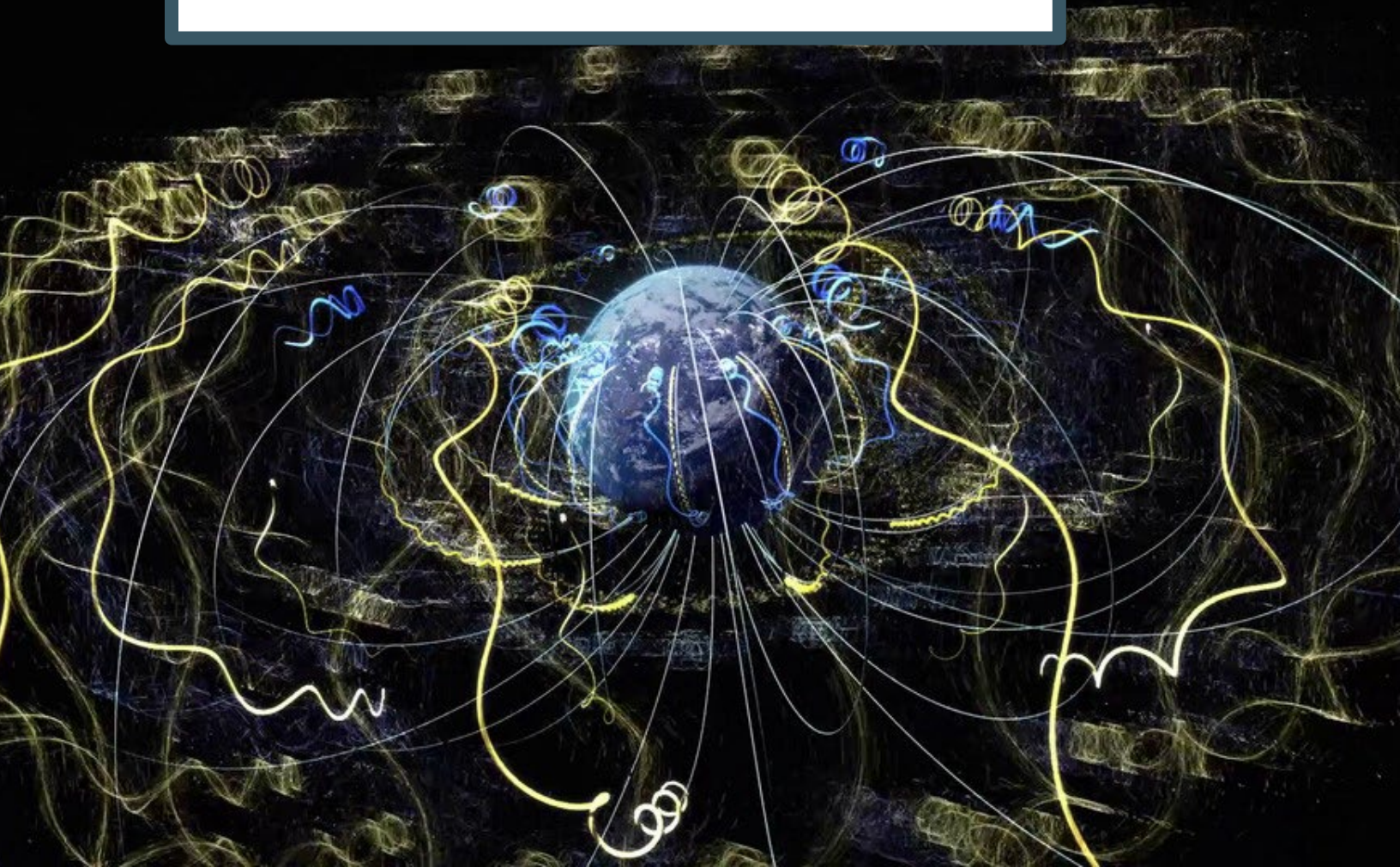


Quantum Sensing for Position, Navigation, and Timing Use Cases

September 2024



Source: NASA Goddard Space Flight Center/Joy Ng

Acknowledgments

Thank you to the Quantum Economic Development Consortium (QED-C) Use Cases Technical Advisory Committee (TAC), especially the Sensing subgroup members (listed in Appendix D). Additionally, this report would not have been possible without the leadership and contributions of the members of the workshop organizing committee:

- Nadia Carlsten, SandboxAQ
- Carl Dukatz, Accenture
- Michael Larsen, Northrop Grumman
- Bonnie Marlow, MITRE
- Julián Martínez-Rincón, Brookhaven National Laboratory
- Rima Oueid, US Department of Energy
- Max Perez, Infleqtion
- Keeper Sharkey, ODE, L3C

The National Institute of Standards and Technology (NIST) provided financial support for this study.

About QED-C

QED-C is an industry-driven consortium managed by SRI. With a diverse membership representing industry, academia, government, and other stakeholders, the consortium seeks to enable and grow the quantum industry and associated supply chain. For more about QED-C, visit our website at quantumconsortium.org.

Suggested Citation

Quantum Economic Development Consortium (QED-C). *Quantum Sensing for Position, Navigation, and Timing Use Cases*. Arlington, VA. September 2024.
<https://quantumconsortium.org/pnt2024>.

Government Purpose Rights

Agreement No.: OTA-2019-0001

Contractor Name: SRI International

Contractor Address: 333 Ravenswood Avenue, Menlo Park, CA 94025

Expiration Date: Perpetual

Use, duplication, or disclosure is subject to the restrictions as stated in the Agreement between NIST and SRI.

Non-US Government Notice

Copyright © 2024 SRI International. All rights reserved.

Disclaimer

This publication of the Quantum Economic Development Consortium, which is managed by SRI International, does not necessarily represent the views of SRI International, any individual member of QED-C, or any government agency.

Table of Contents

Executive Summary	1
Introduction	4
Quantum Sensors	8
Benchmarking Metrics	9
Innovation Landscape	12
Challenges to Scaling Quantum Sensors for PNT	13
Position, Navigation, and Timing Use Cases	16
Impact and Feasibility of Use Cases	17
Sensor Function	20
Sensing Deployment	22
Implementation Details of Selected Use Cases	24
MagNav for Resilient, Unjammable PNT	24
Precision Timing for Space-Based Networks	25
Small Satellite Orientation and Alignment	26
Reference and Resource Maps	26
Standardization and Validation Testbeds for Quantum Sensors	27
Recommendations	28
Appendix A: Methodology	30
Appendix B: Use Cases for Quantum Sensors in PNT	36
Appendix C: Workshop Participants	42
Appendix D: Use Cases Technical Advisory Committee – Sensing Subgroup Members	45

Executive Summary

The demand for precise and reliable position, navigation, and timing (PNT) information has driven innovation in increasingly advanced measurement tools for centuries, and the importance of these systems in today's highly interconnected, technology-dependent world has never been higher. Nearly every industry — including health, defense, communications, transportation, finance, manufacturing, and energy — has some need for PNT tools. More advanced measurement can increase reliability and resilience, and PNT infrastructure can offer a range of capabilities by providing information such as location, orientation, altitude, tilt, directional movement, acceleration, and timing.

The Global Positioning System (GPS) has been the cornerstone of PNT for several decades, and the technology has evolved to increase accuracy, integrity, and security as well as grow its range of uses. Other technologies, such as inertial navigation systems and light detection and ranging (LiDAR), have also emerged to increase the reliability of PNT information. Nevertheless, there are still limitations to all of these tools. For example, GPS's reliance on satellites makes it susceptible to space weather events and potential adversarial actions in space, and threat agents can interfere with GPS systems through jamming and spoofing.

Quantum sensors can provide navigational information in environments where GPS signals are unavailable or unreliable. Such sensors include quantum accelerometers and gyroscopes, quantum magnetometers, and gravimeters and gravity gradiometers, all of which are discussed in this report. Many quantum sensors offer levels of precision not possible with traditional approaches for measuring physical quantities such as time, acceleration, and magnetic fields. Furthermore, networks of quantum sensors can provide additional reliability and accuracy in the collection of PNT information.

Quantum sensors have potential applications in the following high-feasibility, high-impact PNT use cases identified by quantum sensing experts and PNT stakeholders:

- magnetic navigation for resilient, unjammable PNT,
- precision timing for space-based networks,
- small satellite orientation and alignment,
- reference and resource maps, and
- standardization and validation testbeds for quantum sensors.

This report compares performance metrics of quantum sensors and their classical counterparts, reviews challenges to scaling and commercializing quantum sensors, and explores the potential use cases listed above in detail. Additionally, it presents

four recommendations for developing quantum sensors and increasing their adoption in PNT applications:

1. **Invest in photonic integrated circuits R&D:** Photonic integrated circuits (PICs) comprise multiple photonic components integrated on a single platform or substrate. The development of PICs would enable reduced size, weight, power, and cost (SWaP-C) of quantum sensors, as well as make them more robust and reliable. These advances could prove critical for the application and commercialization of quantum sensors and spur adoption of quantum sensors across industries. However, PIC technologies for quantum applications are largely in the early stages of R&D. Federal funding agencies should increase investment in PIC R&D to address materials, integration, interconnect, and other challenges. As these are addressed, industry should be supported to develop PICs for applications relevant to government missions and commercial use cases.
2. **Engage the quantum community to identify opportunities for critical/high-value SWaP-C improvements:** The diversity of components used in quantum sensors across the industry is one of the primary barriers to scale, but there are commonalities in industry's needs. Quantum technology developers should collaborate with organizations such as QED-C in contributing to market studies of the SWaP-C improvements required for adoption. Compiling sensor performance metrics could uncover commonalities that would help technology developers know what capabilities to target. Moreover, identifying opportunities for critical improvements to SWaP-C for even a single use case could spark greater market adoption through economies of scale that trickle back into the supply chain. This could create a virtuous cycle via the supply chain components that in turn benefit the entire quantum sensor market with different SWaP-C requirements. Data collected from the quantum sensor community could be tracked and visualized so that achievement of performance targets is celebrated, remaining gaps are recognized, and high-value targets are pursued.
3. **Be an early adopter of quantum sensor technologies:** The federal government depends on accurate and available PNT information for many important missions, including space exploration (NASA), defense and security (DOD), and energy management (DOE). As such, the federal government should be an early adopter of new quantum sensor technologies for its PNT needs. In this way, government would help fund the derisking and serve as a third-party validator of the technology. This would likely lead to lower cost for the technology, as federal investment would support the technology's initial development and ultimately its broader adoption and scaling. Additionally, collaboration among federal agencies could lead to increased standardization of quantum sensors.
4. **Develop and deploy PNT systems for different platforms and environmental conditions:** As laid out in this report, there are clear PNT use cases for quantum sensors at every elevation level, from subterranean to extraterrestrial, and for

many different industries. Each sensor deployment situation can have unique environmental conditions and requirements for the sensor platform. Reference data for diverse situations will be required for PNT systems to operate and should include data on inertial, vibration, and shock conditions and temperature, humidity, and magnetic environmental conditions. Academia, federal funding agencies, and technology developers should collaborate to collect necessary reference data and develop PNT systems that can be deployed in various conditions, settings, and elevations. End users, including government customers, could be involved as well to provide data on environmental conditions and platform effects to inform quantum sensor engineering requirements and/or opportunities for quantum sensor developers to test prototypes on relevant platforms.

Introduction

The demand for precise and reliable position, navigation, and timing (PNT) information has driven innovation in increasingly advanced measurement tools for centuries, and the importance of these systems in today's highly interconnected, technology-dependent world has never been higher. The value of sophisticated PNT measurement tools extends far beyond basic Global Positioning System (GPS) navigation, the most popular PNT service. Nearly every industry — including health, defense, communications, transportation, finance, manufacturing, and energy — has some need for PNT tools.

The more advanced measurement enabled by PNT can increase reliability and resilience when GPS service is lost or denied. PNT infrastructure can offer a range of capabilities by providing information such as location, orientation, altitude, tilt, directional movement, acceleration, and timing. A wide array of technology systems — including those for navigation, military operations, telecommunications, energy, and financial networks, among others — benefit from or rely on PNT.

The three distinct, fundamental capabilities of PNT are

- **positioning**, the ability to accurately and precisely determine an object's or individual's location (usually latitude and longitude, sometimes altitude) and orientation relative to a reference point;
- **navigation**, the ability to measure and apply corrections to course, orientation, and speed to attain a desired position; and
- **timing**, the ability to acquire, maintain, and/or synchronize accurate and precise time relative to a standard, such as Coordinated Universal Time, within user-defined timeliness parameters.¹

GPS has served as the cornerstone of PNT for several decades, during which the technology has evolved to increase accuracy, integrity, and security and to grow its range of uses. Complementing GPS, wider satellite navigation systems such as global navigation satellite systems (GNSS) enhance accuracy and reliability through multiconstellation solutions. Moreover, GNSS, augmented by LEO constellations, can improve both the accuracy of PNT and the consistency and reliability of secure PNT systems.

In environments where satellite signals are obstructed or unreliable, technologies such as inertial navigation systems (INS) can be effective; they use accelerometers and gyroscopes to maintain accurate positioning. Radio-based systems provide additional layers of redundancy and are often used in maritime and aviation sectors. Although these technologies do not currently offer performance on the same level

¹ US Department of Transportation. What Is Positioning, Navigation and Timing (PNT)? (2017). <https://www.transportation.gov/pnt/what-positioning-navigation-and-timing-pnt>

as GPS/GNSS, some emerging technologies — including advances in navigation using signals of opportunity (e.g., cellular networks, satellite downlinks), light detection and ranging (LiDAR), and vision-based navigation — may offer enhanced reliability as alternatives to GNSS for certain use cases and application domains.

Networks of magnetic navigation or gravitational navigation systems coupled with INS may offer performance on par with GPS/GNSS. Quantum magnetometers, which detect minute changes in magnetic fields; quantum gravimeters and gravity gradiometers, which detect minute changes in gravitational fields; and quantum accelerometers and gyroscopes, which provide highly accurate inertial navigation solutions, could also be networked for more accurate and reliable sensing capabilities.

Although GPS is a powerful and ubiquitous tool, it has several limitations to its use and reliability, primarily stemming from the risks for disruption, denial, and manipulation of GPS services. Both natural and manmade structures can degrade accuracy, and signals are often unavailable indoors. GPS's reliance on satellites makes it susceptible to space weather events and potential adversarial actions in space. Additionally, jamming and spoofing are two methods by which threat agents can interfere with GPS by taking advantage of its vulnerabilities.

Jamming involves deliberately drowning out genuine GPS signals such that they cannot be picked up and used for PNT. The true signals that GPS devices receive to provide location information come from a network of satellites orbiting the Earth; they are very weak by the time they reach the receiver on the ground. If a jammer emits radio frequency signals of the same frequency as satellite signals but at a much stronger level, the former can overwhelm the GPS receiver and make it impossible for the user to access the information. Still, one recent enhancement of GPS security is M code upgrades, which greatly increase the power of signal transmission to devices and thus improve the device's ability to resist traditional jamming attacks.²

In spoofing attacks, a spoofer sends out fake GPS signals with the goal of deceiving a GPS receiver into believing the signals are genuine so that it will rely on the incorrect signals for navigation. Spoofers can provide false location data, time data, or both. The GPS receiver, thinking it is receiving genuine data, will calculate its location incorrectly — without necessarily providing obvious clues to the user that they are being misled. Jamming and spoofing differ in their method of attack, but

² Capt. B. C. Barker, J. W. Betz, J. E. Clark, J. T. Correia, J. T. Gillis, S. Lazar, Lt. K. A. Rehborn, J. R. Straton III. 2000. Overview of the GPS M Code Signal. MITRE Corporation. https://www.mitre.org/sites/default/files/pdf/betz_overview.pdf

both are becoming increasingly prevalent around the world, including in attacks against GPS systems in the Baltic region, Ukraine, and the Middle East.³

Besides spoofing and jamming, GPS faces challenges in GPS-denied or -limited environments, where GPS signals are either unavailable or unreliable. These environments may be due to a variety of reasons, including the following:

- Underground or underwater locations: places where GPS signals cannot penetrate, such as tunnels and mines
- Urban canyons: areas with tall buildings, which can block or disrupt GPS signals, such as with multipath interference
- Natural geographic features: deep valleys and underwater locations where GPS signals cannot reach
- Polar regions: areas near the poles where GPS signals are degraded because of lack of satellite coverage.

Classical sensors, which provide complementary technology in GPS-denied or -degraded locations, also have limitations. For example, vision/celestial navigation may not work under clouds or in certain levels of light, and radar/LiDAR techniques may not work as well over featureless terrain (e.g., maritime environments). Classical clocks often have short holdover time (the period during which a clock can maintain accurate time after no longer being in communication with an external source), which gradually leads to increased error.

On the other hand, many quantum sensors can provide navigational information even in environments where GPS signals are unavailable or unreliable. Such sensors include quantum accelerometers, gyroscopes, magnetometers, and gravimeters and gravity gradiometers. Quantum gravimeters and quantum magnetometers are passive and can operate in all-weather conditions, at any time of day, and over featureless environments like oceans, enabling gravitational anomaly-aided navigation (GravNav) and magnetic anomaly-aided navigation (MagNav).

Many quantum sensors leverage the principles of quantum mechanics to achieve levels of precision not possible with traditional approaches in measuring physical quantities such as time, acceleration, and magnetic fields. Quantum clocks, for instance, offer extraordinary timekeeping precision, which is crucial for synchronizing networks and systems in applications such as telecommunications, energy grid management, resource exploration, and space exploration. Quantum clocks also can offer longer holdover time compared to their classical counterparts. The power of single quantum clocks can be enhanced by networking quantum clocks, which would increase accuracy and boost resilience by limiting the damage from any particular clock being unavailable or attacked. Large enough networks of quantum

³ Matt Burgess. 2024. The Dangerous Rise of GPS Attacks. *Wired*. <https://www.wired.com/story/the-dangerous-rise-of-gps-attacks/>

clocks could even be used in land and sea environments.⁴ Similarly, the precise position and velocity that quantum inertial sensors can calculate make them highly valuable for operating in harsh and/or dynamic environments such as submarines, oil rigs, and space.

Quantum sensors also have some advantages over classical GPS for resisting spoofing and jamming. They can provide alternative PNT information in the event that GPS signals are jammed and help identify when signals have been spoofed, for example by using atomic clocks to provide more accurate time-of-arrival measurements for radio frequency fields. Operators of critical infrastructure are seeking alternatives to GPS that can provide assured PNT solutions for the future.

Networked quantum sensors are expected to provide complementary information to current PNT tools, rather than completely replace GPS in the near term. GPS will continue to evolve with new satellite generations that use advanced quantum sensors/atomic clocks that provide improved signal structures and advanced ground control systems. As quantum sensor technology matures and becomes more commercially viable, its adoption in various PNT applications will likely increase. Hybrid systems are also likely to emerge, leveraging the strengths of both traditional GPS and cutting-edge quantum sensor technologies, in addition to other classical complementary PNT technologies.

The need for reliable, accurate PNT systems was emphasized in a 2020 Executive Order calling for federal agencies and PNT critical infrastructure owners and operators to collaborate to strengthen the resilience of PNT systems.⁵ This report explores the role of quantum sensors in addressing that goal and is based on a workshop that brought together experts from PNT use case sectors, federal government and national laboratories, academia, and the quantum technology industry.⁶ The report examines the challenges and threats to existing PNT systems and assesses where quantum sensors may provide new value and best complement or replace classical PNT tools. It provides recommendations to advance the field and accelerate the development of practical applications and commercialization of quantum sensors for PNT.

⁴ For example, the US Department of Defense is developing a Defense Regional Clock program: <https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodi/465006p.pdf?ver=t6SO1Bw92MXCUnkeM2NKLg%3D%3D>

⁵ Executive Office of the President. 2020. Strengthening National Resilience through Responsible Use of Positioning, Navigation, and Timing Services. Executive Order 13905. Washington. <https://www.federalregister.gov/documents/2020/02/18/2020-03337/strengthening-national-resilience-through-responsible-use-of-positioning-navigation-and-timing>

⁶ See the appendices for the workshop's methodology, generated list of use cases for quantum sensors in PNT, and participants.

Quantum Sensors

Innovation in quantum sensing is advancing rapidly, with significant strides both upstream in fundamental research and downstream in the development of economically valuable applications. Quantum sensor innovation is driven by the ability of new detection technology to achieve unprecedented capabilities, including improved stability and accuracy, along with reduced size, weight, and power (SWaP). Quantum sensors are being developed and refined for a very wide range of applications that include PNT and non-PNT needs.

The main types of quantum sensors relevant to PNT are clocks, magnetometers, gravimeters, and inertial sensors. Atomic clocks rely on discrete atomic energy spectra of, for example, cesium (Cs) or rubidium (Rb) atoms to enable highly accurate and stable timekeeping. Hydrogen masers are one kind of atomic clock with short-term stability superior to Cs and Rb clocks, though they are often prohibitively expensive. PNT systems often rely on atomic clocks because they allow users to synchronize their activities through time information; for example, they provide the time data shared across GPS satellites. They can also provide highly precise time data to systems in GPS-denied environments (e.g., underwater acoustic sensors) or for systems requiring more precise timing than GPS offers (e.g., very long baseline interferometry for radioastronomy).⁷

Quantum magnetometers measure magnetic fields. The two types of quantum magnetometers being developed for MagNav are atomic vapor magnetometers and nitrogen-vacancy (NV) diamond magnetometers. Both typically work by using laser light to prepare the atoms or NV defects, respectively, in a known energy state, allowing that state to evolve under the influence of an external magnetic field, and then measuring the change in the energy state using an optical readout. The field measurements of quantum magnetometers are sensitive enough to detect minute magnetic anomalies, which can then be matched to a known magnetic field map of the Earth to enable navigation. MagNav is most effective for navigation in aerial applications because of the speed at which the sensor passes magnetic anomalies.

Quantum gravimeters measure variations in gravitational fields by using a technology called cold atom interferometry. This is done by cooling atoms to near absolute zero and observing how they behave when they are split and then recombined inside a vacuum chamber. The interference patterns created by the recombined atoms contain information about the accelerations experienced by the atoms in the interferometer. By measuring these small variations, the sensor can

⁷ K. Akiyama, A. Alberdi, W. Alef, K. Asada, R. Azulay, A.-K. Bacsko, D. Ball, M. Baloković, J. Barrett, D. Bintley, et al. 2019. First M87 event horizon telescope results. II. Array and instrumentation. *Astrophysical Journal Letters* 875, no. 1: L2.

provide information about the local acceleration due to gravity, which in turn yields a measure of the local mass distribution of a region. In PNT systems, gravimeters can provide a means for positioning through map-matching to gravitational maps of a region of interest. Like MagNav, GravNav relies on matching anomalies detected by the sensor to known gravitational maps to navigate, particularly in maritime environments. Quantum gravimeters can support the development of more accurate gravity maps.

Quantum inertial sensors measure linear and rotational acceleration by also using atom interferometry, with either cold or thermal (at the temperature of the environment) atoms. As with atomic gravimeters, the interference patterns of the atoms at the output of the interferometer are measured to estimate acceleration and rotation. As part of an INS, inertial sensors can estimate key navigation parameters such as speed and orientation. Although all inertial sensors must contend with the problem of drift (the gradual loss of accuracy for the system's estimation of its location over time, caused by very small measurement errors that accumulate if the position is not regularly corrected by an external reference, such as GPS), quantum inertial sensors are expected to offer the potential for lower drift rates compared to classical inertial sensors of comparable SWaP. Creating a hybrid classical-quantum inertial sensor system and conducting data fusion and filtering between the two sets of inertial outputs can further improve measurement accuracy.

Benchmarking Metrics

To better understand the current state of these sensors, MITRE conducted benchmarking analyses for QED-C that compare atomic clocks, magnetometers, gravimeters, and inertial sensors to their classical counterparts. The preliminary benchmarking data, illustrated in **Figures 1–5**, provide information on key performance metrics (stability, drift, sensitivity) for each sensor type in relation to its size. These bubble charts show the variance in performance and size of sensors, as shown through the size of each bubble in the figures: larger bubbles indicate a greater range in performance and/or size offered by specific sensors in each sensor group. For example, in **Figure 3**, the relatively large size of the bubble for atomic vapor magnetometers is due to the substantial spread in both the sensitivity and size of the many atomic vapor magnetometers on the market for which data were collected. Different types of sensors in each sensor group are shown in different colors.

Figures 1 and **2** show that most types of atomic (quantum) clocks analyzed have better (numerically smaller) short-term stability and less long-term drift than classical clocks and oscillators, indicating an advantage in the performance of quantum sensors. **Figures 3** and **4** indicate that quantum magnetometers and gravimeters can have better sensitivity than their classical counterparts, though both classical and quantum sensors can achieve the sensitivities required for MagNav and

GravNav. **Figure 5** shows that two types of inertial sensors, nuclear magnetic resonance gyroscopes and atomic interferometer gyroscopes, have in-run bias stability within ranges similar to those of classical inertial sensors; with continued R&D, they are expected to offer that level of stability with a smaller sensor volume.

Figure 1: Atomic clocks: Current and emerging short-term stability vs. size. Cs = cesium; MEMS = microelectromechanical systems; OCXO = oven-controlled crystal oscillator; Rb = rubidium.
Source: Reprinted with permission from MITRE.

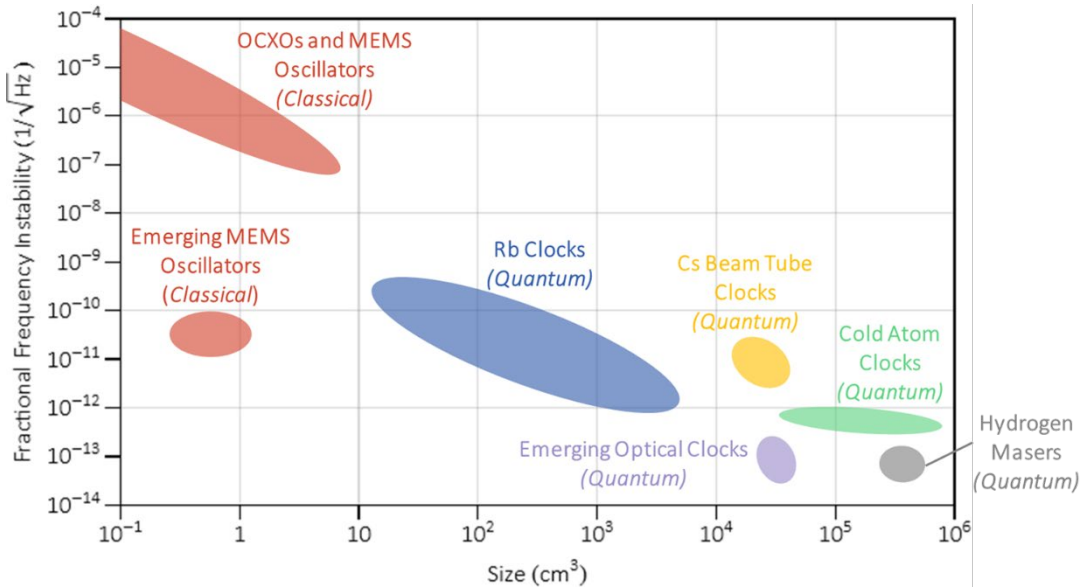


Figure 2: Atomic clocks: Current and emerging long-term drift vs. size. MEMS = microelectromechanical systems; OCXO = oven-controlled crystal oscillator; Rb = rubidium.
Source: Reprinted with permission from MITRE.

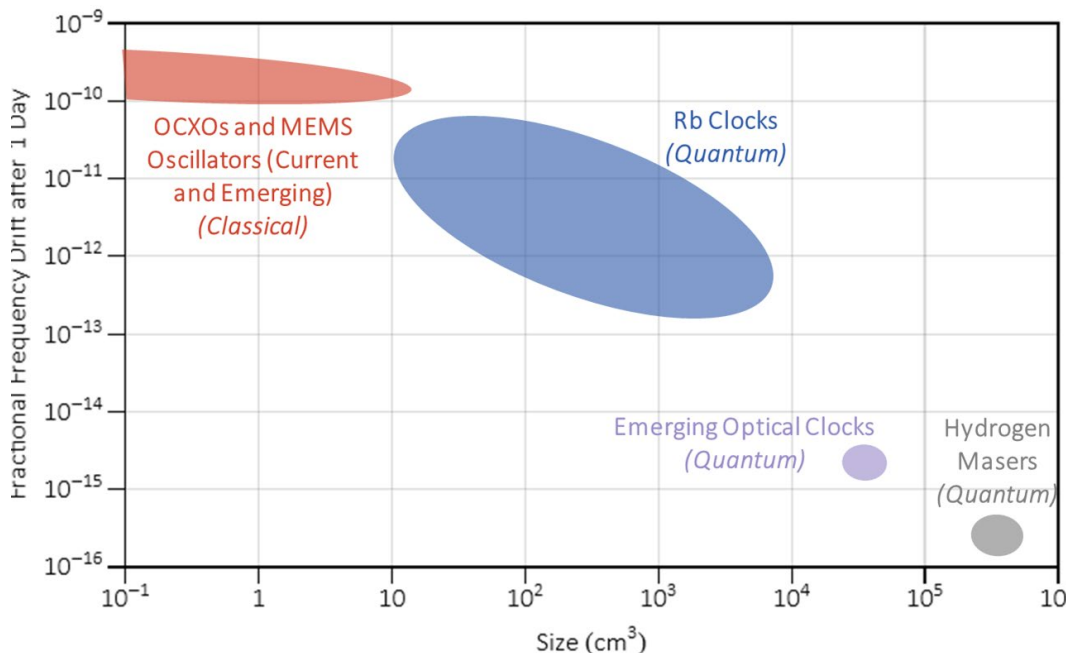


Figure 3: Magnetometers: Current sensitivity vs. size. NV = nitrogen-vacancy; SQUID = superconducting quantum interference device.
 Source: Reprinted with permission from MITRE.

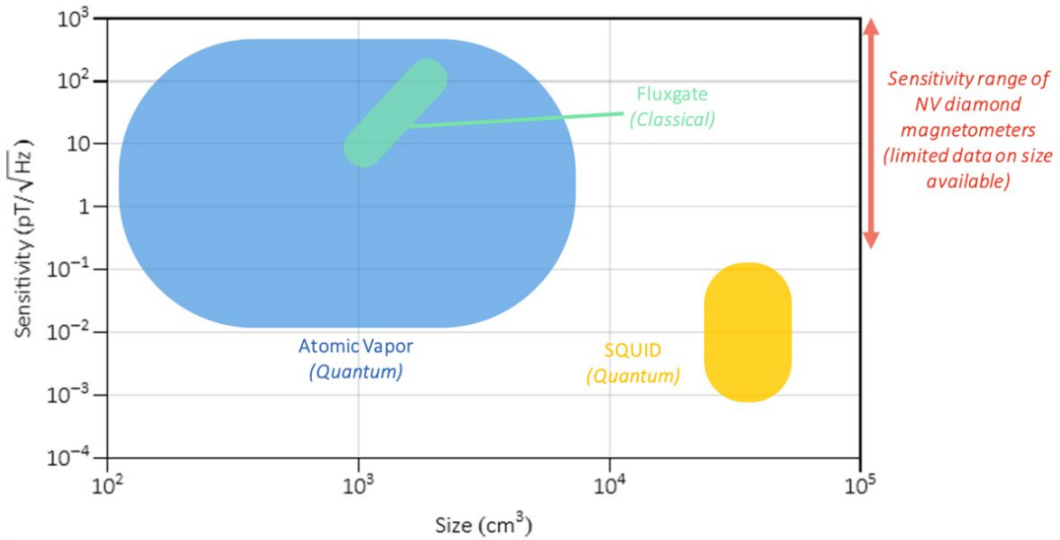
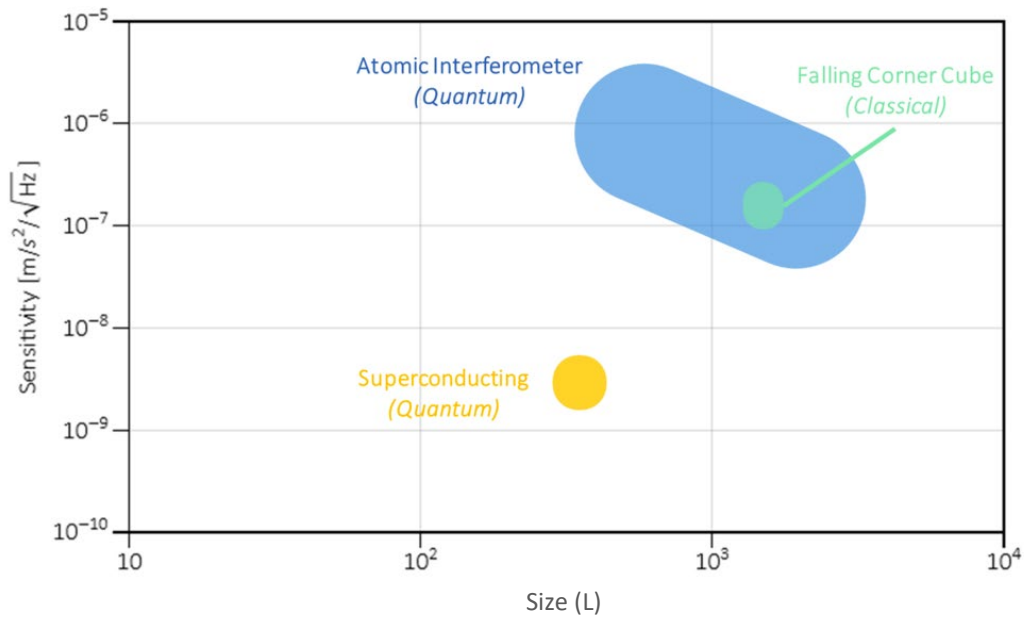
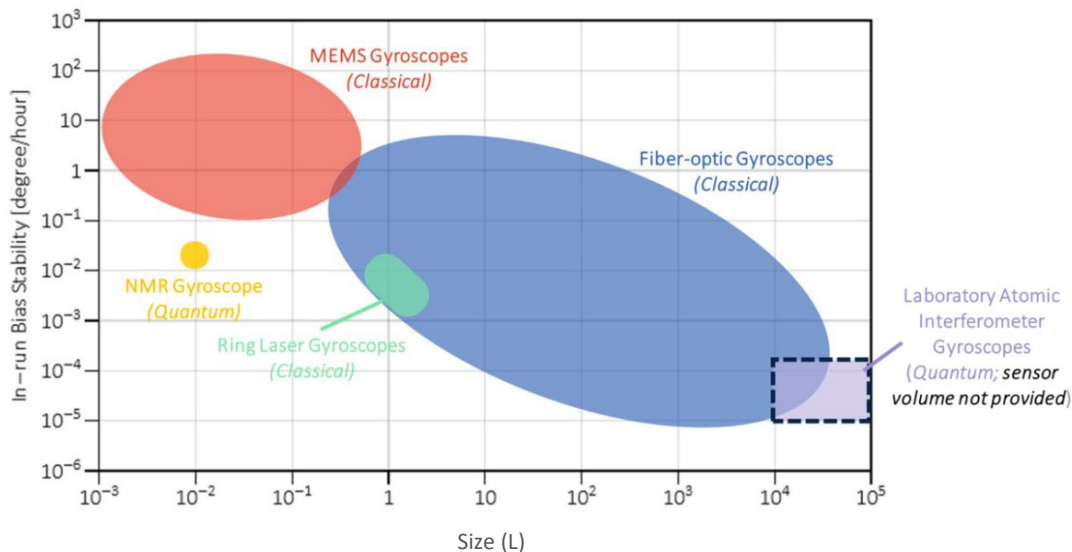


Figure 4: Gravimeters: Current sensitivity vs. size.
 Source: Reprinted with permission from MITRE.



Note from MITRE: "There was very limited data available on long-term drift of quantum gravimeters. A comprehensive data set should include current and future projections for that metric."

Figure 5: Inertial sensors: Current sensitivity vs. size. MEMS = microelectromechanical systems; NMR = nuclear magnetic resonance.
Source: MITRE.



As **Figures 1–5** show, there is often a negative correlation between performance and size; generally, the larger the sensor, the better its performance. However, quantum sensor developers and end users hope that this trade off will eventually diminish as quantum sensors advance. While most classical sensors have been used and improved over decades, most quantum sensors are still considered early-stage technology and have more room for improvement in performance. While there are currently no known fundamental limits to the performance metrics possible for quantum sensors, there are technological limits. Advances in photonic integration and laser miniaturization are needed for reductions in SWaP and improvements to reliability of quantum sensors.

Innovation Landscape

An important trend in quantum sensing innovation is the miniaturization, integration, and packaging of quantum technologies in portable and scalable devices. This shift in system footprint and power needs is making quantum sensors more accessible and practical for everyday uses. For quantum sensors to be valuable to real-world applications, they must be integrated in existing traditional technology systems. Many sensor innovation challenges center on this integration work, a large share of which is being done by startup companies.

This innovation is happening across a variety of quantum sensor types. Quantum sensors have been proposed to detect and measure Earth's magnetic field with high precision. This technology is particularly valuable to ensure continuous and reliable navigation in environments where GPS signals are weak or prone to interference, such as in aerospace. Precision timing for space-based networks is another key focus area. Quantum clocks, such as those based on atomic transitions, are being

explored and deployed in a range of precision timekeeping applications. Continued advances are crucial for synchronizing space-based networks, ensuring data integrity, and enhancing the performance of satellite communication systems for both terrestrial and space application. Currently, space networks serve mainly terrestrial use cases because the clocks' orientation to Earth makes it difficult to obtain signals for space-based use cases.

For small satellites, quantum sensors such as gyroscopes have the potential to dramatically improve orientation and alignment capabilities, and exciting R&D is in the works to test the rigor of early gyroscope prototypes.⁸ These sensors could provide highly accurate measurements of a satellite's position and orientation, critical for maintaining proper alignment and functionality in space. Similarly, quantum-enabled gravity and magnetic-field sensing promise to enable new ways to map the planet, for example, by detecting deviations in underground aquifer levels, monitoring changes in the polar ice caps, identifying potential locations for offshore wind power, and detecting wildfires from space. The sensors may also help with exploration and mining of critical resources in space, such as hydrogen and helium-3, as well as rare minerals, including platinum, iridium, palladium, osmium, ruthenium, and rhodium.

In addition to innovation in specific quantum sensor technologies, there is growing attention to establishing standards and validation methods for quantum sensors. Such standards will help facilitate the commercial development and adoption of the technologies by providing a framework for benchmarking, standardizing, and validating their performance. Standardized testing and validation procedures are crucial for comparing competing quantum sensor implementations objectively and ensuring that they meet performance claims. The resulting user confidence will accelerate adoption.

Challenges to Scaling Quantum Sensors for PNT

One of the key issues workshop participants highlighted regarding the use of quantum sensors for PNT is the significant variation in and specialization of the components needed for the different devices, such as lasers, NV centers in diamonds, and frequency combs. Each can have a wide range of specifications. Moreover, even devices in a particular sensor category (e.g., clocks) can have vastly different requirements for their components, a sign of the relatively early stage of the technology and the highly competitive environment. The high degree of variability complicates the manufacturing process as it is difficult to standardize production and achieve economies of scale.

⁸ Defense Innovation Unit. 2023. *Quantum Sensing Enters the DoD Landscape in First-of-a-Kind, High-Performance Atomic Gyroscope Space Demonstration*. Mountain View, CA. <https://www.diu.mil/latest/quantum-sensing-enters-the-dod-landscape-in-first-of-a-kind-high-performance>

This range of needs and the lack of standards mean that many critical components for quantum sensors have a fragmented or underdeveloped supply chain, which stunts the ability to grow and innovate in the quantum sensor market. Innovation and market growth are further undermined by the tendency of some manufacturers of critical components to view their primary customers as research laboratories rather than commercial end users, resulting in components designed and manufactured specifically for laboratory use, often at high costs. Because of this, there is a lack of innovation aimed at adapting these components for broader commercial use, which would require reducing costs, expanding compatibility, and improving durability. Improvements in size, weight, power, and cost (SWaP-C) are an important factor in the growth of this market. More in-depth market research could reveal specific SWaP-C improvements that could create an inflection point in market adoption and lead to economies of scale.

Beyond access to an adequate supply of components, quantum sensors lack clear and standardized performance metrics, which are essential to enable the sensors to demonstrate their advantages over classical sensors and drive their adoption. Comprehensive testing is needed to accurately assess the current state of the technology. But a lack of testbeds for quantum sensors makes it nearly impossible to collect the performance data necessary for setting standards or showcasing capabilities. Federal funding of testbeds could dramatically accelerate both quantum sensor development and technology adoption.

Several steps can be taken to overcome these obstacles. One strategy that would expand the potential market for these components is to explore and identify use cases for quantum sensor components beyond their traditional application in quantum technology. A frequently cited example is the use of frequency combs for COVID-19 tests,⁹ showing that the sensor components can be repurposed for different uses. By broadening uses for quantum sensor components outside their initial scope, manufacturers have a persuasive reason to scale up production. Diversification of the components' uses will not only increase demand but also encourage innovation and cost reduction, making these components more accessible.

Similarly, sensor developers can consider how one sensor could be used in a variety of applications. For example, atomic vapor magnetometers could be used both in the oil and gas industry for resource exploration and in biomedicine for magnetic imaging of organs, cells, and biomarkers.¹⁰ They could also be used in space for resource exploration of water, rare minerals, and metals. By creating one sensor that

⁹ Lisa Marshall. 2023. New laser-based breathalyzer sniffs out COVID, other diseases in real time. *CU Boulder Today*, April 10. <https://www.colorado.edu/today/2023/04/10/new-laser-based-breathalyzer-sniffs-out-covid-other-diseases-real-time>

¹⁰ See more examples of multiple uses of quantum sensors in QED-C's 2022 report, *Quantum Sensing Use Cases*, <https://quantumconsortium.org/sensing22/>

can be used in multiple industries and applications, sensor developers and manufacturers can broaden the market for their product, which can facilitate scaling up.

Another potential strategy would be the creation of a visualization tool or technology roadmap to help outline components needed for different quantum sensors. The Quantum Economic Development Consortium (QED-C) has created a visualization tool for lasers that could be used as a blueprint for a similar tool for quantum sensors. Such a tool would capture specifications of the various components on the market, helping to identify similar needs across sensors. This would allow for the identification of high-impact, high-value target areas for manufacturers to focus on, such as which SWaP-C improvement to prioritize. In addition, the tool can map the sensors to relevant applications and use cases, which could help accelerate market adoption.

Position, Navigation, and Timing Use Cases

PNT stakeholders and quantum experts at the workshop identified areas where PNT-reliant industries could benefit from current and future quantum technologies. They came up with 129 use cases, listed in Appendix B with the participants' classification of each use case by relevant industry(ies) and applicable elevation(s) from underground to in space.

The industries considered are communications (e.g., telecom, radio); technology (e.g., semiconductors, media, big tech, informatics); health (e.g., providers, caregivers, life sciences, emergency services); financial (e.g., capital market, banking); products (e.g., manufacturing, shipping, vehicles); energy (e.g., resources, utilities, mining, distributed renewable energy resources, transportation, environment); and other (e.g., sensor networks). The elevations that participants considered are, from highest to lowest level, orbital and beyond, aeronautical, ground, oceanic, and subterranean. The use cases associated with potential defense and homeland security applications included undersea and underground protection and awareness.

The aggregated data (**Table 1**) show that participants identified use cases in the energy sector most frequently as well as those applicable most often at the ground level, followed by aeronautical. (Participants could select multiple elevations and industries for a single use case, so totals do not sum to 129.) The number of use cases identified for a given industry is likely influenced by participant background,¹¹ earlier workshop talks, and prior use case reports.

Table 1: Numbers of key position, navigation, and timing use cases identified at the workshop, by industry and elevation

Use case elevation	Communications	Technology	Health	Financial	Products	Energy	Other	Total
Orbital and beyond	6	4	2	1	3	7	7	30
Aeronautical	5	5	5	1	9	3	6	34
Ground	6	8	11	5	7	12	5	54
Oceanic	2	4	--	--	1	4	6	17
Subterranean	1	2	--	--	2	6	6	17
Total	20	23	18	7	22	32	30	

¹¹ Participants and their affiliations are listed in Appendix C.

Impact and Feasibility of Use Cases

The 129 use cases were refined during the workshop into 16 concepts based on participants' prioritization and grouping of the ideas (**Table 2**). They were then ranked based on their impact and feasibility relative to the other concepts. The graphics below show their average impact (x-axis) and feasibility (y-axis) scores; higher scores equate to a higher average ranking on estimated impact or feasibility among all 16 use cases (**Figure 6**). There is a clear positive correlation between the two scores, which may be the result of an unconscious expectation that more feasible use cases will have a greater impact.

The use of quantum sensors for position and navigation in GPS-denied areas was ranked as both the most feasible and the most impactful, followed by the use of magnetic sensors for navigation, particularly in GPS-denied areas. At the other end of the spectrum, the two use cases rated by the group as low-impact, low-feasibility are quantum sensors for air quality monitoring and telecom quantum emitters for quantum key distribution.

Figure 6: Ranking of use case impact and feasibility. (See Table 2 for color coding.)

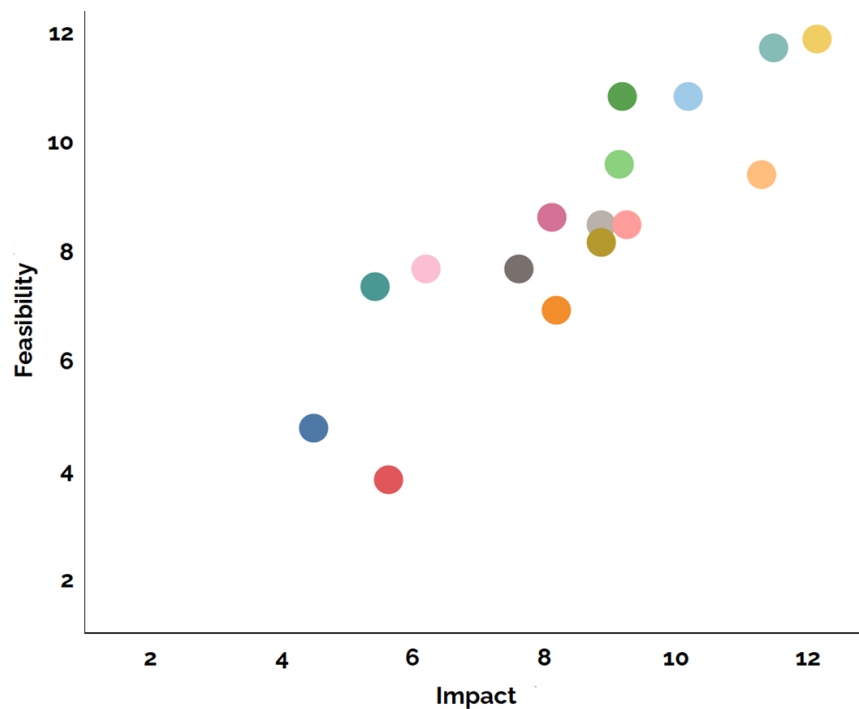


Table 2: Use cases shown in feasibility and impact figures 6–14, with function and elevation classification. IMU = inertial measurement unit.

	Use Case	Function	Deployment Elevation
	Clocks for in-space data centers (timing for networks)	Timing	Air, Space
	Magnetic sensing – nano navigation (PNT resilience)	Navigation	Air
	Atomic inertial measurement unit - including gyro (inertial sensing & holdover)	Navigation	Aquatic, Ground, Air
	Biomedical (e.g., diagnostic microcombs, biomarker detection)	Other	Ground
	Satellite orientation and alignment	Position, Navigation	Ground, Air, Space
	Ice detection and status (navigation)	Navigation, Other	Aquatic
	GPS-denied PNT (PNT resilience)	Position, Navigation	Aquatic, Ground, Air, Space
	Satellite inertial sensing/navigation (PNT)	Position, Timing	Space
	Underground communications & navigation (PNT)	Position	Subsurface
	Standardization & validation (device quality)	All	All
	Autonomous navigation (PNT quality)	Navigation, Timing	Subsurface, Aquatic, Ground, Air
	Clocks for communications (holdover)	Timing	Ground, Air, Space
	Reference and resource maps (PNT)	All	Subsurface, Aquatic, Ground, Air
	Energy systems & critical infrastructure (timing & sync)	Timing	Aquatic, Ground
	Quantum key distribution (security)	Timing	Ground, Air, Space
	Air quality monitoring/sensing (environment)	Position, Timing	Ground, Air

There was some variation in how different sectors of participants ranked the concepts. The industry average (**Figure 7**) aligns closely with the overall scores. On the other hand, representatives from academia, federal laboratories, and federally funded research and development centers (FFRDCs) ranked the GPS-denied PNT use case as only moderately impactful. Instead, academia representatives ranked biomedical and energy systems & critical infrastructure as the most impactful (**Figure 8**), and lab/FFRDC representatives ranked standardization & validation and magnetic sensing as the most impactful use cases (**Figure 9**).

Figure 7: Use case impact and feasibility ranked by industry representatives

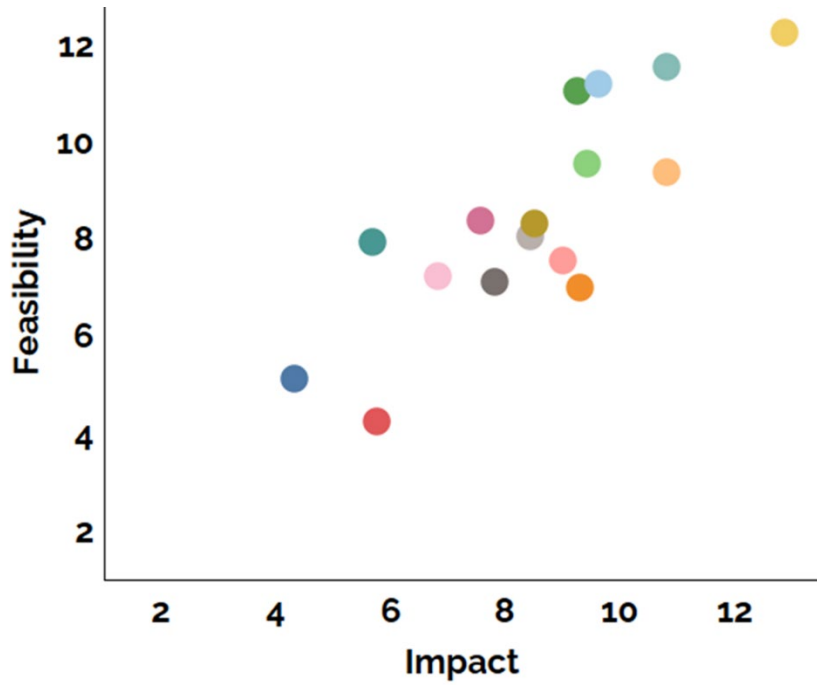


Figure 8: Use case impact and feasibility ranked by academia representatives

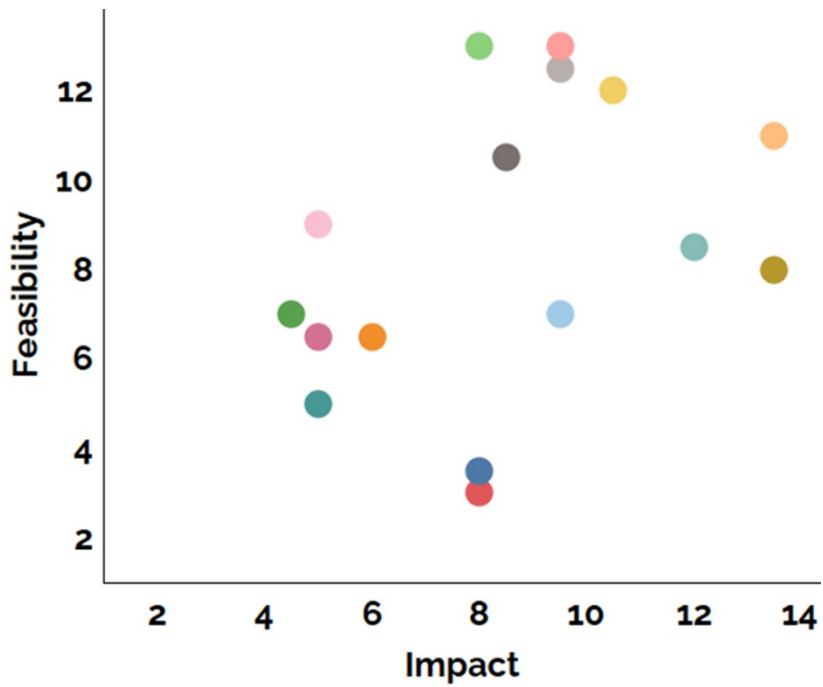
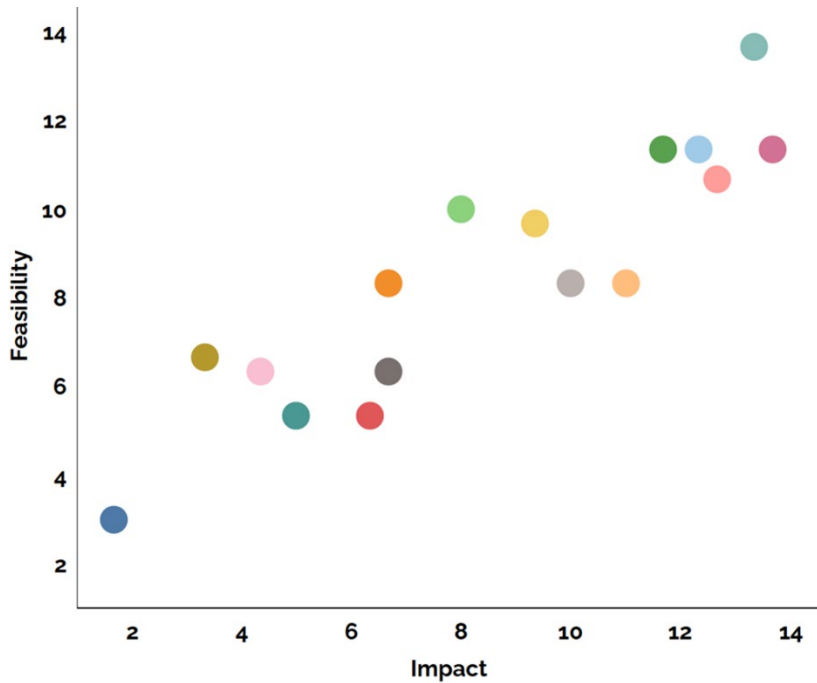


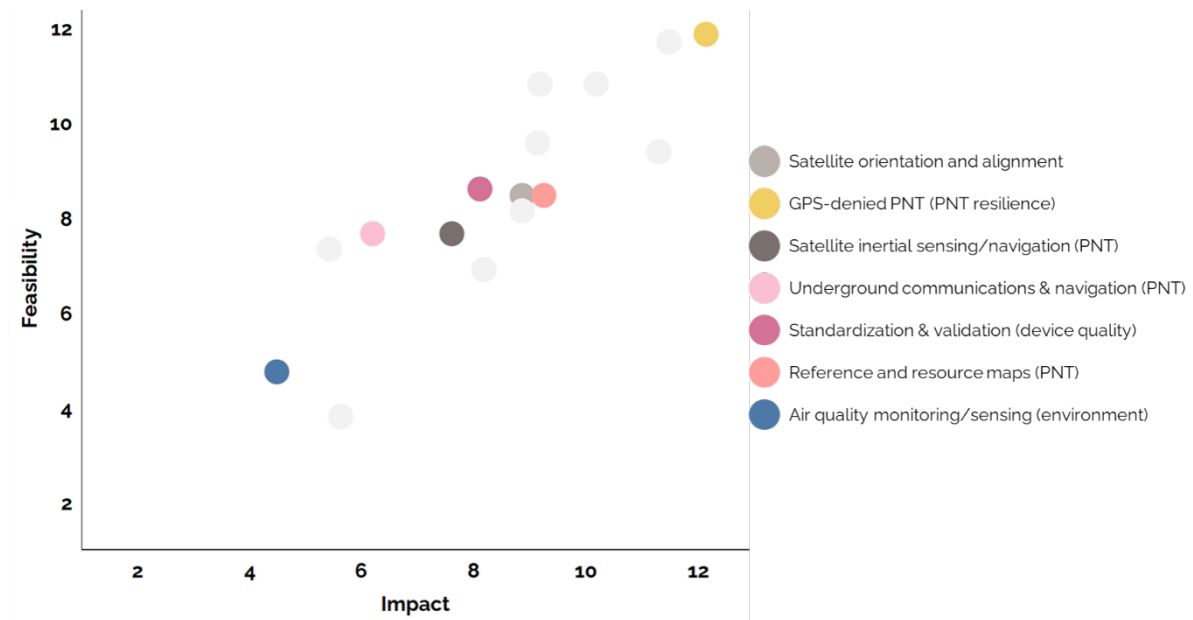
Figure 9: Use case impact and feasibility ranked by federal laboratory and FFRDC representatives



Sensor Function

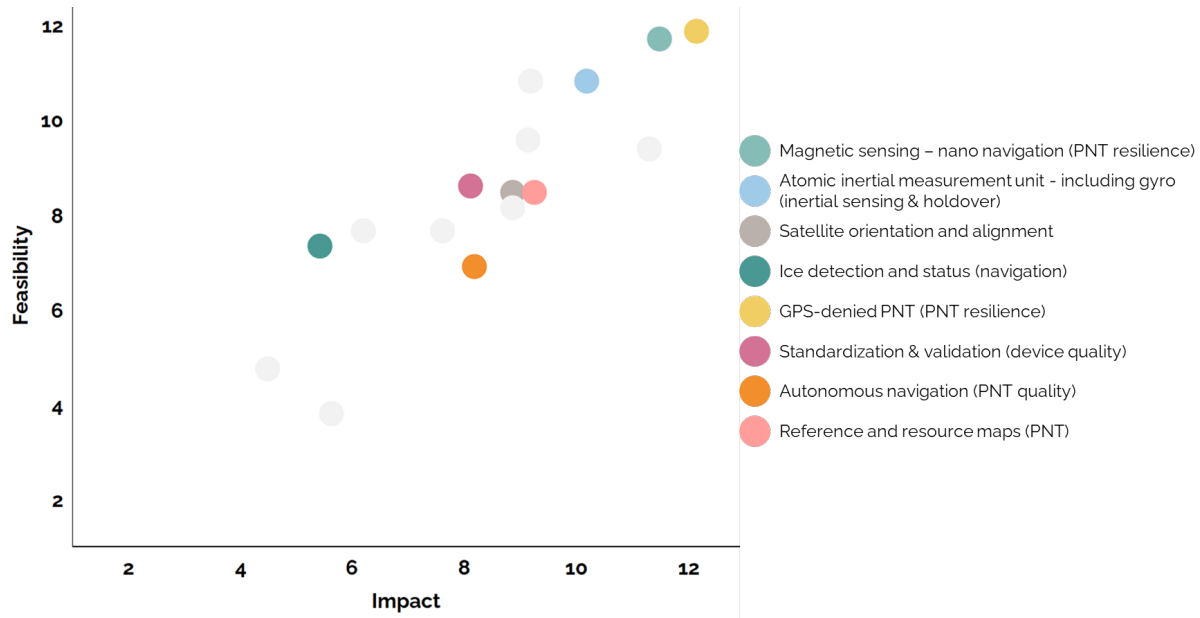
For each of the 16 consolidated use cases, participants recorded the relevant sensor function(s) from among position, navigation, or timing. The position-related use cases primarily clustered in the middle of the impact-feasibility grid with a couple of outliers (Figure 10).

Figure 10: Impact and feasibility ranked for position-related use cases



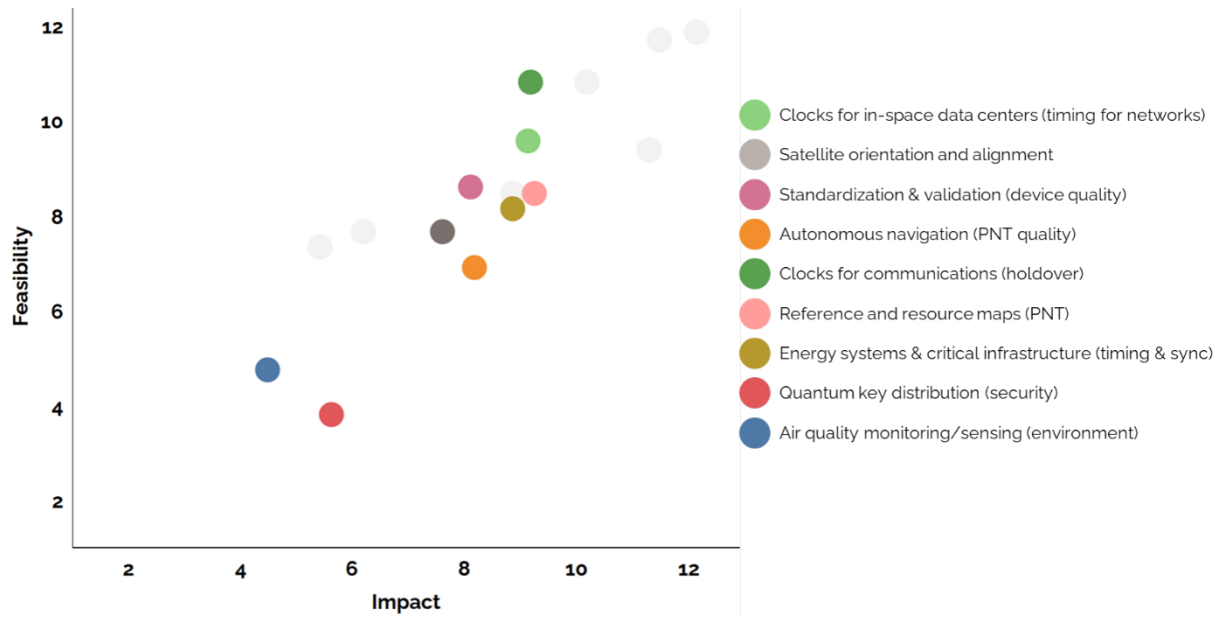
The navigation-related use cases were generally rated as having moderate to high feasibility (**Figure 11**).

Figure 11: Impact and feasibility ranked for navigation-related use cases



The timing-related use cases were judged by participants to have low to moderate impact (**Figure 12**).

Figure 12: Impact and feasibility ranked for timing-related use cases



Sensing Deployment

Workshop participants recorded the elevation(s) where the sensor would be deployed for each of the 16 consolidated use cases. Almost all use cases were considered applicable to several different elevations, with ground and air deployments often selected together. **Figures 13** and **14** present the impact and feasibility of the 16 concepts and the selected elevation for the deployment of each sensor. Contiguous bars denote the same impact or feasibility rating for the two use cases. (See **Table 2** for explanation of the bar colors in **Figures 13** and **14**.)

Figure 13: Assessment of use case elevation and impact

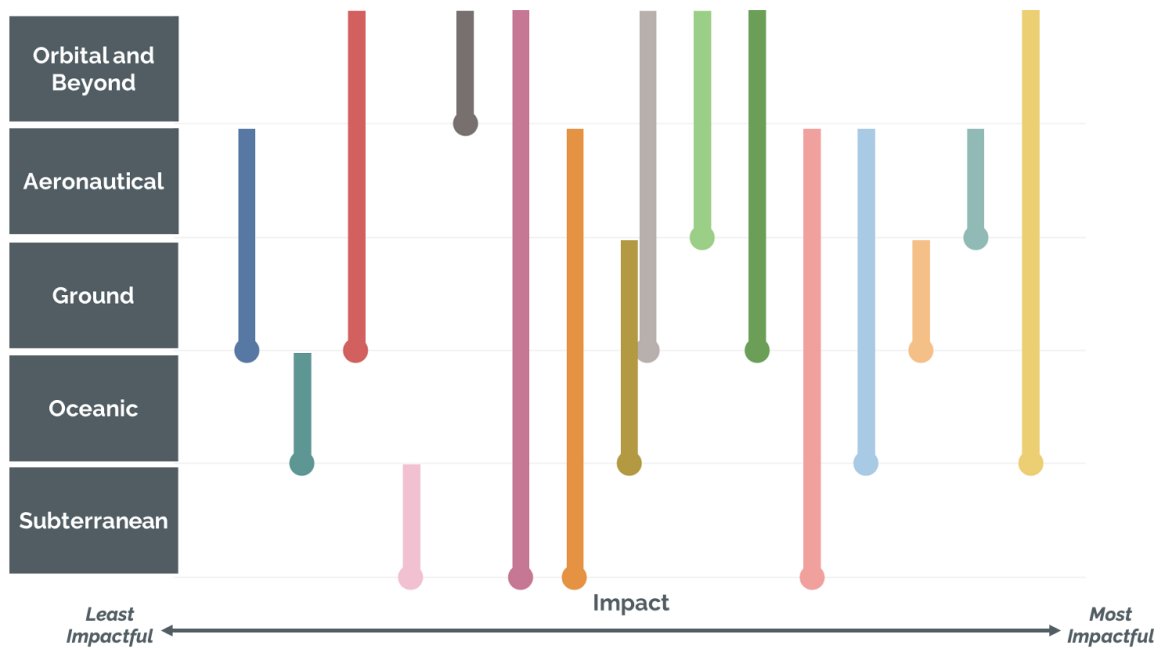


Figure 14: Assessment of use case elevation and feasibility



Implementation Details of Selected Use Cases

Six of the consolidated use cases that were rated highly on the feasibility and impact metrics were further developed. Workshop participants expanded on their description and discussed desired features and functionalities, challenges to be addressed, timelines, and critical stakeholders for implementation based on the security approach selected in the previous activity.

MagNav for Resilient, Unjammable PNT

GPS denial results in the loss of ability to navigate, which affects both defense/military and commercial applications, creating a multisector need for an unjammable and reliable method for navigation. MagNav for resilient, unjammable PNT can be used as a complementary system to GPS to ensure reliable navigation in GPS-denied areas or when GPS is spoofed or jammed. It accurately and stably measures anomaly fields by comparing measured magnetic fields (after removing platform effects and core field) to a reference map and determining latitudinal and longitudinal position.

The initial target audiences for MagNav are government defense and military customers for use at sea or by air. There may also be other defense and commercial aerospace applications in the medium term and commercial shipping applications in the long term. Although no hypothesized or available technologies, including MagNav, can be considered direct replacements for GPS, the value of having accurate complementary navigational tools when GPS is not available or reliable would be extremely valuable to military and civilian users in need of accurate, uninterrupted, and precise PNT information.

The stages of MagNav development include

- prototyping (2–3 years),
- improving platform calibration techniques (2–3 years),
- enhancing data collection and reference mapping mechanisms (3–5 years),
- creating a full architecture for alternative PNT solutions such as MagNav (4–5 years), and
- overcoming manufacturing challenges to produce magnetometers at a large scale (4–5 years).

The ultimate goal is for these stages to lead to reductions in sensor costs; the development of low SWaP sensors for smaller uncrewed aircraft system (UAS) applications; more precise maps over broad areas; and wide-scale, cross-sector utility.

Precision Timing for Space-Based Networks

Precision timing for space-based networks is needed in a range of applications, including radionavigation, distributed sensing, and satellite-based communications. It can be augmented using quantum technology with other emerging technologies, primarily optical clocks.

Commercial optical clocks are relatively mature, with field-deployable capabilities in dynamic environments and for many applications. Optical frequency standards (a component of next-generation optical atomic clocks) have better stability and tighter synchronization, and are highly resistant to jamming, compared to microwave clocks. Furthermore, a network of quantum clocks could support resilience by maintaining good network timing even if some of the clocks' performance is compromised. Developing these clocks terrestrially and incorporating them into satellites will create a network of synchronized clocks and a stable timescale reference that can be communicated to ground stations via optical or radiofrequency links. A network of optical clocks would improve network timing and resilience to spoofing. In time, atomic clocks could be deployed in space data centers, support the potential for in-space quantum computations for quantum-AI algorithms, and improve time transfer performance.

But, although optical clocks are one of the more mature quantum technologies, problem areas must be addressed for their development:

- SWaP-C constraints in many, though not all, of current generation optical clocks limit the potential usefulness of next-generation optical clocks and cavity-stabilized lasers to scientific-oriented missions, though improvements are being made.
- The actual precision and accuracy of optical clocks cannot be compared outside the lab without improvements in time transfer technology.

To work through these problem areas, it will be essential to build a team of experts from a broad spectrum of time and space engineering disciplines along with physicists, cyberphysical experts, and materials scientists. They would also require support from developers and customers in finance, big data, energy, telecommunications, defense, and science to develop the concept further and implement in a reasonable timeframe.

The federal government could serve as both investor and customer by funding early-stage R&D and being an early adopter of the technology. With such support, benchtop demonstrations could be completed in one year followed by two years of flight model development before space qualification — a three-year process. It is estimated to take another three years to be fully operational. Alternatively, if the technology is cost effective and manufactured at scale, launch could happen after flight model development and qualifications could be completed in orbit.

Executing the concept as outlined would also produce applications in dark matter science, big data, and artificial intelligence, among other areas.

Small Satellite Orientation and Alignment

Quantum sensors provide a possible solution for the precise orientation and alignment of small satellites, and would thus be useful in a variety of applications such as communications, defense, imaging, and planetary mineral exploration. Satellites equipped with these sensors would attract interest from a wide range of entities including telecommunications companies, commercial space mining ventures, the National Aeronautics and Space Administration (NASA), and the military.

Advantages of these quantum sensors would include low power consumption, compact size, and high accuracy. On the other hand, the sensors would likely have a high cost associated with launching these components into space. For the sensors to be successful, they would need rapid read times, alignment with required features, and a prototype functioning in space.

Development of these sensors for small satellites will require a diverse team, including quantum physicists, aeronautical and electrical engineers, business development professionals, academics, and representatives from government agencies such as NASA, the Department of Defense (DOD), and the Department of Energy (DOE). Ongoing research related to these sensors could be completed within a year, after which implementation of the findings to create a viable solution would take around two years. Following this, the development process would likely last six to seven years and involve multiple stages, including deployment, evaluation, modification, and redeployment of new iterations.

Reference and Resource Maps

Quantum magnetometer and gravimeter sensors can be used to detect anomalies in existing magnetic and gravitational reference and resource maps, as well as to create new and updated maps, which can be used for other quantum PNT applications that rely on highly accurate, detailed, and secure mapping data. Low SWaP-C quantum sensors will enable multiplatform integration for the generation of required map data. In addition, quantum sensors would allow surveyors to effectively map at the subsurface, aquatic, ground, and air levels.

Developing these maps would require support from multiple partners across different mapping applications. Airlines, cruise liners, and oil and gas companies can all contribute to the development of these maps by deploying sensors to collect relevant data across elevations. Surveyors and data scientists who can support data centralization and reference map development will also be critical for this use case. A public-private partnership that provides monetary and logistical support for coordinating this data collection and sharing is one potential way to accelerate this

process. For instance, agencies such as the Federal Aviation Administration and the Coast Guard could provide support for aviation and oceanic mapping, respectively.

Implementation of these reference and resource maps depends on who the users are and the level at which they are mapping. For example, experts estimate that reference and resource maps for aviation will be available within one to five years, while subterranean maps will require ongoing updating because of tectonics.

Standardization and Validation Testbeds for Quantum Sensors

Currently, quantum sensors lack metrics to evaluate performance. Standardization and validation testbeds must be created to enable validation of quantum sensors within a reference system, so that the value of these sensors can be gauged against traditional PNT sensors while monitoring their enhancement and evolution. Such testbeds should be available to both startups and established organizations. One application of the testbeds could involve using quantum sensors to investigate and validate other quantum sensors and facilitate more scalable manufacturing approaches.

An associated concern is the lack of a nationally recognized platform or user facility to test quantum sensors. Such a platform should establish a uniform evaluation and integration approach for multiple modalities and form factors of quantum sensors. From this platform, testing, benchmarking, and data can be standardized and recorded in a database for future users. An added benefit would be that smaller companies, which sometimes lack resources for research and testing, would have greater ability to test and validate their technologies.

A standardization and validation platform could be established and managed by the National Institute of Standards and Technology. Management would be an ongoing effort because, as new quantum sensor technologies are developed and tested, data and benchmarks will need to be updated.

Biomarker Detection

Biomarker detection was explored during the workshop, but because it is not directly related to PNT, it is only briefly touched on here. For in-depth exploration of quantum sensors in biomedicine, see QED-C's forthcoming report, *Quantum Sensing for Biomedical Applications*.

Quantum sensors may be used in a variety of ways to noninvasively detect low levels of biomarkers. Such uses could improve imaging resolution, provide doctors with better tools to determine physiological states, and assist with early or prediagnosis of disease. Innovation in the biomarker detection space could also provide researchers with a better understanding of underlying biochemical processes.

Recommendations

The following recommendations for developing quantum sensors and increasing their adoption in PNT applications are based on inputs from the workshop and subsequent discussions with experts in the field.

1. **Invest in photonic integrated circuits R&D:** Photonic integrated circuits (PICs) comprise multiple photonic components integrated on a single platform or substrate. The development of PICs would enable reduced SWaP-C of quantum sensors, as well as make them more robust and reliable. These advances could prove critical for the application and commercialization of quantum sensors and spur adoption of quantum sensors across industries.¹² However, PIC technologies for quantum applications are largely in the early stages of R&D. Federal funding agencies should increase investment in PIC R&D to address materials, integration, interconnect, and other challenges. As these are addressed, industry should be supported to develop PICs for applications relevant to government missions and commercial use cases.
2. **Engage the quantum community to identify opportunities for critical/high-value SWaP-C improvements:** The diversity of components used in quantum sensors across the industry is one of the primary barriers to scale, but there are commonalities in industry's needs. Quantum technology developers should collaborate with organizations such as QED-C in contributing to market studies of the SWaP-C improvements required for adoption. Compiling sensor performance metrics could uncover commonalities that would help technology developers know what capabilities to target. Moreover, identifying opportunities for critical improvements to SWaP-C for even a single use case could spark greater market adoption through economies of scale that trickle back into the supply chain. This could create a virtuous cycle via the supply chain components that in turn benefit the entire quantum sensor market with different SWaP-C requirements. Data collected from the quantum sensor community could be tracked and visualized so that achievement of performance targets is celebrated, remaining gaps are recognized, and high-value targets are pursued.
3. **Be an early adopter of quantum sensor technologies:** The federal government depends on accurate and available PNT information for many important missions, including space exploration at NASA, defense and security at DOD, and energy management at DOE. As such, the federal government should be an early adopter of new quantum sensor technologies for its PNT needs. In this way, it would help fund the derisking and serve as a third-party validator of the technology. This would likely lead to lower cost for the technology, as federal

¹² For more information about PICs, see QED-C's November 2023 report, *Photonic Integrated Circuits for Quantum Applications: Challenges and Opportunities*. <https://quantumconsortium.org/PICs23/>

investment would support the technology's initial development and ultimately its broader adoption and scaling. Additionally, collaboration among federal agencies could lead to increased standardization of quantum sensors.

4. **Develop and deploy PNT systems for different platforms and environmental conditions:** As laid out in this report, there are clear PNT use cases for quantum sensors at every elevation level, from subterranean to extraterrestrial, and for many different industries. Each sensor deployment situation can have unique environmental conditions and requirements for the sensor platform. Reference data for diverse situations will be required for PNT systems to operate and should include data on inertial, vibration, and shock conditions and temperature, humidity, and magnetic environmental conditions. Academia, federal funding agencies, and technology developers should collaborate to collect necessary reference data and develop PNT systems that can be deployed in various conditions, settings, and elevations. End users, including government customers, could be involved as well to provide data on environmental conditions and platform effects to inform quantum sensor engineering requirements and/or opportunities for quantum sensor developers to test prototypes on relevant platforms.

Appendix A: Methodology

This report explores quantum sensing as it relates to position, navigation, and timing (PNT) and is largely informed by a virtual workshop organized by the QED-C Use Cases Technical Advisory Committee. The May 14-15, 2024, workshop was conducted via Zoom and attended by 113 stakeholders from quantum; aerospace; mining, oil, and gas; energy; government; academia; and other relevant industries and sectors.

The workshop participants looked at a variety of quantum sensing and PNT approaches (atomic clocks, magnetometers, gravimeters, and inertial sensors) and their ability to solve current problems facing industries and entities that rely on PNT, and identified 129 specific use cases (listed in Appendix B). The ideas were well distributed across industry (communications, technology, health, financial, products, energy, and other); the plurality focused on the ground level of elevation, with the aeronautical and orbital elevations also well represented among the ideas.

Workshop Goals: Surface High-Impact, Feasible Ideas

- Capture many ideas on how to use quantum sensors to solve current challenges in PNT in order to create a diverse set of concepts to investigate.
- Clearly define and refine popular ideas and match to quantum approaches for future exploration, including timeline to realization.
- Isolate the ideas with the highest impact and feasibility, then identify a path to bring these ideas to fruition.

Structure: Encourage Collaboration, Fresh Thinking

The workshop was designed to maximize collaboration opportunities among attendees with knowledge of PNT technologies and applications and attendees familiar with quantum technologies. Facilitators and attendees from the quantum sector were invited to a briefing on the workshop structure and tools several days before the event to ensure effective use of the technology and time. All participants were sent reading materials in advance, describing how quantum sensors might help with securing and improving PNT methods and technology.

The first day of the workshop featured several speakers as well as small and large group discussions. These presentations and discussions helped to provide the foundation of knowledge that enabled subsequent workshop activities. Laura Parker and Ernest Wong, from the Department of Homeland Security (DHS), briefly introduced PNT, concepts related to PNT resilience, and a DHS study of quantum PNT use cases. Karen Van Dyke and Hadi Wassaf, from the Department of Transportation, discussed challenges related to classical PNT technologies and methods, including environmental and infrastructure challenges and signal spoofing and jamming. Igor Teper (AOSense), Robbie Fasano (Inflection), Luca Ferrara (SandboxAQ), and Julián Martínez-Rincón (Brookhaven National Laboratory) each

gave a presentation on quantum PNT types, techniques, and research, including inertial sensors, gravimeters, magnetometers, and atomic clocks. Michael Lee, from SRI, demonstrated the QED-C Laser Prioritization Tool and a dashboard for quantum sensing use cases. In addition to this data tool, Carl Dukatz, from Accenture, presented MIT's Quantum Economic Advantage Calculator. Bonnie Marlow, from MITRE, discussed metrics, strategies, and challenges for benchmarking quantum PNT sensors.

After these presentations, workshop attendees were divided into small groups to identify specifications, data, and information sources for building quantum sensors for PNT. The larger group then reconvened for an expanded discussion.

The second day of the workshop began with five presentations from groups that are actively using PNT and/or improving and increasing the security of PNT using quantum technologies. Amy Cutting, of the United States Coast Guard R&D Center, talked about how the Coast Guard uses PNT for navigation and how quantum PNT can improve the accuracy and timeliness of location data and defend against signal jamming and spoofing. Satyam Priyadarshy, of Reignite Future, described how PNT technology is applied in the resource mining sectors and how quantum PNT technology can improve efficiency and reduce costs. Jay Lowell, of Boeing's Disruptive Computing and Networks division, highlighted Boeing's quantum navigation program, which is flight testing quantum hardware and sensors on planes with SandboxAQ. Greg Drewry, from the Electric Power Research Institute, discussed how quantum sensors for PNT can be applied to the energy sector, such as in high-accuracy clocks for utility operations. Andy Corriveau, of Axiom Space, detailed how quantum PNT can support uses in orbit or space, including space-based manufacturing and assembly, debris detection and removal, satellite communications, and orbital data centers. Randall Nichols and Hans Mumm, of Kansas State University, co-presented on how quantum technologies can improve self-healing capabilities of PNT systems and protect against jamming and spoofing attempts.

Value Chain Matrix: A Bidirectional Flow

For the ideation session, workshop participants were broken into groups that were structured to ensure a balance among attendees from the quantum industry, PNT use case industries, and academia and government. The primary tool to guide conversations during this session was a PNT value chain matrix:

Industry \ Elevation	Communication (telco, radio, etc.)	Technology (semiconductor, media, big tech, informatics, etc.)	Health (provider, caregiver, life sciences, emergency services, etc.)	Financial (capital market, banking, etc.)	Products (manufacturing, shipping, vehicles, etc.)	Energy (resources, utilities, mining, environment, etc.)	Other (sensor networks, etc.)
Orbital and Beyond							
Aeronautical							
Ground							
Oceanic							
Subterranean							

The column on the left side of the matrix lists sensor locations or environments that can support or benefit from quantum PNT: subterranean, oceanic, ground, aeronautical, and orbital and beyond. The top row shows the industries that the use case ideas apply to: communications, technology, health, finance, production, energy, and other. This organizational structure was not intended to restrict thought but rather to provide participants with starting points to think of specific use cases that could benefit from quantum PNT tools. The sensor elevations and industries did not necessarily have to be considered independent of each other either; attendees were encouraged to think about how the categories interact and which processes and operations apply across multiple locations and industries.

Workshop Process: Idea Generator

The workshop was designed for participants to produce as many ideas as possible, methodically select those they thought would be the most important, and then develop the remaining ideas into meaningful and actionable concepts.

Brainstorm, Analysis, Selection

Participants were assigned to small groups for a 35-minute ideation session. First, each participant generated ideas in a 15-minute individual brainstorm and entered them in the value chain matrix under the industry and elevation they considered most applicable. The groups then took 15 minutes to discuss their ideas, and finally five minutes to vote for the ideas they thought had the most potential. To vote for top ideas, participants were each given three sticky dots to place on the value matrix; they could put all their dots on one idea or split them across two or three. Visualizing the vote helped the group easily prioritize choices together and make decisions at the end of a work session.

As noted, the groups' 129 ideas were well distributed across the grid areas by industry, with more of them focused on the ground level than other elevations. Each small group then determined the two to four top ideas based on the ones with the most sticky dots. This yielded 16 top use cases across all groups (after some consolidating of like ideas), which were then developed into concept cards.

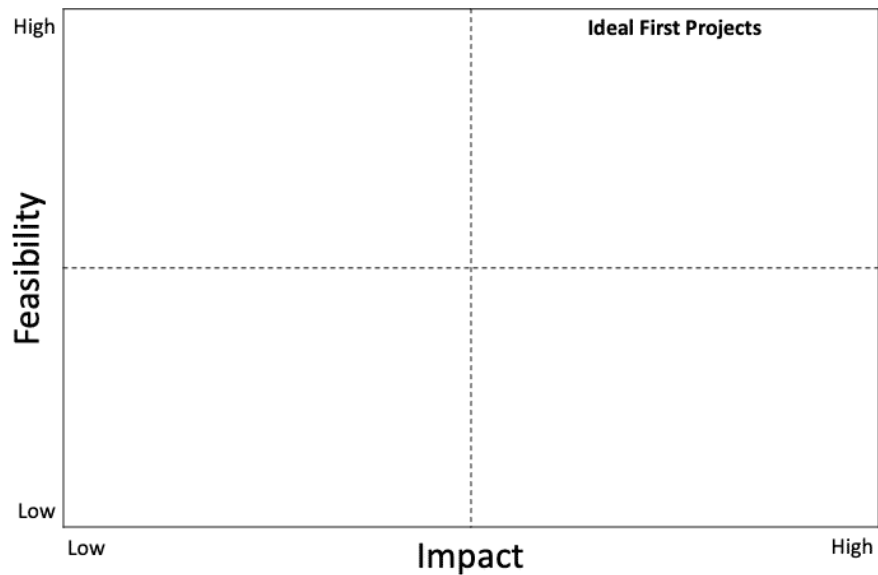
Concept Cards: Winnowing Ideas

The groups selected the ideas that had the most votes and created a concept card for each. As depicted in the figure below, the cards included the name of the concept, the quantum technology best suited to execute the idea, the intended sensor function (position, navigation, or timing), the elevation for sensor deployment, a description of the concept, and the pain points for the concept. The groups had 15 minutes to fill out the concept cards.

Concept Name: -----
Quantum Technology: (circle selections) Clock/oscillator Magnetometer Inertial Sensor Gravimeter Other _____
Sensor Function: (circle selections) Position Navigation Timing Other _____
Sensing Deployment: (circle selections) subsurface aquatic ground air space
Description: ----- ----- ----- -----
Pain points solved for: ----- -----

A Flexible Rating System to Promote Expansive Thinking

Top use case ideas from each small group were then evaluated by the collective group. Attendees ranked each idea based on their assessment of impact and feasibility. The average ranking on both dimensions was then taken for each top idea to graph the group's overall rating of the impact and feasibility of all 16 concepts.



Concept Poster: How to Execute

After further discussing the feasibility and impact of the top ideas, the workshop attendees agreed to focus on the seven concepts that ranked highest on impact and feasibility for development on concept posters (shown below).

Attendees were instructed to use the top idea as a basis for the concept poster but could develop the concept in the direction they felt best. The posters included a description of the concept, how it works, the problem space it occupies, key features, types of professions or industries (“personas”) who would be impacted by the implementation of the concept (e.g., engineers, airline companies, oil and gas companies), and key metrics and outcomes to measure success. The posters also identified potential team members who would be involved in implementation and suggested a timeline to complete the project.

Concept Poster & Collaboration Plan

Concept Name 	Description
Persona 	Features
How it works 	Success Metrics/Outcomes
Problem Space 	

Team Members:

Timeline:

	Start	-	-	-	-	-	-	-	Finish
Research									
Solve									
Develop									

Appendix B: Use Cases for Quantum Sensors in PNT

The table below lists the 129 ideas developed by the workshop participants, as well as the target elevation for the sensor and the applicable industry identified by the participants. Ideas have been only lightly edited.

Concept	Elevation	Industry
A validation platform for establishing reference systems, to accelerate the adoption of quantum sensors	Orbital and Beyond, Aeronautical	Technology, Health
A-PNT, Medical nav in contested environments	Aeronautical	Health
Absolute and relative positioning in fleet (autonomous cars, search and rescue, drones)	Aeronautical	Products
Air quality monitoring	Ground	Other
Airplane navigation	Aeronautical	Products
ASW (antisubmarine warfare)	Oceanic	Technology
Atmospheric radical detection	Aeronautical	Energy
Atomic clocks for autonomous timing supporting radionavigation or other complementary PNT architectures	Aeronautical	Products
Atomic clocks for energy distribution services/networks	Ground	Energy
Atomic clocks for precision timing in satellite networks	Orbital and Beyond	Other
Atomic clocks: Timestamping of financial transactions	Ground	Financial
Atomic clocks: Timing-based encryption schemes	Orbital and Beyond, Aeronautical, Ground, Oceanic	Communications
Atomic gyros: miniaturized inertial sensors (e.g., for drones?)	Aeronautical, Ground	Products
Atomic IMU for long duration holdover	Aeronautical, Oceanic	Other
Atomic inertial sensors and atomic magnetometers for GPS-denied positioning and navigation	Orbital and Beyond, Aeronautical	Products
Atomic inertial sensors and atomic magnetometers/gravimeters for GPS-denied positioning and navigation	Orbital and Beyond, Aeronautical	Products

Atomic magnetometers for low-field magnetic resonance imaging and magnetoencephalography (portable MRIs)	Ground	Health
Atomic magnetometers for low-frequency magnetic communications	Subterranean	Communications
Battery optimization	Ground	Energy
Benchmarking superconductor devices based on magnetic field sensing	Ground	Technology, Health
Biomarker detection with spin sensors	Ground	Health
Chemical sensors – detecting PFAS - food safety	Ground	Health
Clocks for acoustic/seismic surveying correlation	Subterranean	Other
Clocks for very long baseline astronomy	Orbital and Beyond	Other
Clocks with longer holdover & time transfer	Orbital and Beyond, Aeronautical	Financial, Other
Collaborate with standardization bodies to create standard embedded interfaces, reducing integration risks and enabling multi-industry validation	Orbital and Beyond	Other
Dark matter detection	Orbital and Beyond	Technology
Defense underground protection & awareness	Subterranean	Other
Defense undersea protection & awareness	Oceanic	Other
DER, EV, grid synchronization	Ground	Energy
Detection of fluid leaks	Ground	Energy
Distributed sensing of air pollution	Aeronautical	Other
Drones for grid monitoring and resilience	Aeronautical	Energy
Drones to monitor and maintain offshore wind	Oceanic	Energy, Other
Earthquake detection with networks of optical clocks	Ground	Other
Earthquake prediction	Ground	Energy
Enhance satellite orientation precision for reliable internet access in underserved areas	Orbital and Beyond	Communications
Enhanced dynamic positioning of reference systems with broader, more flexible back-and-forth movement		
Earthquake detection & prediction	Subterranean	Other
Establish a multidisciplinary use case for a validation platform, featuring an embedded	Aeronautical	Technology

atomic clock applicable across air, sea, and ground environments		
Establish a national library of interfaces and standard tools that can be shared and used as stepping stones for Q-sensor applications	Aeronautical	Other
EV PNT	Ground	Energy
Fiber microcombs (frequency, electrooptical, etc.) for interoperability used as clocks and used with diagnostic microcombs	Ground	Communications
Floating navigation beacons	Oceanic	Communications
Gaming industry needs better clocks for sync between remote and local servers	Ground	Technology
General factory monitoring	Ground	Products
GPS - knowing all points of references	Ground	Products
GPS - solar events disrupting GPS and automated planting for farming	Ground	Products
Gravimeter tunnel/anomaly detection	Subterranean	Other
Gravimeter, human location	Subterranean	Technology
Gravimeters for mineral detection	Ground	Energy
Gravitometer - navigation purposes for civilian, defense, and commercial	Aeronautical	Technology
Gravity mapping	Subterranean	Energy, Other
Gravity navigation	Oceanic	Other
Ground penetrating radar or gravimetry for underground resource localization	Subterranean	Energy
High cost, low volume in health --> helps to get to low cost, high volume	Ground	Health
High-performance time cards for CPU/GPU load balancing in data centers	Ground	Technology
High-accuracy sync of atomic clocks for financial transactions	Ground	Financial
Holdover clocks to enable high-bandwidth comms under GPS denial	Aeronautical	Communications
Hypervelocity guidance in GPS-denied environments	Aeronautical	Communications, Technology
Imaging sensors for surveillance needs - DOD, LE, IC, GeInt, DHS	Ground	Health
Improved mapping data for gravimetric sensors	Aeronautical	Products
IMU validation facility - especially for small/intermediate scale companies and academic institutions	Ground	Other

Inertial, smartphone	Ground	Technology
INS systems (gyroscope most needed)	Aeronautical	Communications
Interfacing quantum to quantum means you need a quantum link (e.g., fiber optic cable)		
Large-scale mapping using global satellite network using MagNav and GravNav	Aeronautical, Orbital and Beyond	Products
Local clocks for transatlantic server sync	Oceanic	Technology
Long holdover, low-SWaP clocks for marine vehicle nav	Ground	Energy
Long-holdover clocks for electric grid resilience/ synchrophasor measurements	Ground	Energy
Long-term Earth gravity monitoring	Orbital and Beyond	Energy
Low phase noise oscillators for optical transceivers (optical microwave down conversion)	Aeronautical	Technology
Low SNR sensors for HPHT	Subterranean	Energy
Low-SWaP clocks for comm sat	Orbital and Beyond	Communications
Magnetic anomaly detection	Subterranean	Energy
Magnetic mapping (Nav)	Ground	Products
Magnetic mapping (Resources)	Subterranean	Energy
Magnetic navigation - $<nT/\sqrt{Hz}$ @ mHz	Aeronautical	Other
Magnetic sensing for improved resource localization	Subterranean	Energy
Magnetometer - geo detection for mining safety operations	Ground	Energy
Magnetometer for anomaly detect & track - pT/\sqrt{Hz} @ mHz	Oceanic/ Subterranean	Other
Magnetometer, wearable technology; MCG - low pT/\sqrt{Hz}	Ground	Health
Magnetometric sensors for grid sensing (nodal)	Ground	Energy
Measure brain activity at the neuron level	Ground	Health
MEG + MCG	Ground	Health
Miniaturized clocks for autonomous nav	Ground	Products
More precise alignment of CubeSat with ground antennas	Ground	Communications
Network quantum sensors but seems to be limited practical application		
Noninvasive diagnostics with frequency combs	Ground	Health

NV diamond magnetometer: Failure analysis of integrated circuit manufacturing processes	Ground	Technology
PNT for automated systems and space mining	Orbital and Beyond	Energy
PNT for climate modeling	Orbital and Beyond	Energy
PNT for space-to-ground grid monitoring	Orbital and Beyond	Energy
PNT of microscopy platforms and stages to facilitate nanoscale alignment and manufacturing, e.g., quantum electrometry of Moire superlattice patterns of van der Waals 2d materials and TMDCs	Ground	Technology
PNT satellites for sensing pipeline leaks or wildfires	Orbital and Beyond	Energy, Other
Point-of-care biomedical imaging devices	Aeronautical	Health
Precision agriculture, timing and location, gravimeter, and clock	Ground	Products
QKD-based security for financial institutions	Ground	Financial
Quantum accelerometer or gyroscope - assist in navigation	Aeronautical	Technology
Quantum clocks - synchronization	Orbital and Beyond	Communications
Quantum computing for homomorphic encryption	Ground	Technology
Quantum computing, clock qubits	Orbital and Beyond	Energy, Other
Quantum imaging - low-light optics?	Oceanic	Technology
Quantum key distribution	Orbital and Beyond	Communications
Quantum networking of multiple sensors on the grid	Ground	Energy
Quantum Raman spectroscopy for ice detection and water-ice phase transition	Oceanic	Energy
Radiation hardened INS systems	Orbital and Beyond	Communications, Technology
Real-time trading alerts (not a true sensing case yet)	Ground	Financial
Resource mapping	Subterranean	Products
Robotic surgery	Ground	Health
Satellite navigation for e.g. new space (cubesat) quantum gyros	Orbital and Beyond	Other

Secure precise PNT for financial transactions	Ground, Aeronautical	Financial
Sensor for detection of corrosion	Oceanic	Energy
Sensors on drones for field safety, gas leaks, flairs, security	Aeronautical	Energy
Shipboard nav	Oceanic	Products
Soil health monitoring and early disease detection	Aeronautical	Health
Spoof detection using holdover clocks (using air- and ground-mounted systems)	Ground, Aeronautical	Communications
Submarines	Oceanic	Other
Supplemental area navigation network	Aeronautical	Other
Synchronization of energy assets in space	Orbital and Beyond	Energy
Telecom quantum emitters for secure communication	Ground	Communications
Terrestrial timing networks for navigation	Ground	Communications
Thermometer - applications in distributed impact analysis of localized events	Ground	Other
Tracking trains in tunnels	Subterranean	Products
Ultraprecise navigation	Orbital and Beyond	Technology
Underground maintenance and protection	Subterranean	Technology
Undersea maintenance and protection	Oceanic	Technology
Unmanned submarine missions for environmental survey	Oceanic	Energy
Vector magnetometer for automotive orientation determination	Ground	Technology

Appendix C: Workshop Participants

Thank you to all of the workshop participants for sharing their time and perspectives.

Jamil Abo-Shaeer, Vector Atomic

Amit Agrawal, Army Research Lab

Robert Atkins, Department of Homeland Security

Raymond Beecham, Accenture Federal Services

Benjamin Berman, US Coast Guard Research & Development Center

Hari Bhatta, National Energy Technology Laboratory

Malcolm Boshier, Los Alamos National Laboratory

Kenton Brown, Georgia Tech Research Institute

Nadia Carlsten, SandboxAQ

Clarence Chang, Argonne National Laboratory

Yousu Chen, Pacific Northwest National Laboratory

Aaron Cofer, Accenture Federal Services

Andy Corriveau, Axiom Space

Rayelene Covelle, SRI

Andrés Cuéllar Vega, Xairos Systems

Shanying Cui, HRL Laboratories, LLC

Amy Cutting, US Coast Guard Research & Development Center

Fraser Dalgleish, StratConGlobal

Suman Debnath, Oak Ridge National Laboratory

Jack Diab, University of California, Los Angeles

Brian Doolittle, Aliro Quantum

Gregory Drewry, EPRI

Yuhua Duan, National Energy Technology Laboratory

Carl Dukatz, Accenture

Robbie Fasano, Infleqtion

Shane Fazzio, Infleqtion

Luca Ferrara, SandboxAQ

Garland Garris, Accenture Federal Services

Kevin Glynn, Northwestern University

Jacob Gottlieb, SRI

Stephen Harper, Accenture Federal Services

Victoria Hazoglou, Accenture

Rob Hovsopian, National Renewable Energy Laboratory

Matthew Hummon, National Institute of Standards and Technology

Brandon Isaac, Freedom Photonics

Pranav Kalinadhabhotla, Great Lakes Crystal Technologies

Danny Kim, HRL Laboratories, LLC

Mark Klobukov, iDvera Software Inc.

Samuel Knarr, L3Harris

Alexander Konrad, Q.ANT GmbH

David La Mantia, Georgia Tech Research Institute

Kara Lacy, Accenture Federal Services

Michael Lee, SRI

Gabe Lenetsky, Keysight

Stephen Libby, Lawrence Livermore National Laboratory

Jay Lowell, Boeing

Chris Lowrie, L3Harris

Nardo Manaloto, Qubits Ventures

Alberto Marino, Oak Ridge National Laboratory

Bonnie Marlow, MITRE

Julián Martínez-Rincón, Brookhaven National Laboratory

Kirk McGregor, Iff Technologies

Carl Miller, National Institute of Standards and Technology

Tara Mills, Accenture Federal Services

David Mitlyng, Xairos Systems

Shay Moore, SRI

Hans Mumm, IEEE

Bogdan Neculaes, Boeing

Randall Nichols, Kansas State University

Rima Oueid, Department of Energy

Jonathan Ouellet, SandboxAQ

Derek Paley, University of Maryland

Laura Parker, Department of Homeland Security

Elliot Parrish, Department of Homeland Security

Max Perez, Infleqtion

Jacquelyn Piansay, Accenture Federal Services

Calvin Poindexter, Department of Homeland Security

Satyam Priyadarshy, Reignite Future

Carola Purser, Quantum Valley Ideas Lab

Michael Rabin, Los Alamos National Laboratory

Arun Ramasamy, Accenture Federal Services

Lucien Randazzese, SRI

Jeremy Renshaw, EPRI

Greg Rieker, LongPath Technologies, Inc.

Emma Rose, SRI

Tim Schmidbauer, Q.ANT GmbH

Christopher Seck, Oak Ridge National Laboratory

Keeper Sharkey, ODE, L3C

Suzanne Sincavage, Foundation for Biodefense Research

Manish Singh, memQ Inc.

Suren Singh, Keysight

Michael Slocum, Air Force Research Laboratory

Dylan Solden, SRI

Sina Soleimanikahnoj, QuantCad LLC

Joseph South, Lockheed Martin

Oney Soykal, QuaSaR Inc.

Gregory Steinberg, iDvera Software Inc.

Haley Stumvoll, L3Harris

Sugeet Sunder, University of Southern California

Jugal Talukdar, University of California, Los Angeles

Xuecheng Tao, University of California, Los Angeles

Igor Teper, AOSense, Inc.

Peter Udvarhelyi, University of California, Los Angeles

Ceren Uzun, Los Alamos National Laboratory

Prachi Vakharia, ARPA-I

Karen Van Dyke, Department of Transportation

Brandon van Hoff, SRI

David Van Workum, Keysight

Hadi Wassaf, Department of Transportation

Damian Watkins, Aperio Global

Ernest Wong, Department of Homeland Security

Jeffrey Wuenschell, National Energy Technology Laboratory

Annie Wyhof, SRI

Robert Wyllie, Georgia Tech Research Institute

Katie Young, Georgia Tech Research Institute

Brenton Young, AOSense, Inc.

Honghao Zheng, Midcontinent Independent System Operator

Konrad Ziegler, HRL Laboratories, LLC

Anatoly Zlotnik, Los Alamos National Laboratory

Appendix D: Use Cases Technical Advisory Committee – Sensing Subgroup Members

Thank you to the members of the Use Cases Technical Advisory Committee – Sensing Subgroup, who shared their time and expertise in support of this assessment.

Rima Oueid, Department of Energy

David Anderson, Rydberg Technologies

Sophia Bowers, Keysight

Brien Buckman, SRI

Jenna Chan, US Army Research Laboratory

William Clark, Infleqtion

Dani Couger, Lockheed Martin

Ann Cox, Department of Homeland Security

Jim Drakes, L3Harris

Ronald Esman, RTX

Jonathan Felbinger, SRI

Reza Hedayati, NubisAI

Elizabeth Iwasawa, Leidos

John Kitching, National Institute of Standards and Technology

Ben Koltenbah, Boeing

David I Lackner, Lockheed Martin

Claire Lecornu, SRI

Gabe Lenetsky, Keysight

Bonnie Marlow, MITRE Corporation

Julian Martinez-Rincon, Brookhaven National Laboratory

Carl Miller, National Institute of Standards and Technology

Brad Moores, Leidos

Zoe Mullins, Leidos

John Prisco, Safe Quantum

Mike Shahine, RTX

Keeper Sharkey, ODE, L3C

Suren Singh, Keysight

Mark Wippich, MPW

Kubra Yeter Aydeniz, MITRE Corporation

Raymond Zanoni, RTX



QED.C

The logo features the text "QED.C" in a bold, dark teal font. The text is centered and overlaid on a circular pattern of small, light pink dots that radiate outwards from the center of the letters. The background is white, with a black triangle in the top right corner and a dark teal triangle in the bottom left corner, separated by a diagonal pink line.