RESEARCH AND ENGINEERING

SUBJECT: Final Report of the Defense Science Board (DSB) Task Force on Applications of Quantum Technologies

I am pleased to forward the final report of the Defense Science Board Task Force on Applications of Quantum Technologies, co-chaired by Dr. John Manferdelli and Dr. Robert Wisnieff.

Quantum technologies exhibit remarkable potential to enhance or upend current warfighting capabilities. Fields such as sensing, computation, and communications are key mission areas in which quantum could make a significant impact. It is crucial that the Department of Defense (DoD), along with our allies and partners, maintain the leading edge in understanding advances in these technologies. Industry and academia also play a vital role in the development of quantum technologies, and their collaboration with DoD could reap benefits for all parties. This is particularly pressing given adversarial investments being made towards quantum superiority, if not dominance.

The most urgent focus, however, must be applied to the enabling components that underpin a broad swath of quantum technologies. This is where the DoD may gain the most persistent advantage.

I agree with the recommendations detailed in this report and urge the DoD to move quickly toward their adoption.

Dr. Craig Fields
Chairman, DSB

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DEFENSE SCIENCE BOARD

OFFICE OF THE SECRETARY OF DEFENSE
3140 DEFENSE PENTAGON
WASHINGTON, DC 20301–3140

MEMORANDUM TO THE CHAIRMAN, DEFENSE SCIENCE BOARD

SUBJECT: Final Report of the Defense Science Board (DSB) Task Force on Applications of Quantum Technologies

Attached is the final report of the Defense Science Board Task Force on Applications of Quantum Technologies. The Task Force was commissioned to accomplish the following objectives:

- Evaluate the level of technology readiness of quantum technologies and the technological challenges they face in order to be considered for DoD applications;
- Evaluate the level of research and development in these technology areas in universities, government laboratories, and industry, both domestically and in other countries;
- Evaluate which applications will be developed for commercial use and which will be primarily unique to the DoD. For DoD applications, evaluate if the technologies required for design, fabrication, testing, and use provide a persistent differentiation; and
- Evaluate the ancillary technologies required for implementation of these technologies.

The Task Force found that the Department can glean the most opportunity in three technology areas: quantum sensing, quantum computing, and quantum communications (empowered by entanglement distribution). Quantum sensing applications are currently poised for mission use whereas quantum computing and communications are in earlier stages of development. Applications in each of these technology areas could offer critical value to DoD and must be pursued vigorously.

Where the most persistent differentiation may be found, however, is in the technology that spans the breadth of quantum technology applications – the enabling components. Reliable, well-characterized, trusted, and well-manufactured components, coupled with practiced integration, may be the biggest factor in achieving quantum superiority and competitive advantage. This is crucial if the United States is to maintain its edge in a race in which its competitors are already nipping at its heels.

This report outlines current technology readiness levels of the various quantum applications and explores their applicability to the DoD mission.

The Task Force has provided a series of recommendations that the DoD should adopt without delay. Doing so will enable the United States to lead the world in quantum research, development, and application. We hope that this report finds a receptive audience among the Nation’s top military and policy leaders.

Dr. John Manferdelli
Co-Chairman

Dr. Robert Wisnieff
Co-Chairman

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# Executive Summary of the DSB Report on Applications of Quantum Technologies

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# Executive Summary of the DSB Report on Applications of Quantum Technologies

## Scope of the Study

Quantum technologies have shown increasing capabilities, many of which will benefit the Department of Defense (DoD). In particular, applications to sensing systems, computation, and communications systems will create a new era of quantum-enabled capabilities in the mission space of the DoD. At the core, the promise and impacts of quantum science and technology are about the collection, generation, processing, and communication of information. Critical to these advances are the components used broadly across many quantum technology areas. Developing these components may afford the most persistent advantage to DoD.

Quantum sensors have been demonstrated to outperform current sensors and offer the potential for dramatically improved performance for critical DoD missions, including: maintaining timing and positioning accuracy in Global Positioning System (GPS)-challenged or GPS-denied environments; enabling magnetometry for maritime security; using gravimeters to detect the location of underground structures and special nuclear material; position updates via gravity mapping to bound inertial system errors for long-term submarine navigation; and strategic-grade inertial navigation systems (INS) relying on precision gravity maps to correct for local gravity perturbations. However, as DoD interest in these technologies far outweighs commercial interest at this time, the Department will need to be the key investor to bring these technologies to fieldable readiness levels.

Quantum computers can potentially give DoD substantial computation power for cryptography, signal processing, physical simulation, and artificial intelligence/machine learning. Global industry is heavily invested in this field. The Department must monitor and understand technological progress in quantum computing, both domestically and abroad, in order to rapidly take advantage of emerging advances.

Entanglement and its distribution, which can potentially give DoD practical access to quantum's "spooky action at a distance,"[1] can be used to develop high-accuracy, large-aperture sensors with stunning resolution. It is also a critical driver for communication and computing. This technology is in the early research phase, requiring modest investment, but it may offer some critical DoD-specific capabilities, especially in computing and sensing. The Department must also monitor and understand domestic and global technological progress in this field.

Lastly, the DoD faces a shortage of technical talent in the quantum workforce and should partner wisely with academia and industry to address the shortfall. Without a strong quantum workforce,

[1] Albert Einstein dismissed quantum entanglement — the ability of separated objects to share a condition or state — as "spooky action at a distance."

the DoD will not be able to capitalize on the opportunities that advancements in quantum technologies provide.

## Quantum Sensing Findings

- **Finding 1**: There are many laboratory demonstrations of quantum sensors with performance eclipsing fielded instruments, presenting opportunities for significant return on investment for engineering/development.
  - Clocks, accelerometers, and magnetometers may be the best opportunities.
  - For inertial applications, quantum accelerometers offer significant advantages over current strategic-grade solutions.
  - Analysis indicates more performance is possible from Interferometric Fiber Optic Gyros (IFOGs), making cold atom gyros less compelling.
- **Finding 2:** There is a notable lack of rigorous analysis tying performance to mission specifications and/or novel capability. Different applications of quantum sensors with different platforms have differing size, weight, and power (SWaP) considerations.
- **Finding 3:** Bringing quantum sensors to maturity will require investment in component and enabling technology, which will benefit computing and communications.
- **Finding 4:** Quantum radar will not provide upgraded capability to DoD.
- **Finding 5:** Quantum illumination may provide enhanced imaging in certain contexts; research is in its infancy.
- **Finding 6:** Miniaturized antennas with significant potential application within DoD may be possible with quantum electrometers (e.g., Rydberg antennas).
- **Finding 7:** Gravimeters and gravity gradiometers based on atom interferometry could enable capabilities including airborne tunnel detection, detection of nuclear material, gravity-aided navigation, and geodesy.
- **Finding 8:** No existing gravimetric sensors provide sensitivity or applicability to dynamic platforms needed by DoD applications.
- **Finding 9:** Several atomic interferometric approaches have demonstrated gravimetric sensitivity and portability for DoD applications with potential for increased sensitivity.
- **Finding 10:** The challenge of atomic interferometer systems is to reduce SWaP-C and transfer state-of-the-art performance demonstrated in the laboratory to field-qualified systems. Dynamic platforms are particularly challenging.

## Quantum Computing Findings

- **Finding 1**: The development of reliable one and two qubit gates is critical to building a quantum computer. Two bit entangling gates are challenging and especially important.

- **Finding 2:** Current promising qubit technologies have developed varying gate fidelities and coherence time. It is still unclear which has the most promise. The principal qubit technologies include:
  - Superconducting Josephson junction qubits;
  - Ion-based qubits;
  - Semiconductor based qubits;
  - Topological qubits; and
  - Photonic qubits.
- **Finding 3**: The utility of "adiabatic quantum computers" will be determined by architecture and applications and is speculative right now.
- **Finding 4:** Commercial industry is integrating tens to hundreds of qubits, in cloud-available systems, to find a useful near-term application and prove out the technology.
- **Finding 5:** Industry is not pursuing quantum emulation.
- **Finding 6:** Worldwide investments have led to advances in quantum hardware, software, and algorithms.
  - High levels of foreign investments could lead to rapid advances, breakthroughs, and technological surprise.

## Quantum Communications and Entanglement Distribution Findings

- **Finding 1**: Entanglement distribution will allow teleportation which will result in technological disruption.
- **Finding 2:** Quantum networks will allow distributed quantum computing.
  - They will provide scalability and modularity.
  - They will allow remote, secure quantum computing (e.g., blind quantum computing).
- **Finding 3**: State of the art in entanglement distribution is limited to proof-of-concept, point-to-point experiments in laboratories. The most advanced experiment demonstrated entanglement distribution over a few kilometers (at Delft University of Technology).
- **Finding 4:** Entangled photons can currently be generated and distributed at the 10s of kilobits per second.
- **Finding 5:** Memories can currently be entangled at 10 bits per second.
- **Finding 6:** In principle, quantum key distribution (QKD) provides natural information theoretic (Shannon) cryptographic security. QKD systems do not support *authenticated* key exchange.

- **Finding 7:** QKD has not been implemented with sufficient capability or security to be deployed for DoD mission use. The Task Force concurs with the National Security Agency (NSA)'s assessment of QKD certification.
- **Finding 8:** QKD developments and use by foreign parties should be understood and tracked.

# Appendix A: Task Force Terms of Reference

THE UNDER SECRETARY OF DEFENSE
3030 DEFENSE PENTAGON
WASHINGTON, DC 20301-3030

RESEARCH AND ENGINEERING

JUN 1 8 2018

MEMORANDUM FOR CHAIRMAN, DEFENSE SCIENCE BOARD

SUBJECT: Terms of Reference - Defense Science Board Task Force on Applications of Quantum Technologies

Quantum technologies have shown increasing capabilities in metrology, sensing, communications, and computation. Increases in precision and sensitivity will extend the capability of existing systems and allow new types of measurements to be made. Quantum-based communication techniques have been developed for over 30 years and provide a means for secure communications in contested environments. Quantum computation and simulation have made significant progress in recent years. Understanding the state-of-the-art and the likely trajectory of these technologies will allow the Department of Defense (DoD) to strategically incorporate these technologies into its systems.

The Air Force Science Advisory Board studied quantum science and technologies in 2015. Progress across the breadth of quantum-enabled technologies including recent announcements of the use of quantum computers to simulate atomic properties and the possibility of using quantum technologies in more application areas, including land, sea, and sub surface applications, makes the topic worthy of additional investigation.

For each of these missions or capability areas, the key technology questions to be considered are:

- What is the level of technology readiness of these technologies? What technological challenges do they face in order to be considered for DoD applications?
- What is the level of research and development in these technologies in universities, Government laboratories and industries both domestically and in other countries?
- Which technologies will be developed for commercial applications? Which areas will be applicable to primarily unique DoD applications? For DoD applications: will the technologies required for design, fabrication, testing, and use provide a persistent differentiation?
- What are the ancillary technologies (refrigeration, filters, interconnect, packaging, specialized materials, etc.) required for implementation of these technologies?

I will sponsor the study. Dr. John Manferdelli and Dr. Robert Wisnieff will serve as the co-Chairmen of this study. Mr. Paul Lopata will serve as the Executive Secretary. Lt Col Milo Hyde will serve as the Defense Science Board Secretariat representative.

The task force members are granted access to those DoD officials and data necessary for the appropriate conduct of their study. The Under Secretary of Defense for Research and Engineering will serve as the DoD decision-maker for the matter under consideration and will coordinate decision-making as appropriate with other stakeholders identified by the study's findings and recommendations. The nominal start date of the study period will be within 3 months of signing this Terms of Reference, and the study period will be between 9 to 12 months. The final report will be completed within three months from the end of the study period. Extensions for unforeseen circumstances will be handled accordingly.

The study will operate in accordance with the provisions of Public Law 92-463, "Federal Advisory Committee Act," and DoD Instruction 5105.04, "DoD Federal Advisory Committee Management Program." It is not anticipated that this study will need to go into any "particular matters" within the meaning of title 18, United States Code, section 208, nor will it cause any member to be placed in the position of action as a procurement official.

Michael D. Griffin

# Appendix B: Task Force Membership

## Co-Chairs

Dr. John Manferdelli
*Northeastern University*

Dr. Robert Wisnieff
*IBM Corporation*

## Members

Dr. Zachary Dutton
*Raytheon Company*

Dr. Gerald Gilbert
*The MITRE Corporation*

Dr. Joan Hoffmann
*Johns Hopkins University, Applied Physics Laboratory*

Dr. Christopher Lirakis
*IBM Corporation*

Dr. Mark Maybury
*Stanley Black & Decker, Inc.*

Dr. Steven Rinaldi
*Sandia National Laboratories*

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*Private Consultant*

Dr. Peter Weinberger
*Google LLC*

Dr. David Whelan
*University of California, San Diego*

## Government Advisors

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*U.S. Air Force Research Laboratory*

Dr. Gerald Baumgartner
*National Security Agency*

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*U.S. Army Research Laboratory and National Aeronautics and Space Administration*

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*U.S. Navy Office of Naval Research*

Lt Col Daniel Schnick, USMC
*Office of the Deputy Commandant of the Marine Corps for Information*

Dr. Kathy-Anne Soderberg
*U.S. Air Force Research Laboratory*

Dr. Charles Tahan
*University of Maryland, Laboratory for Physical Sciences*

## Executive Secretary

Dr. Paul Lopata
*Office of the Under Secretary of Defense for Research and Engineering*

## Defense Science Board Secretariat

Mr. Kevin Doxey
*Executive Director*

Lt Col Milo Hyde IV, USAF
*Designated Federal Officer*

## Study Support

Ms. Clare Mernagh
*SAIC*

Ms. Brenda Poole
*SAIC*

# Appendix C: Recommendations

## [1] Quantum Components

### 1.1. Under Secretary of Defense for Research and Engineering (USD(R&E)) support the development of a broad, trusted industrial supply base. Specifically:

- Deputy Director of the Defense Advanced Research Projects Agency (DARPA) Microsystems Technology Office should broaden the Electronics Resurgence Initiative or create a new program to develop components and integration technologies enabling fieldable quantum systems, including:
  - Discrete and integrated photonics at desired wavelengths;
  - Narrow-band, solid-state lasers;
  - High efficiency single-photon detectors;
  - Single- and entangled-photon sources;
  - Low-loss switches and other optical components;
  - Low-loss filters, circulators, and other microwave components;
  - Vapor cells and vacuum system packaging;
  - Dilution refrigerators; and
  - Cryogenic electronics.
- USD(R&E) support, monitor, and leverage indigenous manufacturing critical to quantum technology. In particular, this means the ability to manufacture potentially ITAR-restricted and proprietary designs at DoD laboratories and contractors.
- Director of DARPA, CNR, Director of Research at NRL, Director of the Air Force Office of Scientific Research (AFOSR), Executive Director of the Air Force Research Laboratory (AFRL), Director of the Army Research Laboratory (ARL), and Director of the Army Research Office (ARO) invest in the critical components that are necessary for near term applications and will ultimately be useful for quantum computing, including:
  - Microwave to optical transduction devices that are quantum coherent, with efficiencies approaching 100 percent;
  - Low-noise quantum amplifiers;
  - Electronics and optics for high speed, high precision quantum control; and
  - Cryogenic electronics enabling low temperature quantum control to simplify design and integration.

## [2] Quantum Sensing

**2.1. Assistant Director of Quantum Science (OUSD(R&E)) establish a next-generation clock product program.**

- Leverage chip-scale atomic clock (CSAC) and DARPA atomic clock with enhanced stability (ACES) technology.
- Target performance of 10-100x improvement in precision and stability over CSAC with comparable SWaP.
- Include DoD ManTech funding to stimulate manufacturing base.
- Structure program to develop multiple sources to address price versus cost issues.
- Demonstrate commercial time applications (e.g., cloud computing, banking) in GPS-denied scenarios. Raise awareness across government of broad impact of losing GPS-time.
- The Task Force estimate is that this would take less than 5 years and cost $100-200M.

**2.2. Assistant Director of Quantum Science (OUSD(R&E)) establish a program to deliver a fieldable IMU for GPS-denied high-precision navigation and positioning.** Goals are:

- Performance target: x1-10 strategic grade accuracy at <10 percent strategic grade price, enabling tactical use.
- Quantum accelerometers are the highest impact investment due to the need for a solid state strategic-grade accelerometer. Because of the current performance and potential improvements in IFOGs, quantum gyros may be less compelling because of implementation challenges; however, the cold atom based gyros may ultimately outperform IFOGs. The technology effort to develop a cold atom accelerometer will settle many of the issues for gyros at the same time.
- Product specifications must be motivated by DoD missions, for example:
  - SLBM guidance
  - GPS-denied navigation
- The Task Force estimate is that this would take 10 years and cost $300-400M to get to technology readiness level (TRL) 8.

**2.3. Assistant Director for Quantum Science (OUSD(R&E)) conduct a systems-level analysis of applicability of laboratory-demonstrated quantum gravimeters for detection of subsurface structures/facilities and long-term submarine navigation.**

**2.4. Assistant Director for Quantum Science (OUSD(R&E)) fund gravimetric sensor programs.**

## [3] Quantum Computing

**3.1. Director, National Security Agency and the DoD Chief Information Officer, in conjunction with Director, National Institute of Standards and Technology, select and deploy quantum-resistant public key infrastructure algorithms and protocols.** This work is vital and must continue in earnest.

**3.2. Directors, DoD Military Department Laboratories work with commercial, academic, and other government partners to exploit noisy intermediate-scale quantum (NISQ) and quantum emulators as intermediate steps to fully fault tolerant quantum computation.**

**3.3. U.S. Army Deputy Assistant Secretary for Research and Technology (High Performance Computing Modernization Program), in collaboration with DoD Military Department Laboratories, investigate the potential for large-scale, error-corrected quantum computers for DoD applications by performing detailed costing and systems analyses.**

- This must include DoD experts in computational tasks and associated mission applications.
- Enable rapid capitalization upon advances for mission-specific applications, regardless of the source of the advancement (domestic/foreign, industry, academia, or government laboratory).

**3.4. ARO, AFOSR, and ONR continue to invest in fundamental research into a variety of qubit/quantum computing technologies to avoid technological surprise, measuring developments against the NAS-proposed metrics and milestones.**

- Provide an understanding of when and how to best exploit quantum computing.
- Target research and development (R&D) investments strategically.
- Avoid technological surprise from developments abroad.
- Create opportunities for technological surprise by targeted and rapid incorporation of such advancements.

## [4] Quantum Communications

**4.1 Assistant Director of Quantum Science (OUSD(R&E)) conduct studies with representation across DoD and the Intelligence Community to identify and quantify entanglement applications and implementation, in connection with quantum computing and sensors.** For example, possible applications include:

- Quantum sensor arrays;
- Clock synchronization; and
- Long-baseline interferometry.

The output of these studies should inform current state of technology, technology gaps, required component operational parameters, potential system designs, expected performance metrics, and timelines for development.

**4.2. Assistant Director of Quantum (OUSD(R&E)) direct DoD R&D entities to create integrated development environments, "testbeds," for quantum networking testing and validation.** Testing should include:

- The ability to connect different types of qubits (ions, photons, superconducting, etc.);
- The ability to connect different functionalities (even with the same qubit type);
- A field environment to vet quantum science technologies outside of the laboratory;
  - Incorporate three or more memory nodes;
  - Connect two or more qubit technologies; and,
- A platform to integrate memory with integrated quantum photonic devices to distribute, verify, and validate entanglement.

**4.3. USD(R&E) sustain long-term research and development efforts that systematically identify and retire challenges to advancing the development of heterogeneous distributed quantum information processing platforms.**

- Demonstrate connecting and operating quantum systems of different physical types.
- Demonstrate connecting and operating quantum systems of different functions.
- Demonstrate modular building blocks of a scalable system.
- Utilize heterogeneous distributed quantum information processing platforms of increasing complexity to demonstrate DoD applications performed uniquely (beyond classical) and advantageously.

## [5] Quantum Workforce

**5.1. The Military Department Academies, to include the Air Force Institute of Technology (AFIT) and the Naval Postgraduate School (NPS), should add a one-semester quantum technology class for engineering, science, and computer scientists and continue to partner with research universities on sensor and computing research.** The senior military colleges (Norwich University, Virginia Polytechnic Institute and State University, The Citadel, The Military College of South Carolina, Virginia Military Institute, Texas A&M University, and the University of North Georgia) should also add quantum technology to their curriculum.

- Despite this, DoD should avoid the idea that quantum computing will replace classical computing or engineering.

**5.2. Assistant Director of Quantum Science (OUSD(R&E)) create a consortium to bring commercial and university quantum experts to study applications to DoD problems.**

**5.3. USD(R&E) advocate DoD participation in the National Quantum Initiative.**

# Appendix D: Briefings Received

## 25-26 October 2018 Meeting

Discussion of National Academy of Science Quantum Computing Report
*Task Force Co-Chair*

Office of the Secretary of Defense Plan to Assure Strategic Advantage in Quantum Information Science
*Office of the Under Secretary of Defense for Research and Engineering*

Threat Briefing
*Intelligence Community*

Discussion of United States Air Force Scientific Advisory Board Study
*United States Air Force Scientific Advisory Study Chair*

Quantum Computing Research at Laboratory for Physical Sciences
*University of Maryland, Laboratory for Physical Sciences*

## 13-14 November 2018 Meeting

United States Army Research Laboratory Quantum Networking Research
*United States Army Research Laboratory*

QKD Discussion
*Intelligence Community*

QKD Hardware Research
*Intelligence Community*

Quantum Applications to Undersea Warfare
*Johns Hopkins University, Applied Physics Laboratory*

## 10-11 December 2018 Meeting

Advancing the Foundation for Quantum Computing;
Opportunities for Next-Generation Quantum Sensors;
Quantum Computing;
Emerging Opportunities for Quantum Communication;
Quantum Processing of Classical Optical Signals;
Quantum Communications; and
Quantum Radar Analysis
*MIT Lincoln Laboratory*

Quantum Systems;
CSAC and Atomic Magnetometry;

ACES/STOIC;
C-SCAN; and
Trident Integration Laboratory
*The Charles Stark Draper Laboratory, Inc.*

Quantum Algorithms; Adiabatic Computing
*Raytheon Company*

The MITRE-MIT-AFRL Quantum Moonshot Program
*The MITRE Corporation; Massachusetts Institute of Technology; U.S. Air Force Research Laboratory*

The HHL Algorithm
*Massachusetts Institute of Technology*

## 14-15 January 2019 Meeting

Intelligence Advanced Research Projects Activity's (IARPA) Quantum Programs
*IARPA*

Quantum Information Science Research in the United Kingdom and the European Union
*Cambridge Quantum Computing*

Discussion with the Deputy Under Secretary of Defense for Research and Engineering
*Deputy Under Secretary of Defense for Research and Engineering*

The Threat – DoD Perspective
*National Air and Space Intelligence Center*

Sensors/Rydberg antennas/Electrometry
*ColdQuanta, Inc.*

## 13-14 February 2019 Meeting

AOSense Quantum Programs
*AOSense, Inc.*

Quantum Sensing and Ion Trap Quantum Information; and
Quantum Architecture Testbeds
*Lawrence Livermore National Laboratory*

Quantum Computation/National Academy of Sciences Report;
The Stanford QIS Initiative Overview/Quantum Photonic Systems;
Quantum Sensing; and
Quantum Nanophotonics
*Stanford University*

Microsoft's Quantum Computing and Algorithms
*Microsoft Corporation*

Executive Overview of IBM Research
*International Business Machines Corporation*

Ion Traps and Quantum Processing at NIST; and
Quantum Sensing and Metrology at NIST
*National Institute of Standards and Technology*

QC Ware Overview
*QC Ware, Corp.*

NISQ Machines and Algorithms
*University of California, Berkeley*

## 28-29 March 2019 Meeting

Blind Quantum Computing
*University of Ottawa*

## 15-16 April 2019 Meeting

Optical Interferometry for Deep Space Surveillance
*MIT Lincoln Laboratory*

Expanding American Leadership in Quantum Information Science
*White House Office of Science and Technology Policy*

Quantum Sensors
*Intelligence Community*

## 22-23 May 2019 Meeting

United States Air Force Cryptology Modernization Program
*The MITRE Corporation*

# Appendix E: Acronyms and Abbreviated Terms

| | |
|---|---|
| ACES | Atomic clock with enhanced stability |
| AFIT | Air Force Institute of Technology |
| AFOSR | Air Force Office of Scientific Research |
| AFRL | Air Force Research Laboratory |
| ARL | Army Research Laboratory |
| ARO | Army Research Office |
| CSAC | Chip-scale atomic clock |
| C-SCAN | Chip-scale combinatorial atomic navigator |
| DARPA | Defense Advanced Research Projects Agency |
| DoD | Department of Defense |
| GPS | Global positioning system |
| IFOG | Interferometric Fiber Optic Gyro |
| ITAR | International Traffic in Arms Regulation |
| NAS | National Academy of Sciences |
| NISQ | Noisy intermediate-scale quantum |
| NPS | Naval Postgraduate School |
| NRL | Naval Research Laboratory |
| NSA | National Security Agency |
| ONR | Office of Naval Research |
| OUSD(R&E) | Office of the Under Secretary of Defense for Research and Engineering |
| QKD | Quantum key distribution |
| R&D | Research and development |
| SWaP | Size, weight, and power |
| SWaP-C | Size, weight, power, and cost |
| TRL | Technology readiness level |
| USD(R&E) | Under Secretary of Defense for Research and Engineering |