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How Quantum Sensing Will Help Solve GPS Denial in Warfare

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Executive Summary

The U.S. military's ability to posture, deter, and prevail in future conflicts may rest on the quantum sensing position, navigation, and timing (PNT) capabilities that are currently being developed. Heavy reliance on GPS signals for PNT has become a critical vulnerability for the U.S. military. Meanwhile, the conflict in Ukraine has demonstrated that GPS denial and electronic warfare (EW) is now a key component of modern combat and satellite-guided munitions are reportedly being rendered ineffective. The Department of Defense (DOD) is focusing on upgrading GPS to use stronger, military-specific signals, which will still be vulnerable to EW and anti-satellite capabilities. A more diverse and resilient alternate-PNT strategy is needed to ensure mission success.

Quantum Sensing is poised to revolutionize PNT in the coming years. Advancements in quantum sensing have produced high-stability clocks and inertial sensors that can provide precise PNT data during short-term GPS outages. Breakthroughs in quantum gravimeters and magnetometry have enabled map-matching navigation. These sensors are unaffected by EW and work in any location and weather. While no single alternative can match GPS for accuracy and reliability, a combination of sources can ensure mission success during GPS outages.

China's significant investment in quantum technologies has resulted in quantum sensing research quality comparable to the United States.[1] This parity opens the possibility of China achieving independence from satellite PNT signals in combat first. To avoid reaching a point where China holds a significant advantage in future conflicts, the United States must accelerate its alternate PNT programs and leverage the diverse portfolio of similar R&D in allied countries. Continued investment and DOD involvement in quantum sensing research and development (R&D) will accelerate the process of reducing the U.S. military's over-reliance on GPS. Achieving and protecting this capability will require strong DOD technical leadership and logistical support. With effective DOD management and close collaboration with allies, quantum sensing PNT devices could secure the Joint Force's future effectiveness without relying on GPS.

Key Takeaways

- The U.S. military's heavy reliance on GPS for PNT makes signal loss crippling for mission execution and significantly weakens the U.S. space deterrent.
- Modern conflicts, such as in Ukraine, incorporate GPS denial tactics which have reportedly rendered satellite-guided weapons like Excalibur shells and JDAM-ER missiles ineffective.[2]

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[1] Hodan Omaar and Martin Makaryan, "How innovative is China in Quantum?" Information Technology and Innovation Foundation (September 9, 2024). https://itif.org/publications/2024/09/09/how-innovative-is-china-in-quantum/. Accessed January 7, 2025.

[2] Isabelle Khurshudyan and Alex Horton. "Russian jamming leaves some high-tech U.S. weapons ineffective in Ukraine." *The Washington Post*. (May 24, 2024).

- Russia and China are investing in anti-satellite capabilities that could weaken or cripple GPS in space, while advancing their own PNT resilience strategies in parallel.
- Advances in quantum sensing, the most mature quantum technology, are enabling and delivering alternative PNT solutions immune to electronic and space-based warfare now.
    - **Inertial Sensors**: Track movement from a known location but drift over time. Quantum inertial sensors using atom interferometer technology offer over 10 times longer stability than classical sensors, significantly increasing holdover times.
    - **Atomic Clocks**: Provide precise timekeeping. Next-generation optical atomic clocks and chip-scale atomic clocks (CSACs) offer superior precision and portability, respectively.
    - **Magnetometers**: Navigate using Earth's magnetic field, achieving accuracy on the order of 100s of meters with detailed maps. Well suited for airborne vehicles, with ongoing R&D for chip-scale versions that could be used for munitions and drones.
    - **Gravimeters**: Navigate using Earth's gravitational field. Best suited for ships and submarines. Positioning accuracies are limited by map resolution (1 nautical mile).
- Startup companies are leading many alternate PNT quantum sensing R&D efforts; several prototypes were fielded during the Rim of the Pacific (RIMAC) Military exercise in 2022.[3]
- The extensive GPS M-code upgrade will still be vulnerable to EW and space-based attacks.
- If China surpasses the U.S in quantum sensing alternate PNT and eliminates the need for GNSS signals in combat first, it will gain a significant advantage in future conflicts.

Policy Options

- The United States must incorporate PNT resilience in its deterrence policy, so the cost of an adversary's space-based attack far outweighs the perceived gain.
- The quantum sensing market dies without DOD: it should increase engagement with quantum sensing startup companies developing alternate-PNT prototypes to ensure products traverse the "valley of death."
- Dedicated DOD technical leadership, separate from the PNT Oversight Council, should be allocated to efficiently leverage the widespread domestic and allied quantum sensing PNT R&D efforts so it reaches a point of GPS non-reliance before China does.
- DOD should leverage the GPS M-Code upgrade to ensure that new infrastructure incorporates open-system navigation architecture, enabling seamless integration of multiple alternate-PNT sources, including future quantum sensing devices.

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https://www.washingtonpost.com/world/2024/05/24/russia-jamming-us-weapons-ukraine/. Accessed August 13, 2024.

[3] "Vector Atomic Validates Quantum Navigation Sensor at Sea," BusinessWire (March 28, 2023). https://www.businesswire.com/news/home/20230327005642/en/Vector-Atomic-Validates-Quantum-Navigation-Sensor-at-Sea. Accessed November 20, 2024.

Introduction

The U.S. military's heavy reliance on Global Positioning System (GPS) technology for PNT and targeting is seen as an exploitable vulnerability by our adversaries. However, an ongoing technological revolution in quantum sensing has the potential to address this vulnerability within the next few years, provided it receives adequate cultivation and resources.

Using GPS signals for timing and navigation is deeply ingrained in the U.S. military's infrastructure. Much of their advantage is built on precision-GPS-guided weaponry, with even higher precision possible as the GPS system undergoes military-specific upgrades. In parallel, the competition to block and receive GPS and telecommunication signals has become a centerpiece of warfare, as is evidenced by the Ukraine conflict where reports have indicated advanced, U.S.-made, satellite-guided weaponry such as Excalibur shells, JDAM-ER missiles, and HIMARS launchers, experiencing dramatic reductions in effectiveness.[4] Adversaries have also clearly signaled their intent to hold U.S. space assets, including GPS at risk.[5] The 2021 National Defense Authorization Act directed DOD to integrate alternate means of PNT within the next few years.[6] However, current alternate-PNT technology has significant performance and usage limitations.

Unlike quantum computing, which is still years from being useful, quantum sensing is delivering significant advances on alternate PNT solutions now.[7] Many of these technologies are already commercially available or have had prototypes fielded in recent military exercises and flight tests. These quantum sensing devices will enable new capabilities and supply game-changing performance over their classical counterparts. China is also rapidly developing PNT quantum sensors and may soon reach the point where it no longer relies on satellite navigation (SatNav) signals in combat, potentially outpacing the United States. DOD must ensure that R&D efforts are sufficiently resourced and informed to produce these devices quickly and at scale, while also acting as a key market driver for startups developing alternative PNT prototypes. DOD should also collaborate with allies to ensure PNT interoperability.

In this report, I first describe how GPS works, why it is vulnerable, and what alternate options for PNT are available. Second, I explore the current circumstances surrounding the U.S. military's over-

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[4] Isabelle Khurshudyan and Alex Horton. "Russian jamming leaves some high-tech U.S. weapons ineffective in Ukraine."
[5] Chris Gordon, "Space Force No. 2 Says there is Risk of China or Russia Launching Large-Scale Attack in Orbit," Air & Space Forces Magazine (August 24, 2024). https://www.airandspaceforces.com/space-force-no-2-risk-china-russia-large-scale-attack/. Accessed January 9, 2025.
[6] William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021, H.R.6395 S.1611, 116th Cong. (2021). https://www.congress.gov/bill/116th-congress/house-bill/6395. Accessed January 8, 2025.
[7] Aaron McDade, "Quantum Computing Stocks Sink as Nvidia CEO says Tech is 15-30 Years Away," Investopedia (January 8, 2025). https://www.investopedia.com/quantum-computing-stocks-sink-as-nvidia-ceo-says-tech-is-15-to-30-years-away-8771205. Accessed January 9, 2025.

reliance on GPS signals for PNT information. Next, I outline how adversaries are honing strategies to exploit this vulnerability as EW becomes central to conflict. I then describe what quantum sensing is and how it can contribute to resolving the vulnerability posed by adversary targeting of GPS. Subsequent sections cover the four types of quantum sensors that will advance the alternate PNT mission, each with diverse benefits and challenges. I then conclude by analyzing the United States' progress in accelerating quantum sensing PNT applications, with a few recommendations of what more can be done.

GPS and the Scope of Threat

- *The U.S. military's heavy reliance on GPS for PNT makes signal loss crippling for mission execution and significantly weakens the U.S. space deterrent.*
- *Modern conflicts, such as in Ukraine, incorporate GPS denial tactics which have reportedly rendered satellite-guided weapons like Excalibur shells and JDAM-ER missiles ineffective.* [8]
- *Russia and China are investing in anti-satellite capabilities that could weaken or cripple GPS in space, while advancing their own PNT resilience strategies in parallel.*
- *The United States must incorporate PNT resilience in its deterrence policy, so the cost of an adversary's space-based attack far outweighs the perceived gain.*

GPS has become nearly ubiquitous in daily life. Since the technology was made available for civilian use in 1983, industries leveraging its signals have reaped over a trillion dollars in cumulative economic benefits. Consequently, our dependence on GPS has grown to the point where it provides the foundational clock for our schedules and precise location coordinates for nearly all our navigation needs. Common holdover PNT sources like inertial and clock technology have become smaller, cheaper, and less stable as GPS has grown. Meanwhile, older, large-scale alternatives have been retired and dismantled. SatNav has been so reliable throughout its lifetime that it is difficult to imagine life in its absence. A 2019 study found that a 30-day GPS outage would cause economic damage equivalent to that of a mid-sized hurricane. [9] However, the researchers did not account for productive time lost by a smartphone-dependent population having to re-learn how to use maps. Civilians are not the only ones who would be lost without GPS; much of the U.S. defense infrastructure also relies on GPS signals to execute missions. Troops, ground vehicles, ships, submarines, drones, and aircraft all rely on GPS. Satellite-guided missiles cannot reach their

[8] Isabelle Khurshudyan and Alex Horton. "Russian jamming leaves some high-tech U.S. weapons ineffective in Ukraine."
[9] O'Connor, A.C., Gallaher, M.P., Clark-Sutton, K., Lapidus, D., Oliver, Z.T., Scott, T.J., Wood, D.W., Gonzalez, M.A., Brown, E.G., and Fletcher, J. 2019, June. Economic Benefits of the Global Positioning System (GPS). RTI Report Number 0215471. Sponsored by the National Institute of Standards and Technology. Research Triangle Park, NC: RTI International. https://dpjh8al9zd3a4.cloudfront.net/publication/economic-benefits-global-positioning-system-gps/fulltext.pdf. Accessed August 19, 2024;
"U.S. Billion-Dollar Weather and Climate Disasters." NOAA National Centers for Environmental Information. https://www.ncei.noaa.gov/access/billions/. Accessed August 10, 2024.

target if GPS signals are lost. The timing information provided by GPS provides essential synchronization of encrypted communication and precisely-timed operations. Our adversaries are aware of this vulnerability.

What is the GPS?

GPS is a system of 31 U.S.-owned satellites orbiting 20,000 kilometers (km) above Earth and operated by ground-based control stations.[10] The satellites transmit radio-wave signals that provide positioning and timing data anywhere in the world with accuracies within 2 meters (m) and 30 nanoseconds (ns), respectively.[11] User-experienced accuracy depends on the receiver quality and if their location is interfering with signal reception. GPS signals are known to be weak and determining a location requires undisrupted signals from four satellites simultaneously. As a result, GPS has degraded service in cities with large buildings, in canyons or valleys, under dense foliage, etc. The satellite signals cannot penetrate underground and underwater at all, so other forms of navigation would be required. The U.S. Space Force oversees all components of the system and is working to modernize the system.

GPS is a Global Navigation Satellite System (GNSS), which includes all SatNav constellations fielded by various space-faring nations. Including GPS, there are six total systems. Russia, China, and the European Union (EU) have also fielded constellations that provide global coverage similar to GPS. The remaining systems from India and Japan provide regional coverage around their respective territories.[12]

What is electronic warfare (EW)?

The struggle to receive and deny GPS signals during conflict began in the Gulf War but has since become a centerpiece of warfare.[13] DOD's definition of EW is "military activities that use electromagnetic waves to control the electromagnetic spectrum and attack an enemy".[14] The seasoned reader might remember once having to tune a radio to the frequency corresponding to their desired station. GPS signals and general telecommunications operate the same way. There are three openlyknown radio frequency bands on which GPS transmits signals to users.[15]

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[10] Earth's diameter is ~12,700 km for comparison. This altitude is classified as medium-Earth orbit (MEO).
[11] "GPS Accuracy," GPS.gov (March 3, 2022). https://www.gps.gov/systems/gps/performance/accuracy. Accessed January 9, 2025.
[12] "Other Global Navigation Satellite Systems (GNSS)" GPS.gov (March 3, 2022). https://www.gps.gov/systems/gnss/. Accessed January 9, 2025.
[13] Larry Greenemeier, "GPS and the World's First Space War." *Scientific American* (February 8, 2016). https://www.scientificamerican.com/article/gps-and-the-world-s-first-space-war/. Accessed August 13, 2024
[14] *"Defense Primer: Electronic Warfare,"* Congressional Research Service, IF 11118 (November 14, 2022). https://crsreports.congress.gov/product/pdf/IF/IF11118. Accessed January 9, 2025.
[15] "Time and Frequency from A to Z. G," NIST (March 1, 2023). https://www.nist.gov/pml/time-and-frequency-division/popular-links/time-frequency-z/time-and-frequency-z-g. Accessed January 9, 2025.

For the purposes of this report, there are two main kinds of EW relevant to GPS. The first and most common type is "jamming." This strategy would employ a radio frequency (RF) transmitter to overpower GPS signals in all directions on the relevant frequency bands an adversary wants jammed. The proximity of terrestrial GPS jammers has the effect of "screaming" at frequencies used by GPS signals and would prevent any receivers nearby from distinguishing true signals from the noise.[16] The second type of EW, "spoofing," is more sophisticated and sinister. In this case, an adversary might create fake signals that appear like ones from GPS satellites but instead contain misleading data.[17] Without an uncompromised, alternate PNT source to contradict the fake GPS signals, the unaware vehicle could be led far astray from their destination.

Both EW techniques can be mitigated by finding ways to strengthen GPS signals, adopting software to better identify true signals in jammed areas, or utilizing alternate frequencies/GNSS systems (to name a few). However, these strategies are only effective until the adversary's engineers find a way to circumvent or counter the hack that overcame their original attack. The alternate PNT strategies enabled by quantum sensing would change the GPS countermeasures game, serving as more permanent solutions that require no external signals and are immune to jamming and spoofing.

GPS Denial on Earth

The current conflict in Eastern Europe has reached a crescendo in EW. Soon after their initial invasion was stifled, Russia ramped up their efforts to jam the frequencies Ukrainian drones needed to communicate with operators and receive GPS signals.[18] With significant prior investment in EW systems and extensive battle-testing a decade earlier in Syria and Crimea, the Russians are at the forefront of this new type of warfare.[19] Reports indicate that once-reliable U.S.-made weapons, such as Excalibur shells and JDAM-ER missiles, have been rendered partially or completely ineffective by Russian-deployed systems designed to jam GPS signals.[20] U.S. companies have been working diligently with Ukraine to devise solutions to the rapidly evolving circumstances, such as providing maps of electronic jamming activity and Starlink terminals.

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[16] Lisa Sodders and Brad Smith, "Focused on the Threat: Electronic Warfare," U.S.S.F. Space Systems Command (September 17, 2024). https://www.nist.gov/pml/time-and-frequency-division/popular-links/time-frequency-z/time-and-frequency-z-g. Accessed January 9, 2025.
[17] Jesse Khalil, "GNSS spoofing threatens airline safety, alarming pilots and aviation officials," GPS World (September 24 2024). https://www.gpsworld.com/gnss-spoofing-threatens-airline-safety-alarming-pilots-and-aviation-officials/. Accessed January 9, 2025.
[18] T. Gibbons-Neff and Y. Shyvala, "'Jamming': How Electronic Warfare Is Reshaping Ukraine's Battlefields," *The New York Times* (March 12, 2024). https://www.nytimes.com/2024/03/12/world/europe/ukraine-drone-russia-jamming.html. Accessed January 11, 2025.
[19] "The latest in the battle of jamming with electronic beams." *The Economist*. (June 3, 2023). https://www.economist.com/special-report/2023/07/03/the-latest-in-the-battle-of-jamming-with-electronic-beams. Accessed August 11, 2024.
[20] Isabelle Khurshudyan and Alex Horton. "Russian jamming leaves some high-tech U.S. weapons ineffective in Ukraine."

Unfortunately, each fix only lasts until the enemy finds a way to circumvent or overpower the solution.

Since the conflict between Israel, Hamas, and subsequently Hezbollah began after the October 7, 2023 terrorist attack perpetrated by Hamas, Israel has been making significant use of EW. Much of Middle Eastern airspace has been polluted with spoofed GPS signals, which puts civilian aircraft at higher risk of making fatal mistakes.[21] At least one plane has nearly entered hostile airspace before realizing it was chasing a false signal. Israel eventually released a warning to pilots that GPS was "restricted," and that aircraft should rely on alternative navigation methods.[22]

Without reliable GPS signals or sufficient time to program individual routes and target coordinates into each munition, an army is effectively set back to the tactics of warfare from over a century ago. Precision, satellite-guided missiles become regular artillery shells, data from non-stationary surveillance platforms would be degraded, encrypted communication that relies on precise timing signals would be disrupted, and troops would have to find other means of navigating and preventing friendly fire. As tensions ratchet up worldwide, both the United States and China are closely monitoring developments in warfare innovation, anticipating a future conflict where access to GPS or similar space-based PNT systems is not guaranteed.

GPS Denial in Space

Far above terrestrial strife, the constellation of satellites that make up GPS are themselves being held at risk by our adversaries.[23] These satellites are part of a larger cohort of space assets that also support communication and surveillance objectives for DOD. Both the American warfighting strategy and nuclear deterrent are critically dependent on these satellites.[24] Reliance on these assets is so great, during a recent federal emergency response tabletop exercise, potential damage to space assets was a key component of the debate over whether to save central North Carolina

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[21] Jesse Khalil, "Israeli air base identified as alleged soured of GPS disruptions in Mideast," GPS World (July 10, 2024). https://www.gpsworld.com/israeli-air-base-identified-as-alleged-source-of-gps-disruptions-in-mideast/. Accessed January 11, 2025.
[22] Selam Gebrekidan, "Electronic Warfare Confounds Civilian Pilots, Far From Any Battlefield." *The New York Times*. (November 21, 2023). https://www.nytimes.com/2023/11/21/world/europe/ukraine-israel-gps-jamming-spoofing.html. Accessed August 11, 2024.
[23] U.S. Department of Defense. *2022 National Defense Strategy* (October 2022). https://media.defense.gov/2022/Oct/27/2003103845/-1/-1/1/2022-NATIONAL-DEFENSE-STRATEGY-NPR-MDR.PDF. Accessed August 10, 2024.
[24] Michael P. Gleason and Peter L. Hays, *Getting the Most Deterrent Value from U.S. Space Forces*. Aerospace Corporation, Center for Space Policy and Strategy, (October 2020). https://csps.aerospace.org/sites/default/files/2021-08/Gleason-Hays_SpaceDeterrence_20201027_0.pdf. Accessed August 12, 2024.

from being obliterated by a hypothetical asteroid impact using a last-ditch nuclear mitigation mission.[25]

Unfortunately, despite their immense value to U.S. interests, many of these satellites were deployed during a time where space was considered an operational sanctuary and thus have negligible defense mechanisms.[26] The world has since changed substantially, and adversaries are deploying capabilities to undermine U.S. space dominance as a strategy to reduce the Joint Force's effectiveness enough to prevail in future conflicts.[27] Within the past twenty years, both Russia and China have demonstrated the ability to hit satellites with ground-based missiles, creating massive debris fields that pose significant risks to other space infrastructure.[28] In parallel, both nations have also been pursuing more subtle anti-satellite capabilities, such as space-based projectile launching and directed energy attacks using lasers or microwaves.[29] Russia has even begun designing a nuclear-armed satellite, which could indiscriminately destroy large swaths of satellites if detonated.[30]

United States Space Deterrence Posture

Given the aggressive development of counter-space measures by adversaries and their preparation of backup options in case of conflict, it is likely that the current U.S. strategy is insufficient to deter an attack on our space assets.[31] As long as the United States' ability to conduct military operations remains heavily dependent on GPS, the space deterrent will remain weak. There is currently no

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[25] NASA Planetary Defense Coordination Office. *Planetary Defense Interagency Tabletop Exercise 4 After Action Report*. (August 5, 2022), pg. E-8 https://cneos.jpl.nasa.gov/pd/cs/ttx22/PD-TTX4-AAR-master-05August2022_final.pdf. Accessed August 13, 2024

[26] Charles S. Galbreath, *Building U.S. Space Force Counterspace Capabilities: An Imperative for America's Defense*. The Mitchell Institute for Aerospace Studies, Air and Space Forces Association, (June 2023). https://mitchellaerospacepower.org/wp-content/uploads/2023/06/Building-U.S.-Space-Force-Counterspace-Capabilities-WEB.pdf. Accessed August 8, 2024.

[27] The White House. *United States Space Priorities Framework*. (December 2021), https://www.whitehouse.gov/wp-content/uploads/2021/12/United-States-Space-Priorities-Framework-_-December-1-2021.pdf. Accessed August 12, 2024.

[28] A. Boley and M. Byers. "Anti-satellite weapon tests to disrupt large satellite constellations." *Nature Astronomy* 8 (2024), pp 10–12. https://doi.org/10.1038/s41550-023-02173-9. Accessed August 14, 2024.

[29] Clayton Swope, Kari A. Bingen, Makena Young, Madeleine Chang, Stephanie Songer, and Jeremy Tammelleo. *Space Threat Assessment 2024*. Center for Strategic International Studies (April 2024). https://aerospace.csis.org/wp-content/uploads/2024/04/240417_Swope_SpaceThreatAssessment_2024.pdf. Accessed August 14, 2024.

[30] "Nuclear Threats and the Role of Allies: A Conversation with Acting Assistant Secretary Vipin Narang." Center for Strategic and International Studies (August 1, 2024). https://www.csis.org/analysis/nuclear-threats-and-role-allies-conversation-acting-assistant-secretary-vipin-narang. Accessed August 10, 2024.

[31] Punishing attacks on space infrastructure requires accurate attribution, which is challenging due to natural threats like space weather and debris. Distinguishing between these threats demands a higher level of space situational awareness. Even if accurate attribution was achieved, the damage from an attack would primarily affect the economy and military, making a proportional response challenging to formulate without risking escalation.

comprehensive backup capability for the Joint Force to rely on in the event of a widespread outage.[32] The responsibility of safeguarding our invaluable space assets falls to the United States' general deterrent and the newly established Space Force. Until recently, their strategy heavily relied on deterrence by punishment, which is particularly fraught in the space domain.[33]

Deterrence is most effective when it employs a nuanced strategy beyond mere punishment, a concept embraced by the Biden Administration.[34] In response, DOD has been developing a more tailored approach that includes elements of denial and resilience, which creates a more comprehensive space deterrent. The denial aspect of the strategy aims to prevent adversaries from achieving their objectives through a space attack by building alternative capabilities (ideally not in space), or by developing more resilient space infrastructure that can better withstand attacks.

The obvious way to dominate the ground-based EW arms race to disrupt GPS signals is to develop an alternative capability that cannot be jammed or spoofed. Fortunately, years of military and civilian investment into quantum sensing research have begun to bear fruit. With careful cultivation and continued investment in this field, a complete, ground-based, PNT capability impervious to electronic and space warfare can become available within the next few years.

Adversaries are leading in GPS resilience

Alongside their counter-space development efforts, adversaries are also taking steps to reduce reliance on their own vulnerable SatNav systems, albeit through very different means. Unlike the United States, both China and Russia have retained a World War II-era capability (Loran) that uses radio towers to transmit timing signals, effectively a ground-based system that could supply regional PNT information in the event of a widespread GNSS outage. China has even been working to upgrade and expand this system by augmenting it with thousands of miles of fiber-optics cables to create one of the world's largest and most precise timing systems.[35] Russia, on the other hand,

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[32] Michael P. Gleason and Peter L. Hays, *Getting the Most Deterrent Value from U.S. Space Forces*.

[33] Deterrence by punishment threatens severe penalties, such as nuclear escalation or severe economic sanctions, if an attack occurs; Michael J. Mazarr, “Understanding Deterrence,” RAND Corporation (April 19, 2018). https://www.rand.org/content/dam/rand/pubs/perspectives/PE200/PE295/RAND_PE295.pdf. Accessed February 11, 2025; The White House, *National Security Strategy of the United States of America* (December 2017). https://trumpwhitehouse.archives.gov/wp-content/uploads/2017/12/NSS-Final-12-18-2017-0905.pdf. Accessed August 16, 2024.

[34] Stephen J. Flanagan, Nicholas Martin, Alexis A. Blanc, and Nathan Beauchamp-Mustafaga, *A Framework of Deterrence in Space Operations*, RAND Corporation (August 2023). https://www.rand.org/pubs/research_reports/RRA820-1.html. Accessed August 16, 2024; The White House, *National Security Strategy of the United States of America* (October 2022). https://www.whitehouse.gov/wp-content/uploads/2022/10/Biden-Harris-Administrations-National-Security-Strategy-10.2022.pdf. Accessed August 16, 2024.

[35] Selam Gebrekidan, John Liu, and Chris Buckley, “One Satellite Signal Rules Modern Life. What if Someone Knocks It Out?” *The New York Times* (March 28, 2024). https://www.nytimes.com/2024/03/28/world/asia/as-threats-in-space-mount-us-lags-in-protecting-key-services.html. Accessed August 14, 2024.

struggles to maintain and modernize GLONASS, their version of GPS, as the equipment is stretched far past its intended lifespan. Russia has taken to using stolen Starlink terminals to supplement their combat PNT needs.[36] In either case, both nations are striving to ensure that their domestic populations and regional defense are not impacted by a large-scale, indiscriminate attack on the world's satellite systems.

An Overview of Navigation Methods: Advantages and Limitations

- *Advances in quantum sensing, the most mature quantum technology, are enabling and delivering alternative PNT solutions immune to electronic and space-based warfare now.*

There are several alternate navigation methods that could be employed if GPS is unavailable. Each comes with limitations and conditions. A resilient alternate PNT system would combine positioning information from multiple sources to create the best possible data. Table 1 lists most major navigation methods available, with GNSS as the first entry for comparison.

The core of a PNT system uses inertial navigation combined with a clock, which tracks the vehicle's movements over time from a last known location to determine a current position. Without consistent recalibration to a known location and time, usually with GPS, the inertial system's PNT information degrades over time. Other navigation means must be employed for longer outages. Signals of opportunity, such as from ground-based RF transmitters or low-earth orbit (LEO) satellites, like SpaceX could be employed for positioning data. A vehicle could also use passive position-fixing or map-matching methods including terrain/image matching, celestial, magnetic, and gravitational navigation if an opportune signal never arrives.

Inertial, magnetic, and gravitational navigation are the three alternate PNT methods that are being revolutionized by quantum sensing R&D. Quantum atom interferometer prototypes used for inertial navigation have demonstrated significant advances in the length of time they can remain accurate compared to their classical counterparts. Similarly, navigating by map-matching to Earth's magnetic and gravitational fields has been made possible by the high-performance quantum sensing devices currently under development. All the quantum sensing alternate PNT methods would be internal to their vehicle and are therefore immune to EW tactics and space-based attacks.

[36] Clayton Swope and Makena Young, *Is There a Path to Counter Russia's Space Weapons*? Center for Strategic International Studies (June 28, 2024). https://www.csis.org/analysis/there-path-counter-russias-space-weapons. Accessed August 16, 2024.

Table 1. Collected navigation methods, with their capabilities and limitations. The methods that are being enabled or enhanced by quantum sensing are in bold. References for each row are listed in the footnotes.

Method Type	Accuracy (m)	Limitations	Best Used For
GNSS[37]	0.01 to 5	High-end accuracy requires more equipment.[38] Signals are weak and can easily be spoofed or jammed. They cannot penetrate underground, underwater, or places with substantial material blocking the signals.	This is the highest-performing PNT method when signals are available.
Inertial Navigation[39]	Time-Dependent	Navigates by referencing the last known position, but accuracy degrades over time. The best non-quantum systems are can last ~1 day before accumulating errors over 2 km.	Any vehicle, either for short-term intervals or with another PNT method to limit drift.
Magnetic Navigation (MagNav)[40]	100 to 1,000	Accuracy is dependent on velocity, altitude, correcting for the vehicle's magnetic field, and the map's quality/resolution. Navigation will deteriorate in a space with minimal anomaly features.	Best: Aircraft, guided munitions, drones (altitudes > 300 m). With caution: ships, underwater vehicles.
Gravitational Navigation (GravNav)[41]	2,000 to 10,000	Limited by the resolution and quality of available gravitational anomaly maps. Performance will also deteriorate in places with minimal gravitational anomaly features.	Ships, underwater vehicles; could be used for land vehicles if no other landmarks/ signals are available.

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[37] "GPS Accuracy," GPS.gov; Global GPS Systems, "GNSS Surveying Methods: Exploring Accuracy and Techniques" https://globalgpssystems.com/gnss/gnss-surveying-methods-exploring-accuracy-and-techniques. Accessed December 10, 2024.
[38] Centimeter-level accuracy can be achieved with the real-time kinematic method, but it requires an additional terrestrial base station to receive/transmit GNSS signals.
[39] N. El-Sheimy and A. Youssef, "Inertial sensors technologies for navigation applications: state of the art and future trends." *Satell Navig* **1**, 2 (2020). https://doi.org/10.1186/s43020-019-0001-5. Accessed November 14, 2024.
[40] Aaron Canciani, "Magnetic Navigation Overview," Defense Systems Information Analysis Center, (May 28, 2020). https://www.dsiac.org/wp-content/uploads/2020/03/DSIACWebinar_MagNav_Canciani.pdf. Accessed October 28, 2024.
[41] J. Kohler *et al*. "Performance Validation of a Strapdown Absolute Quantum Gravimeter for Gravity-aided Inertial Navigation," Institute of Navigation Joint Navigation Conference, June 3-6, 2024. https://www.ion.org/jnc/abstracts.cfm?paperID=13411. Accessed November 24, 2024; ,Hubiao Wang *et al*. "Characteristics of Marine Gravity Anomaly Reference Maps and Accuracy Analysis of Gravity Matching-Aided Navigation" *Sensors*. 17. 1851. (2017). http://dx.doi.org/10.3390/s17081851. Accessed December 10, 2024

Celestial Navigation[42]	25 to 2000	Requires a clear view of the sky; works best without clouds or at high altitudes.	Aircraft and ships; also useful for land vehicles if no other landmarks/signals are available.
Image/Terrain-Based Navigation[43]	1 to 30	Cannot be used over featureless terrain. Light/laser-based methods have degraded performance in bad weather. Sensors must have access to a terrain database to match signals.	Guided munitions, aircraft, submarines (sonar), airborne and underwater drones.
Radio Frequency Navigation[44]	10 to 500	Requires costly and extensive infrastructure, which cannot be built on enemy territory. Signals are still susceptible to jamming/spoofing and require a moderately clear path to a receiver.	Ships and underwater vehicles at shallow depths (when using very low frequency signals)
Low-Earth Orbit Satellites[45]	20 to 200	Will require a mega-constellation (such as a completed Starlink) to achieve global coverage. Signals are still susceptible to jamming/spoofing, may have incomplete PNT information, paywall barriers, or require decoding.	All above-water and above-ground vehicles.

Figure 1 illustrates where each of the above navigation methods would be best applicable. There are many cases where GPS might be unavailable and outages could either be short (caused by EW or environmental effects), or long term (caused by a large and widespread attack). Having multiple alternatives available would allow navigators to customize a combination of the most effective positioning techniques to suit each specific scenario. No single alternate PNT source can fully

[42] Ahjay Rai, "Honeywell Successfully Demonstrates Alternative Navigation Capabilities in GPS-Denied Environments," Honeywell (April 20, 2022). https://aerospace.honeywell.com/us/en/about-us/press-release/2022/04/honeywell-demonstrates-alternative-navigation-capabilities; Davis Instruments, "What is a Sextant?" https://www.davisinstruments.com/pages/what-is-a-sextant. Both accessed December 10, 2024.
[43] Geoffrey B. Irani and James P. Christ, "Image Processing for Tomahawk Scene Matching," *Johns Hopkins APL Technical Digest*, J5-3 (1994). https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V15-N03/15-03-Irani.pdf. Hyun Cheol Jeon, Woo Jeong Park, Chan Gook Park, "Accurate and Efficient Terrain Referenced Navigation Using Multiple Measurements by Flash LiDAR," *Proceedings of the 30th International Technical Meeting of the Satellite Division of The Institute of Navigation* pp. 1658-1668 (2017). https://doi.org/10.33012/2017.15130. Both accessed December 11, 2024.
[44] Matteo Luccio, "eLoran: Part of the solution to GNSS vulnerability," GPS World (November 3, 2021). https://www.gpsworld.com/eloran-part-of-the-solution-to-gnss-vulnerability/. Accessed December 11, 2024; U.S. Government Accountability Office, *Defense Navigation Capabilities,* GAO-21-320SP (May 2021). https://www.gao.gov/assets/gao-21-320sp.pdf. Accessed December 11, 2024.
[45] "Enter LEO on the GNSS Stage: Navigation with Starlink Satellites," Inside GNSS (November 29, 2021). https://insidegnss.com/enter-leo-on-the-gnss-stage-navigation-with-starlink-satellites/; Zizhong *et al.* "New Method for Positioning Using IRIDIUM Satellite Signals of Opportunity." *IEEE Access* (2019). http://dx.doi.org/10.1109/ACCESS.2019.2924470. Both accessed December 10, 2024.

match GPS in terms of accuracy and widespread availability, so a blend of multiple sources would be needed to ensure the Joint Force's ability to execute missions remains uncompromised.[46]

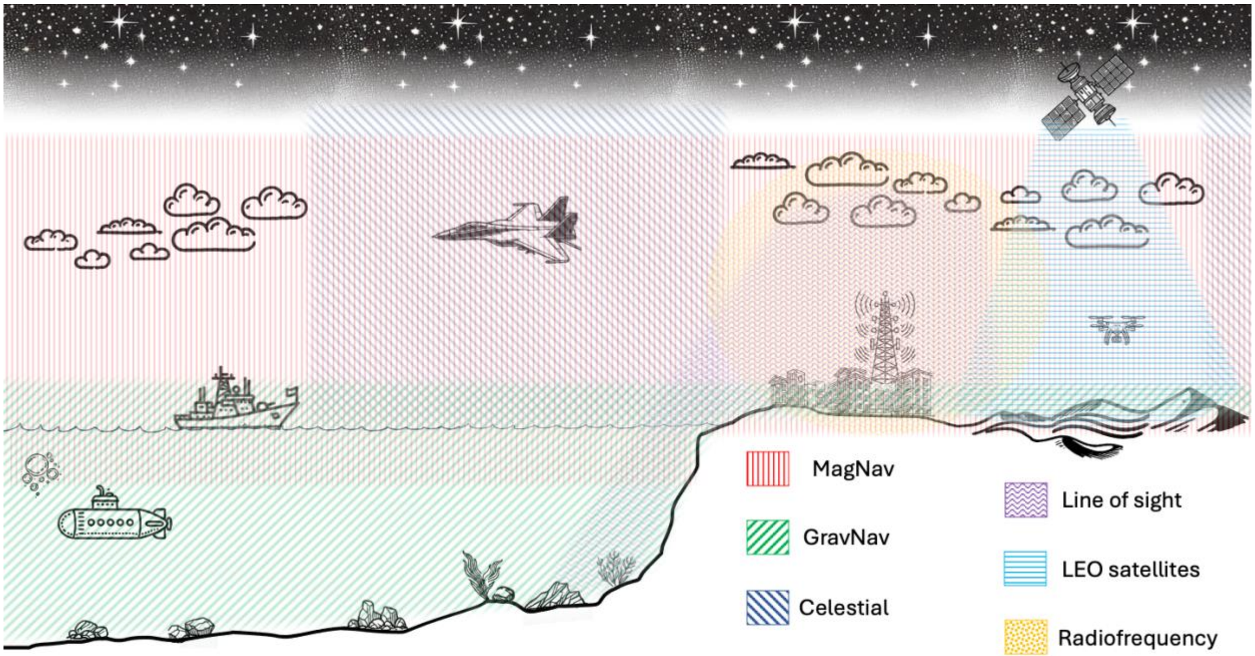

Figure 1. Diagram depicting where alternate PNT methods would be useful versus impractical. The color legend for each method is on the right. Inertial navigation is available in all vehicles that have an IMU, in any circumstances. Images generated with the assistance of DALL-E.

What is Quantum Sensing?

Quantum sensing is advanced technology that uses the quantum properties of particles to measure time, gravity, and electromagnetic fields with orders of magnitude more accuracy and precision than non-quantum (classical) sensors.[47] Quantum sensing, alongside quantum computing (QC) and quantum communications (QComm), are part of a rapidly accelerating revolution in Quantum Information Science and Technology (QIST) that has captured the attention of scientists and policymakers. Of the three technologies, quantum sensing is the least known, while also being the most established. By contrast, QC and QComm take the lion's share of attention given to QIST and are often used as engines for demonstrating scientific prowess on the

[46] More information about non-quantum alternate PNT methods can be found here: U.S. Government Accountability Office, *Defense Navigation Capabilities;* "Alternative Navigation Systems," Honeywell. https://aerospace.honeywell.com/us/en/products-and-services/product/hardware-and-systems/sensors/alternative-navigation-systems. Accessed Feb 28 2024.
[47] "Steady progress in approaching the quantum advantage," McKinsey (April 24, 2024). https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/steady-progress-in-approaching-the-quantum-advantage. Accessed January 11, 2025.

global stage. Despite being in the spotlight, both fields are still many years away from being fully realized.[48]

The current QIST surge marks the second wave in innovation for quantum sensing. The first wave happened several decades ago and yielded invaluable technologies such as medical MRI, lasers, and digital imaging. This current technological revolution will open a new range of applications for quantum sensors by pushing the limits of sensitivity while miniaturizing, hardening, and ruggedizing the prototypes enough to be fielded. These advances will allow next-generation, high-precision quantum sensors to debut many new spheres of industry and defense, including for PNT.

The Quantum Advantage

Quantum technology relies on the "quantized" behavior of particles, such as atoms or electrons: at low energies, particles can only occupy a few well-defined energy levels. This property allows users to quantify the particles' energy with exceptional precision and substantially decreases the need for calibration in some types of sensors. Also, unlike a machined or fabricated component that would inform a classical sensor, the particles used in quantum sensor are the exact same from sensor to sensor, which enhances reliability.[49]

Quantum sensors only require a single quantized particle system to measure changes in the outside world, which is a low bar for performance compared to other quantum technology. By contrast, QCs require many quantum systems to work together in unison with as little calculation-disrupting noise from the outside world as possible, both of which require herculean feats of engineering. Thus, useful quantum sensors are commercially available now, while QCs still require substantial R&D.

Main Components of a Quantum Sensor

Any quantum sensor has three fundamental components that allow it to function.

- The sensor's core quantum system is often composed of highly controlled particles in a specialized container. The particles' behavior is extremely sensitive to the environment.
- Electronics, often including lasers, will be needed to control and communicate with the quantum particles so the information can be read out.[50] Configuring these components into a small, hardened, and rugged container is the biggest challenge when fielding quantum sensors for PNT.

[48] The usefulness of Quantum Communications has been a topic of debate. DOD has not heavily pursued it.
[49] The electronics and particle containers may still cause some variability between sensors.
[50] Specialized electronics are required for measuring different kinds of forces and the particle container may have enhancements to minimize other forces in favor of the desired one. Even if a quantum sensor can measure multiple different forces at once, most are currently designed for only one application. This may change in the future.

- Specialized software is needed to turn the collected data into useful information and filter away unwanted signals. AI may contribute to this effort.

Many of the quantum sensor prototypes described in this paper require R&D on all three lines of effort to be successful.

Quantum Sensor Performance Metrics

When comparing sensors, there four often-used categories of quality measurement, which can be found in Table 2. The specific values for each type of quantum sensor can vary in name and what quality they measure, but the overarching purposes are consistent.

Table 2. Common metrics used to measure the performance of quantum sensors

Name	Description	Units
Size, Weight, Power, (Cost) (SWaP or SWaP-C)	How "fieldable" is a device? Can it fit and be operated in the vehicle it is designed for without offending budget officials?	liters (S), kilograms (W), watts (P), and dollars (C)
Precision	What the smallest signal strength a sensor can detect over the duration of a measurement? Is often correlated with the "noise level:" the strength of undesired signals that can drown out the desired one.	Listed in the units of the quantity the sensor is measuring.
Stability	How long can a sensor remain accurate before needing to be recalibrated to a known value?	Listed in units of the measured quantity's drift over time.
Bandwidth	How quickly can a sensor deliver new measurements? How long does it take to deliver a single measurement?	Number of measurements per unit of time (hertz)

Types of quantum sensors used for PNT

Quantum sensor development is underway for a wide variety of applications (well beyond just PNT), which makes tracking their progress challenging.[51] The sensors themselves could also be named by either what they measure or the type of quantum system they employ, which makes the field even

[51] Jean-Francois Bobier, Matt Langione, Cassia Naudet-Baulieu, Thilo Tamme, and Antoine Gourévitch, "Making Sense of Quantum Sensing," *Boston Consulting Group* (July 20, 2023). https://www.bcg.com/publications/2023/making-sense-of-quantum-sensing. Accessed September 24, 2024.

more difficult to characterize. I focus only on the sensors that are being outfitted specifically for PNT applications. These include:

- **Inertial Measurement Units (IMU)**, formed by accelerometers and gyroscopes, which measure acceleration and rotation rates, respectively
- **Atomic Clocks**, which measure time[52]
- **Magnetometers**, which measure a magnetic field
- **Gravimeters**, which measure the strength of gravity

Another popular defense-related quantum sensor is called a Rydberg RF receiver. It is primarily being developed for telecommunication purposes, so it will not be covered in this work.[53] PNT applications for Rydberg receivers may emerge in the future.

Each of the following sections will outline how each sensor type can be applied to PNT, what major technologies are being employed, how they compare to their equivalent non-quantum, "classical" sensors already in use, and what challenges they face.

Inertial Measurement Units

- *Inertial sensors track movement from a known location but require consistent recalibration. Quantum inertial sensors using atom interferometer technology offer over 10 times longer stability than classical sensors.*

Inertial Measurement Units (IMUs) are combinations of sensors that form the centerpieces of Inertial Navigation Systems (INSs), which processes the sensor data into useful PNT information. These devices have been in use since World War II.[54] Classical versions of this technology are already well-developed and extensively utilized across many different platforms including aircraft, naval vessels, and land vehicles. GPS-aided INSs form the core of aviation and maritime PNT systems. An INS can serve as a crucial backup for the various instances (both predictable and hostile) where GPS signals are either obstructed or unavailable, ensuring continued navigation

[52] Atomic clocks are often combined with another type of sensor to provide a high-precision time history of the other sensor's readings.
[53] Matt Swayne, "Rydberg Technologies Demonstrates World's First Long-Range Atomic RF Communication with Quantum Sensor at U.S. Army NetModX23 Event," The Quantum Insider. December 22, 2023. https://thequantuminsider.com/2023/12/22/rydberg-technologies-demonstrates-worlds-first-long-range-atomic-rf-communication-with-quantum-sensor-at-u-s-army-netmodx23-event/. Accessed September 25, 2024. For more information, please see: QED-C "Quantum Sensors: Rydberg Receivers Part I," YouTube (June 24, 2024). https://www.youtube.com/watch?v=NKV2ZjqX5c8l; QED-C "Rydberg Receivers (Part II)," YouTube (July 5, 2024). https://www.youtube.com/watch?v=WZWazDR1AJo. Both accessed January 11, 2025.
[54] W. Wrigley, "History of Inertial Navigation," NAVIGATION: Journal of The Institute of Navigation, vol. 24, no. 1, pp. 1-6, 1977. https://www.ion.org/publications/abstract.cfm?articleID=100716. Accessed September 24, 2024.

capabilities for a limited time. Quantum IMUs have the capacity to dramatically increase the length of time an INS can navigate accurately and will likely be first deployed on ships and submarines.

How it works:

An INS is typically made of three components. The IMU is the foundation and often includes three accelerometers and three gyroscopes to measure linear and rotational movement across the each of the three spatial dimensions (3D). The other two components include a clock for precise timekeeping and a computer to calculate the new position based on collected data. Sometimes, to help constrain errors that would accelerate drift, INS systems are outfitted with other simple sensors, such as a magnetometer to maintain alignment with true north, and (if relevant) either a barometer or bathometer for determining altitude or water depth, respectively.[55]

The fundamental principle behind INSs is related to a navigation method known as "dead reckoning." This technique involves taking the last known location of a vehicle and meticulously tracking its movements (acceleration and rotation rate) to determine a new location relative to the initial point. The information is internal to the INS on the vehicle, so it cannot be marred by the general techniques of EW. However, even the best INS will be slightly wrong every time it takes a measurement. Each new position the INS calculates is based on the previous measurement, which will contain accumulated errors of all the measurements made since the it was provided with precise PNT information, such as a GPS signal. This means INS systems "drift" or become more inaccurate over time. If an INS can incorporate an aiding source, the drift is collapsed to the accuracy of the aiding source and the sensor will be more accurate for a period of time. However, without eventually resetting to a known location (such as with a GPS signal), the INS will eventually drift so off-course, its positioning capabilities will be rendered useless. Thus, the main performance metrics for INSs are either how quickly they accumulate drift or how long they can maintain sufficiently accurate PNT readings (often called stability or holdover time). For instance, submarines rely on inertial navigation while underwater, but will periodically surface to receive a GPS signal and correct the drift of their INS.[56]

Types of INSs, Based on Performance:

Because INS systems are used in so many applications and vehicles, the industry has categorized them based on their performance. The three types relevant to this report are:[57]

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[55] Vectornav, "Inertial Sensing Nomenclature," https://www.vectornav.com/resources/inertial-navigation-primer/theory-of-operation/theory-inertial. Accessed November 14, 2024.
[56] "Navigating a Submarine," Smithsonian: Time and Navigation. https://timeandnavigation.si.edu/satellite-navigation/reliable-global-navigation/first-satellite-navigation-system/navigating-a-submarine. Accessed January 10, 2025.
[57] N. El-Sheimy and A. Youssef, "Inertial sensors technologies for navigation applications: state of the art and future trends."

- Tactical grade: found on larger unmanned arial systems (UASs) and guided weapons, usually costing <$50,000, with drift rates between 18 and 37 km/hr. These units are best used without a PNT aiding source like GPS for less than 10 minutes.[58]
- Navigation grade: found on commercial and military aircraft, usually costing upwards of $100,000, with drift rates between 0.5-1 meters/second. These units are best used without aiding for no more than a couple hours.
- Strategic grade: found on submarines, ships, and intercontinental ballistic missiles, costing over 1 million dollars, with drift rates between 30 and 100 meters/hr. These units could remain useful for about a few days, depending on navigation needs.[59]

Thus, in cases such as the ongoing conflict in Israel, where GPS is actively being jammed, navigation-grade INS systems already present on aircraft can navigate reasonably well for the hour or two it takes to fly over the affected area, though any other aircraft capabilities requiring SatNav will likely remain degraded before receiving true GPS signals again. Even if a spoofed GPS signal were received by an aircraft in the compromised area, a well-implemented INS could in principle have sufficient accuracy to help recognize and reject the wayward signal.[60]

Where quantum IMUs can contribute:

The area where quantum-based accelerometers and gyroscopes have the greatest potential is providing stability and accuracy for timescales longer than a day (strategic-grade) for surface vessels and submarines.[61] With sufficient improvements in SWaP, other, smaller vehicles may also eventually benefit.

In the event of a widespread GPS outage, a quantum IMU's increased stability would decrease navigators' urgency to secure a means to recalibrate the location, either via a signal of opportunity, a ground-based positioning signal, or using one of the map-matching techniques described in the following sections. Even without a GPS outage, improvements in this area would greatly benefit vehicles that travel in GPS denied areas such as underwater and underground by enabling longer missions and achieving higher-precision navigation or strikes for a given mission duration.

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[58] Vectornav, "Grades of Inertial Sensors," https://www.vectornav.com/resources/inertial-navigation-primer/theory-of-operation/theory-inertial. Accessed November 14, 2024.
[59] U.S. Air Force, "LGM-30G Minuteman III" (February 2019), https://af.mil/About-Us/Fact-Sheets/Display/Article/104466/lgm-30g-minuteman-iii/. Accessed November 14, 2024
[60] Stephen Hammack, **"**Inertial Reference Systems - GPS Spoofing and Jamming," Honeywell Aerospace Technologies, https://aerospace.honeywell.com/us/en/about-us/blogs/spoofing-and-jamming. Accessed November 14, 2024
[61] Ryan Cassel, William Tobias, and Bonnie Marlow, "Quantum vs Classical Complementary PNT," MITRE (March 2023), https://www.mitre.org/sites/default/files/2024-06/PR-23-0577-Quantum-vs-Classical-Complementary-PNT.pdf. Accessed November 14, 2024.

Quantum-based IMU Sensors

A leading quantum-based IMU being considered as a potential replacement for classical systems is an atom interferometer.[62] This technique separates atoms into two paths and observes their how their behavior has been changed by the system's acceleration and rotation when the paths are allowed to recombine.[63] There are two main types of atom interferometers: ones using cooled atoms, which offer greater precision and sensitivity provided by the system's low temperatures, and ones using thermal, or ambient temperature atoms, which have better SWaP potential.[64] Unlike classical accelerometers and gyroscopes, an atom interferometer can serve either function, and depending on the sophistication, measure in all three dimensions. Their high-sensitivity capabilities are also useful for determining the relative strength of gravity (as a gravimeter), which is discussed in a later section.

Atom interferometers have garnered enough optimism to attract the interest of venture capital (VC) investment. There are startup companies working on this technology in the United States (Vector Atomic, AOSense), the United Kingdom (MSquared), France (iXblue), and Australia (Q-CTRL) just to name a few. [65] Many of these companies are likely combining quantum accelerometers with classical gyroscopes and accelerometers to form a hybrid system, which leverages the high precision of quantum sensors and the high bandwidth of classical sensors to maximize performance. For now, the gain from switching to a quantum gyroscope from a classical one is less than for an accelerometer. Regardless, a few startups are already advertising impressive units, with Q-CTRL promising an INS that can maintain 1 mile accuracy for 1000 hours (over 10x longer than the strategic range listed earlier).[66]

With regards to SWaP, the IMUs advertised by these startups tend to be roughly the size of a large suitcase. Further decreasing their prototype's size is an area of active research. Cold atom

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[62] A quantum-based nuclear magnetic resonance (NMR) gyroscope was also explored. Northrop Grumman and DARPA developed a promising prototype in the early 2010s, but little progress on improving the prototype has been made since.

[63] Advanced Navigation, "Interferometry in Quantum Mechanics" (August 25, 2022). https://www.advancednavigation.com/tech-articles/the-future-of-inertial-navigation-is-classical-quantum-sensor-fusion/#h-interferometry-in-quantum-mechanics. Accessed November 14, 2024.

[64] F. A. Narducci, A. T. Black and J. H. Burke, "Advances toward fieldable atom interferometers", Advances in Physics: X, 7:1, 1946426, (2022) https://doi.org/10.1080/23746149.2021.1946426. Accessed November 14, 2024.

[65] Vector Atomic "Infinitesimal Forces. Enormous Impact." https://vectoratomic.com/#inertial_section; M. Swayne "Boeing's Quantum-based Navigation System Takes Flight in Historic Test," Quantum Insider (August 9, 2024) https://thequantuminsider.com/2024/08/09/boeings-quantum-based-navigation-system-takes-flight-in-historic-test/; M Squared, "Quantum Accelerometer" https://m2lasers.com/quantum-accelerometer.html. iXblue "A leap towards quantum inertial sensing for onboard applications with atom interferometry" (July 31, 2024). https://www.ixblue.com/north-america/a-leap-towards-quantum-inertial-sensing-for-onboard-applications-with-atom-interferometry/; Q-CTRL, "Detect the undetectable," https://q-ctrl.com/q-ctrl-sensing. All accessed November 14, 2024.

[66] Q-CTRL, "Detect the undetectable."

interferometers use lasers to manipulate the atom clouds and collect data, which requires a sophisticated optics setup and specialized electronics.[67] Engineering the laser setup so that it is optimized for performance while maintaining a small spatial footprint is its own area of research, often referred to as "integrated photonics." More progress in integrated photonics engineering will be needed to continue decreasing SWaP-C and facilitate a prototype that can be manufactured at scale.

Figure 2. Picture depicting Q-CTRL's compact, 3-axis quantum IMU.[68]

INSs Still Rely on Other Means of Navigation

Even with quantum sensing's ability to extend the holdover time of INS systems, inertial navigation will still require consistent, though less frequent, recalibration to a known location. These systems cannot be a substitute for GPS signals on their own. However, they provide the foundation to effectively leverage as many other available navigation techniques as possible. The next two sections will cover how two other forms of quantum sensors can contribute to additional layers of navigation. Quantum IMUs are not yet positioned to displace classical IMUs, which remain essential for navigation needs. However, advancements in engineering such as integrated photonics may eventually lead to affordable, short-duration quantum IMUs in the future.

[67] R. Geiger, A. Landragin, S. Merlet et al. High-accuracy inertial measurements with cold-atom sensors. AVS Quantum Sci. (2020);2:24702. https://arxiv.org/abs/2003.12516. Accessed November 14, 2024.
[68] Q-CTRL, "Detect the undetectable."

Atomic Clocks

- *Atomic clocks provide precise timekeeping. Next-generation optical atomic clocks and chip-scale atomic clocks (CSACs) offer superior precision and portability, respectively.*

Atomic clocks are quantum timekeeping devices that were first developed in the 1940s and are now widely used around the world and in space for precise time measurement.[69] GPS satellites use atomic clocks to provide timing information in their signals, which ensures that everyone is operating on the same clock (to within 30 ns).[70] The synchronized timing information provided by GPS is essential for many military systems. This capability allows various sensors' data to be fused into a coherent series of events, facilitates coordinated precision strikes, and even helps define the frequency needed to transmit, receive, or disrupt communications.[71] When GPS signals are unavailable, these capabilities would be degraded, endangering mission success. Fortunately, the solution to losing GPS timing information is having a high-performing local clock (immune to EW) available to step in and "hold over" until outside timing information is received again, just like the IMU systems discussed in the previous section. The IMU itself would also require local time readings from a clock to calculate the vehicle's movements. This quantum technology is already either available or in the prototype stage, having benefitted from decades of investment and effort.

Though atomic clocks already set the standards for stability and accuracy, they continue to improve due to the rising interest and investment in quantum sensing. Next-generation optical atomic clocks are being explored as eventual replacements for the clocks on GPS satellites, once they are sufficiently miniaturized and ruggedized.[72] Meanwhile, researchers are pushing the limits on short-term stability and accuracy for current-generation atomic clocks mounted on a small chip.[73] These emerging prototypes have the potential to dramatically improve performance both onboard GPS satellites and in GPS-denied environments.

Next-Generation Quantum Optical Clocks:

Optical clocks represent the latest generation of quantum atomic clocks, offering vastly superior accuracy and stability. Similar to the IMU, even the highest-performing clocks require calibration.

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[69] "A Brief History of Atomic Time," NIST (October 7, 2024). https://www.nist.gov/atomic-clocks/brief-history-atomic-time. Accessed February 11, 2025.

[70] "GPS Accuracy," GPS.gov.

[71] Tom Hawkes and Blake McMahon "Time Warfare: Threats to GPS Aren't Just About Navigation and Positioning," Defense One (May 10 2017) https://defenseone.com/ideas/2017/05/time-warfare-anti-gps-arent-just-about-navigation-and-positioning/137724/; John Delcolliano and Paul Olson, "It's About Time – All of It," U.S. Army (July 19, 2016). https://www.army.mil/article/171743/its_about_time_all_of_it. Both accessed Jan 1, 2025.

[72] "Providing GPS-quality timing accuracy without GPS," DARPA (January 20, 2022). https://www.darpa.mil/news/2022/accuracy-without-gps. Accessed January 1, 2025.

[73] "DARPA Making Progress on Miniaturized Atomic Clocks for Future PNT Applications" DARPA (August 20, 2019). https://www.darpa.mil/news/2019/miniaturized-atomic-clocks. Accessed November 27, 2024.

For vehicles operating in a chronically GPS denied environment, such as submarines, and on GPS satellites themselves, having a clock that can maintain a precise and accurate time for days to weeks is immensely valuable. However, these high-stability clocks tend to have poor enough SWaP-C to discourage mass production and distribution.

GPS satellites use mostly Rubidium-based atomic clocks to inform their PNT signals. These timepieces work by exposing a prepared Rubidium gas to microwave radiation tuned to maximize the gas's energy absorption at a specific quantum transition. This finely tuned frequency determines the clock's "tick."[74] Without recalibrating to a control tower, the clocks in current GPS satellites will drift at a rate of a few ns or roughly 1 m in positional error per day.[75] Optical clocks have a similar setup of atomic gas, but instead use a quantum transition that happens with light. Light occupies a higher frequency band than microwave radiation and therefore allows for over 100 times higher precision than a normal atomic clock, in part due to the shorter "ticks."[76] However, optical clocks require laser cooling the atomic gas and extra infrastructure for distinguishing the clock's minuscule ticks, which presents challenges for moving this technology out of the lab.

The United States' R&D ecosystem is pursuing solutions. Vector Atomic, a California-based startup, has been pioneering ruggedized versions of many different quantum sensors for PNT applications. Their portfolio includes optical clock prototypes, which were successfully tested at the July 2022 RIMPAC Military Exercise. During the demonstration, three shoebox-sized, rack-mounted timepieces were sent to sea aboard a naval ship and operated for 20 days with less than 0.3 ns of drift per day (a 10x improvement over Rubidium atomic clocks).[77] Such a device would be an excellent holdover timepiece in a GPS-denied scenario. The Vector Atomic team has already implemented several upgrades to improve accuracy and SWaP. They hope future models of their device could be used to replace the Rubidium clocks aboard GPS satellites.[78] Upgrading GPS to optical clocks could push positional accuracy (when signals are available) down to a centimeter. Similar ruggedized optical clock prototypes are also being developed at other startups such as Infleqtion (Tiqker, flight tested in the UK) and QuantX (Tempo, based in Australia) and at NASA.[79]

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[74] R. Beard and K. Senior, "Clocks," in *Springer Handbook of Global Navigation Satellite Systems*. P.J Teunissen, and O. Montenbruck, eds. (Cham Switzerland: Springer, 2017) pp 121-164. https://doi.org/10.1007/978-3-319-42928-1_5.
[75] "Rubidium Clock: A Workhorse with Many Uses," NIST (August 22 2024). https://www.nist.gov/atomic-clocks/clocks-galore. Accessed January 2, 2025.
[76] "World's Most Accurate and Precise Atomic Clock Pushes New Frontiers in Physics," NIST (July 1, 2024). https://www.nist.gov/news-events/news/2024/07/worlds-most-accurate-and-precise-atomic-clock-pushes-new-frontiers-physics. Accessed January 2, 2025.
[77] J.D Roslund, A. Cingöz, W. D. Lunden, *et al*. "Optical clocks at sea"
[78] Elizabeth Gibney, "Atomic clock keeps ultra-precise time aboard a rocking naval ship" Nature News (April 24, 2024). https://www.nature.com/articles/d41586-024-01166-6. Accessed November 27, 2024.
[79] Dina Genkina, "Startups squeeze room-size optical atomic clocks into a briefcase," IEEE Spectrum (October 15, 2024). https://spectrum.ieee.org/optical-atomic-clocks. Matthew Kaufman, "Reinventing the

The tech needed to achieve reliable timekeeping for GPS-denied situations is quickly becoming commercially available. DOD should ensure that these products successfully pass the "Valley of Death" and can be integrated into the military's infrastructure.

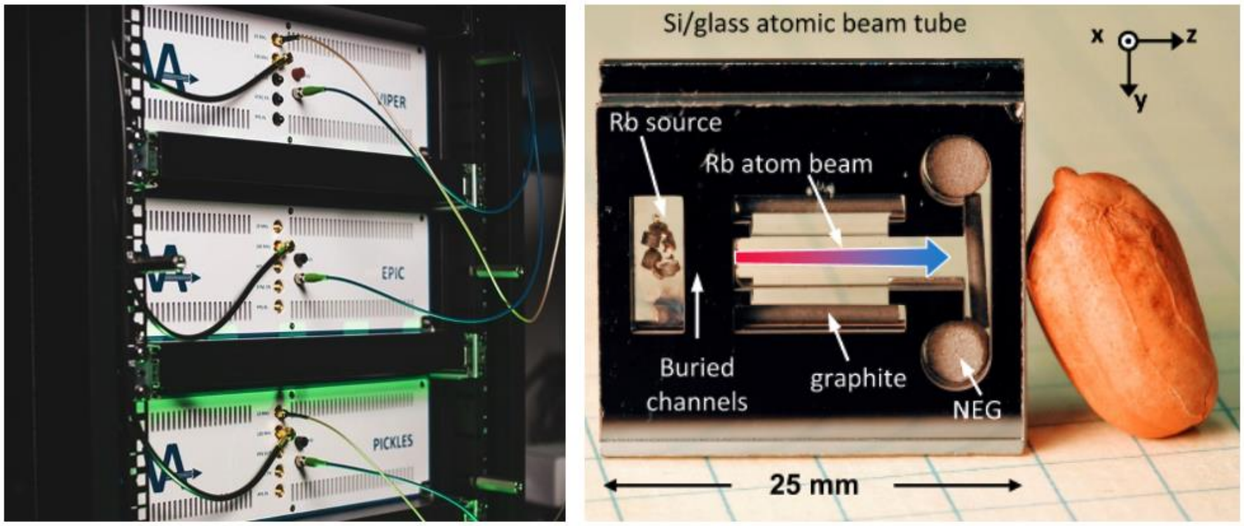

Figure 3. Left: three rack-mounted optical clock prototypes fielded by Vector Atomic during the RIMPAC Exercise.[80] *Right: Chip-scale rubidium atomic clock prototype developed by NIST.*[81]

Chip-Scale Atomic Clocks (CSAC)

CSACs are specialized quantum atomic clocks that have been miniaturized to roughly the size of a coin, making them easy to integrate into a wide range of devices and vehicles while maintaining precise timekeeping. CSACs have already been on the market for over 10 years and serve as short-term timing holdovers in GPS-denied scenarios for portable, battery-powered devices. The ongoing development of this technology has been spearheaded by the (Defense Advanced Research Projects Agency) DARPA. After funding development of first-generation chip-based atomic clocks in the early 2000s (NIST: ~10 μs drift per day), the agency recently finished its next-generation CSAC program, called Atomic Clocks with Enhanced Stability (ACES).[82] ACES aimed to create devices with 1000 times improvement in performance over the original CSACs (that used less than 0.25

Clock: NASA's New Tech for Space Timekeeping," NASA (September 18, 2024). https://www.nasa.gov/technology/reinventing-the-clock-nasas-new-tech-for-space-timekeeping/. Both accessed January 2, 2025.

[80] Elizabeth Gibney, "Atomic clock keeps ultra-precise time aboard a rocking naval ship." Image credit: Will Lunden.

[81] G.D. Martinez, C. Li, A. Staron, et al. "A chip-scale atomic beam clock." *Nat Commun* **14**, 3501 (2023). https://doi.org/10.1038/s41467-023-39166-1. Accessed January 11, 2025.

[82] "NIST Unveils Chip-Scale Atomic Clock," NIST (August 27 2024). https://www.nist.gov/news-events/news/2004/08/nist-unveils-chip-scale-atomic-clock. Accessed January 1, 2025.

Watts of power and fit in a person's hand).[83] Three separate research teams, led by NIST, Honeywell, and NASA's Jet Propulsion Lab (JPL) were awarded ACES contracts and all demonstrated substantial progress in just a few years.[84] In 2020, the Army initiated a separate development call for a low-cost CSAC priced under $300 per unit, with SWaP that matched or exceeded the best commercially available options.[85] DARPA is continuing to push development of CSACs, this time with a program named "H6." This endeavor was announced in 2022 and aims to create third-generation CSACS that have less than 1 µs drift per week in an easily fieldable package at a wide temperature operation range.[86] The contracts were awarded to HRL Laboratories (partially owned by Boeing) and Northrop Grumman, with work beginning in early 2023.[87]

DARPA's transition from funding mostly academic and government institutions to fully embracing corporate research centers is a strategic one. By moving CSAC prototype development to companies that participate in manufacturing, the evolution to a scalable commercial product will be more efficient. Companies that have established offices with experience navigating DOD's acquisition process will also see their products approved more quickly. Since companies like Honeywell, Northrup Grumman, and Boeing already serve as DOD suppliers, they could also directly incorporate their CSAC designs into equipment they are tasked with manufacturing for the U.S. military. All these factors will immensely hasten the process of fielding CSACs. The timing resiliency they deliver will help ensure the continued security and assurance of communication in GPS-denied situations. There is still plenty more room for further CSAC development, with even optical clocks being considered for chip-mounting.[88] In the meantime, if the CSAC devices developed via ACES and H6 are successfully fielded, their path could serve as a model for implementing other quantum technologies.

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[83] "Reducing Tics in the Tocks of Atomic Clocks," DARPA (December 23, 2015). https://www.darpa.mil/news/2015/atomic-clock. Accessed January 2, 2025.
[84] "DARPA Making Progress on Miniaturized Atomic Clocks for Future PNT Applications," DARPA.
[85] "Low-Cost Chip-Scale Atomic Clock (LC CSAC)," Grants.gov (June 22, 2020). https://grants.gov/search-results-detail/326841. Accessed June 2 2025.
[86] "H6 program fields proposals for GPS-independent clocks that sustain weeklong microsecond timing to support mission success," DARPA (May 17, 2022). https://www.darpa.mil/news/2022/tactical-grade-clock. Accessed January 3, 2025.
[87] "H6, ID: HR001122S0038, Contract Awards" HigherGov (May 17, 2022). https://www.highergov.com/contract-opportunity/h6-hr001122s0038-p-2cf79/. Accessed January 2, 2025.
[88] J. Kitching, M. Hummon, W. McGehee, Y. Wang, and S. Schima, "Next-Generation Chip-Scale Atomic Clocks", Proceedings of the 9th Symposium on Frequency Standards and Metrology: Kingscliff, AU (October 16, 2023). https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=957364. Accessed January 2, 2025.

Magnetometers

- *Magnetometers navigate using Earth's magnetic field, achieving accuracy on the order of 100s of meters with detailed maps. Well suited for airborne vehicles, with ongoing R&D for chip-scale versions that could be used for munitions and drones.*

Of the PNT-related quantum sensors presented in this report, magnetometers have the largest untapped potential. The U.S. Air Force in particular has been spearheading research and flight demonstrations using this technology for the past few years. There are several types of quantum magnetometers, ranging from decades-old designs to new prototypes still under development. Notably, the next generation of quantum magnetometers could be miniaturized to a chip. This configuration would enable guided munitions, drones, and planes to fly with a consistent backup to GPS. Magnetic navigation (MagNav) is particularly attractive because it works any time of day, in any weather, and anywhere on Earth while being immune to the usual methods of electronic warfare. Early tests achieved accuracies within 10 meters (~2 times that of GPS) in highly optimized conditions, with realistic expected accuracies on the order of 100s of meters eventually possible.[89]

How it works:

Over millennia, the magnetization of different materials in Earth's crust by the core, north-pointing magnetic field created distinct magnetic features that vary based on location and are static over many human lifetimes. Compiling these features into a map would enable navigation to specific coordinates rather than a general direction (as with a compass). Many countries, including the United States, have created maps of these magnetic "anomaly" fields over their land to locate minerals for mining (see Figure 4).[90]

[89] Aaron Canciani and Christopher Brennan, "An Analysis of the Benefits and Difficulties of Aerial Magnetic Vector Navigation," *IEEE Trans. Aerosp. Electron. Syst.* 56, no. 6 (2020), pp 4161-4176. https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9076056. Accessed October 28, 2024.
[90] U.S. Environmental Protection Agency, "Magnetic Method" (June 17, 2024). https://www.epa.gov/environmental-geophysics/magnetic-method. Accessed October 26, 2024.

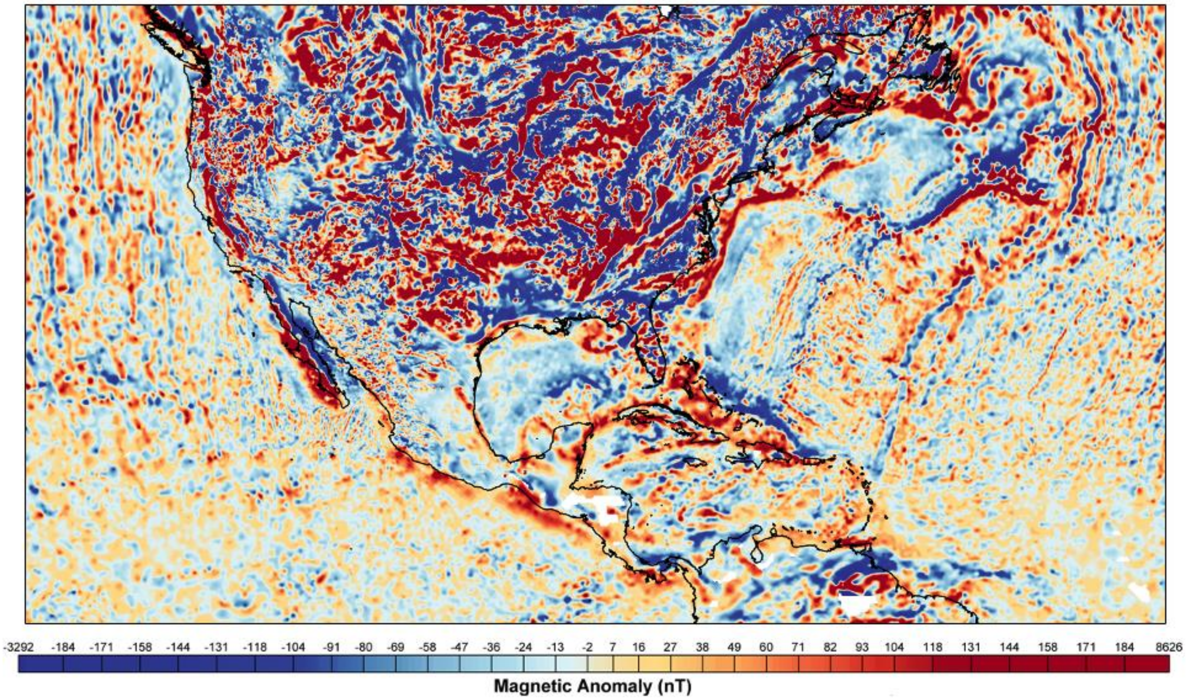

Figure 4. Map of North America's magnetic crustal anomaly field (EMAG2v3) at 4 km altitude[91]

Once formed over geological timescales, magnetic signatures in the Earth's crust cannot be erased or significantly altered by any man-made technology, since a field's strength diminishes rapidly as distance from the source increases. [92] Any adversary attempts to alter the magnetic signature of the Earth's crust would be impossible.

There are other, natural, time-varying sources of magnetic fields (such as space weather and currents in the Earth's mantle) that would need to be accounted for when utilizing magnetic maps. Fortunately, there is a sweet spot between a couple hundred meters and a few kilometers above Earth's surface where contributions from time-dependent magnetic fields and man-made structures are minimized and the crustal anomaly field shines through.[93] This makes MagNav particularly attractive for arial vehicles and guided munitions, provided the quantum sensors can meet the stringent SWaP requirements they require. MagNav is still possible close to Earth's surface, though accuracy may be more limited. Using the magnetic anomaly field for navigation provides the greatest advantage over water, where visible landmarks are unavailable. Some

[91] "Earth Magnetic Anomaly Grid (EMAG) 2" NOAA National Centers for Environmental Education. https://www.ngdc.noaa.gov/geomag/data/EMAG2/EMAG2_V3_upcontposter.png. Accessed January 11, 2025.
[92] The magnetic field strength of a double-poled magnet decreases as the inverse distance cubed ($1/R^3$). The field strength 2 meters away from the source will be 1/8 as strong as 1 meter away.
[93] Aaron Canciani, "Magnetic Navigation Overview;" Neil Claussen *et al.* "Magnetic Navigation for GPS-Denied Airborne Applications," Sandia National Laboratories, (October 16, 2020). https://www.osti.gov/servlets/purl/1817974 Accessed October 28, 2024.

preliminary experiments using a submarine and a (non-magnetic) wooden ship have been attempted, but more research will be needed.[94]

Flight tests with first-generation quantum magnetometers

Most of the recent MagNav flight demonstrations have used cesium or rubidium vapor-cell magnetometers.[95] These quantum sensors have been around for decades and are already commercially available at performance levels required for navigation (an example is shown in Figure 5). Under a narrow range of near-perfect conditions, these sensors can navigate accurately to within a range of 10s of meters.[96]

However, better MagNav performance will be needed for the chronically un-optimized conditions conflict usually presents. Many of the highest-performing flight tests kept to low altitudes, employed specialized (non-magnetic) geosurvey planes, and constructed exquisitely accurate maps from extensive flight surveys beforehand.[97] In order to make MagNav practical:

- The magnetic fields generated by the aerial vehicles movement must be filtered from the sensor's readings.
- The sensors must be stable enough to measure frequency data from the magnetic anomaly field on the order of millihertz.
- Sufficiently detailed magnetic anomaly maps must be available for locations the vehicle is traveling in.

Fortunately, separating the plane's magnetic field and removing it from the sensor's readings, (so it can't be confused with the Earth's field) is already being addressed using advanced software

[94] P. Frontera, S. Alessandrini and J. Stetson, "Shipboard calibration of a diamond nitrogen vacancy magnetic field sensor," *2018 IEEE/ION Position, Location and Navigation Symposium (PLANS)*, Monterey, CA, USA, 2018, pp. 497-504, doi:10.1109/PLANS.2018.8373418. Accessed October 28, 2024; Aaron Canciani, "Magnetic Navigation Overview."
[95] Taylor Lee, "Aerial Simultaneous Localization and Mapping Using Earth's Magnetic Anomaly Field," Air Force Institute of Technology, (March 21, 2019), https://apps.dtic.mil/sti/tr/pdf/AD1075642.pdf. (Accessed October 28, 2024); Albert Gnadt, "Advanced Aeromagnetic Compensation Models for Airborne Magnetic Anomaly Navigation," Massachusetts Institute of Technology, (May 2022). https://dspace.mit.edu/handle/1721.1/145137. Accessed October 28, 2024.
[96] Aaron Canciani, "Magnetic Navigation Overview;" Aaron Canciani and Christopher Brennan, "An Analysis of the Benefits and Difficulties of Aerial Magnetic Vector Navigation."
[97] Albert Gnadt *et al.* "Signal Enhancement for Magnetic Navigation Challenge Problem," *arXiv*, pp. 1–12, 2023, doi:10.48550/arXiv.2007.12158. (Accessed October 28, 2024)

solutions.[98] The other two limitations require greater magnetometer capability, which will be enabled by the next generation of quantum sensors.

More information and higher performance:

The vapor cell quantum sensors used for previous flight tests measure only magnetic field strength (often referred to as "scalar" sensors). Most currently available magnetic anomaly maps also only contain the field's strength. However, magnetic fields have both strength and direction, which means a substantial amount of positioning information is being left unused. Most MagNav demonstration flight tests pair highly stable quantum magnetometers that measure field magnitude with low-SWaP, non-quantum, commercial fluxgate magnetometers, which measure both the direction and magnitude (known as "vector" sensors). These vector sensors were primarily used to isolate the aircraft's induced magnetic field from Earth's field, however, suffer from considerable drift and cannot be used solely for navigation.[99] If a vector sensor with sufficient bias stability were available (likely with quantum technology), simulations suggest that positional accuracy could improve by a factor of 2 to 3, with up to two orders of magnitude improvement in altitude accuracy.[100]

Several types of vector quantum magnetometers are being considered to replace their scalar, vapor-cell predecessors, with nitrogen-vacancy (NV) center diamond quantum magnetometers emerging as the leading candidate. Lab prototypes have demonstrated sensitivities and bandwidths that meet or exceed the requirements for MagNav.[101] These sensors also operate across a wide temperature range without needing a gas-filled cavity (also called "solid-state"). Thus, with sufficient miniaturization of the laser optical fiber systems, the sensor could eventually be integrated entirely on a chip. There is extensive research and some commercial projects, like Lockheed Martin's "Dark Ice," focused on applying NV center magnetometers for navigation.[102]

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[98] "MagNav project successfully demonstrates real-time magnetic navigation" Department of the Air Force-Massachusetts Institute of Technology AI Accelerator (May 26, 2023). https://www.af.mil/News/Article-Display/Article/3408951/magnav-project-successfully-demonstrates-real-time-magnetic-navigation/. Accessed October 28, 2024.

[99] Another common, non-quantum, vector magnetometer with stability and sensitivity comparable to the vapor cells is a superconducting quantum interference device or SQUID. These do not have low enough SWaP to be considered for flight.

[100] Aaron Canciani and Christopher Brennan, "An Analysis of the Benefits and Difficulties of Aerial Magnetic Vector Navigation"

[101] Zhecheng Wang *et al.* "Picotesla magnetometry of microwave fields with diamond sensors," *Sci. Adv.* **8**, eabq8158 (2022). DOI:10.1126/sciadv.abq8158. Accessed October 28, 2024.

[102] "Tech That's Cool as [Dark] Ice," Lockheed Martin (April 1, 2019). https://www.lockheedmartin.com/en-us/news/features/2019-features/tech-thats-cool-as-dark-ice.html. Accessed October 28, 2024.

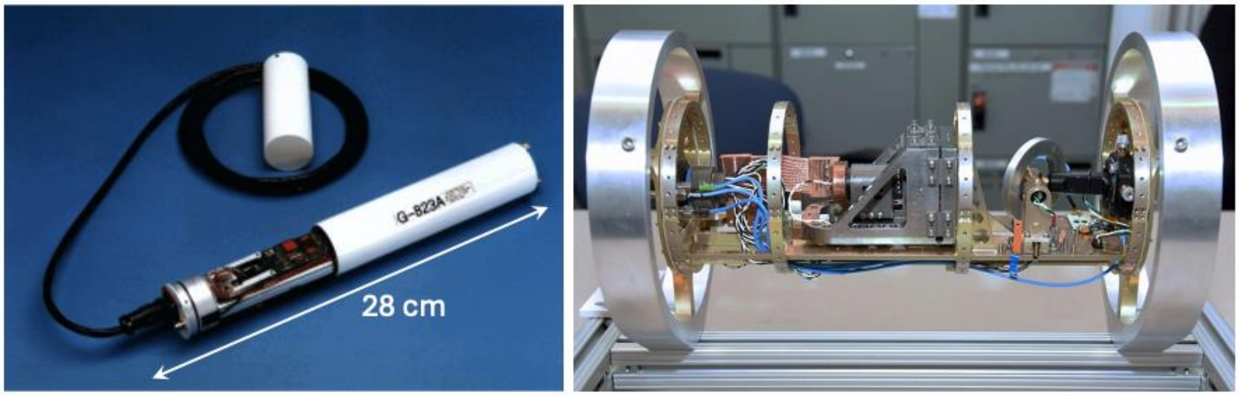

Figure 5. Left: Geometrics cesium atomic vapor cell magnetometer (G-823A) used for MagNav demonstration flight tests.[103] *"Dark Ice" NV center diamond magnetometer prototype developed by Lockheed Martin.*[104]

Another promising, but under-researched option includes the similar, Silicon-Vacancy centers in Silicon Carbide (SiC), which could use electronic signals rather than lasers to effectively read out data.[105] This could enable reaching SWaP requirements for a chip-based magnetometer sooner and allow already-existing silicon microchip facilities to quickly manufacture devices at scale. Though SiC does not currently boast the same sensitivity as NV diamonds, substantial gains still being reported.[106] Another possible next-generation magnetometer under development is a more sophisticated atomic vapor cell that could operate as a full vector sensor.[107] Though the vector vapor cell sensor would not be a solid-state device, significant commercial development is in progress.

Map-making and reading:

MagNav only works if there is a sufficiently high-resolution map. In order to achieve the highest accuracy in navigation, high-accuracy vector magnetometers, likely quantum-based, will be needed to construct these maps.[108] The data for magnetic map-making will likely be supplied by a variety of sensors on vehicles crossing the globe by land, air, sea, and in space, with different

[103] "Geometrics G-823 Cs Magnetometer," GeoRESULTS. https://www.georesults.com.au/products/p/g-823. Accessed January 11, 2025; Aaron Canciani, "Magnetic Navigation Overview.
[104] "Tech That's Cool as [Dark] Ice," Lockheed Martin.
[105] S Castelletto *et al.* "Quantum systems in silicon carbide for sensing applications." *Rep. Prog. Phys.* **87** 014501 (2024). https://iopscience.iop.org/article/10.1088/1361-6633/ad10b3. Accessed October 29, 2024.
[106] I. Lekavicius *et al*. "Magnetometry Based on Silicon-Vacancy Centers in Isotopically Purified 4H-SiC," *Phys. Rev. Applied* **19**, 044086 (2023). https://link.aps.org/doi/10.1103/PhysRevApplied.19.044086 Accessed October 29, 2024.
[107] Tadas Pyragius *et al.* "Voigt-effect-based three-dimensional vector magnetometer," *Phys. Rev. A* **100**, 023416 (2019) https://link.aps.org/doi/10.1103/PhysRevA.100.023416. Accessed October 29, 2024.
[108] Quantum Economic Development Consortium (QED-C). "Quantum Sensing for Position, Navigation, and Timing Use Cases." Arlington, VA. September 2024. https://quantumconsortium.org/pnt2024. Accessed October 28, 2024.

specifications for each environment. Collecting and standardizing the map data from so many sources will also be a significant logistical challenge.[109] On the aerial vehicle itself, utilizing the data from either a vector or scalar map requires sufficiently fast and accurate readings of the altitude (which a magnetometer does not measure). This information could be supplied by either an altimeter or IMU. Finally, deploying multiple sensors at various locations on the vehicle has the potential to better filter out the aircraft's magnetic field interference, though this strategy has not yet been flight tested.[110]

While MagNav will not reach the level of accuracy provided by GPS signals, early tests have demonstrated promising results, with accuracies on the order of 100s of meters using current technology. Given MagNav's drift-free nature, reliable performance over oceans, and potential for improvement, continued R&D in this form of navigation is a worthy investment.[111]

Gravimeters

- *Gravimeters navigate using Earth's gravitational field. Best suited for ships and submarines. Positioning accuracies are limited by map resolution (1 nautical mile).*[112]

Utilizing variations in Earth's gravity is another potential method of map-matching navigation that is immune to jamming and spoofing. The GravNav approach is particularly beneficial for vehicles traveling underwater, such as submarines and underwater autonomous vehicles (UAVs). GPS signals lose their strength quickly in water, so undersea vehicles must already rely heavily on dead-reckoning navigation using INS, which requires regular resetting to a known location.[113] Recalibrating via outside signal, such as resurfacing to use GPS or employing sonar to identify underwater features risks exposing a covert vehicle.[114] MagNav, though still possible, would be more susceptible to time-dependencies in the magnetic field Earth's mantle currents, which would make map-matching more difficult. Thus, GravNav becomes one of the best options for aiding INS underwater while also serving as an attractive supplement to MagNav on surface ships.

[109] Quantum Economic Development Consortium (QED-C). "Quantum Sensing for Position, Navigation, and Timing Use Cases."
[110] Measuring the change in magnetic field extracts even more information from the Earth's magnetic field, leading to even further potential improvements in accuracy. For scalar sensors, this information is called the "scalar gradient" and for vector sensors, it is called "tensor."
[111] Aaron Canciani and Christopher Brennan, "An Analysis of the Benefits and Difficulties of Aerial Magnetic Vector Navigation."
[112] "Vector Atomic Validates Quantum Navigation Sensor at Sea," BusinessWire.
[113] See earlier section on inertial measurement units. A strategic-grade INS that might be found on a submarine would give readings that drift away from the true location on the order of 1 mile per day.
[114] Alexander M. Phillips, Michael J. Wright, Isabelle Riou, Stephen Maddox, Simon Maskell, Jason F. Ralph, "Position fixing with cold atom gravity gradiometers." *AVS Quantum Sci.* 1 June 2022; 4 (2): 024404. https://doi.org/10.1116/5.0095677 Accessed November 22, 2024.

How it works:

GravNav shares many characteristics with MagNav. Like Earth's magnetic field, the strength of Earth's gravity varies slightly by location due to terrestrial features like mountains, valleys, and heavy-metal deposits. However, gravitational changes are weaker and occur over longer distances than magnetic anomalies. The sparse signals limit GravNav's precision and require more measurement time and distance to be covered (tens of miles, or hours to days) for gathering sufficient data to deliver a location reading.[115] Using multiple, spaced-out gravimeter sensors to create a gradiometer can enhance location precision significantly. A global map with 1 nautical mile resolution of Earth's gravitational variations, compiled from satellite data by the International Geometric Bureau, is readily accessible online.[116] If IMU data is processed alongside data from a gravity map, it can better isolate accelerations from the vehicle, further reducing navigation errors.

How Quantum Gravimeters Can Contribute:

Quantum gravimeters and gradiometers have already surpassed their classical counterparts in sensitivity, fieldability, and accuracy, promising a substantial upgrade to the utility of GravNav. The idea of gravity-aided inertial navigation using classical sensors has been around for several decades.[117] However, the classical devices with sufficient sensitivity for the job, such as falling corner cubes and spring-based sensors, are informed by moving mechanical parts. These components have heavily degraded performance in vibrating environments, wear out quickly, and in some cases, also require consistent recalibration.[118] By contrast, none of those issues are present when a quantum atom interferometer sensor (previously discussed in the IMU section) is used to measure gravity instead. These atomic gravimeters are becoming increasingly compact and ruggedized, require no recalibration, and already offer better long-term stability and higher precision than their classical counterparts despite being a relatively immature technology.[119]

Fielded Quantum Gravimeters and Future Work:

Just like their IMU counterparts, fieldable quantum atom interferometer gravimeters are under rapid development all over the world, with many startups and research groups producing and fielding

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[115] B. Wang, T. Cai and K. Fang, "The Quantification Method of Matching Capability of Areas in Gravity-Aided Inertial Navigation," in *IEEE Sensors Journal*, vol. 22, no. 21, pp. 20958-20967 (2022), https://ieeexplore.ieee.org/document/9906791. Accessed November 23, 2024.

[116] S. Bonvalot *et al.* (2012). World Gravity Map WGM2012. Bureau Gravimétrique International. https://doi.org/10.18168/bgi.23. Accessed November 23, 2024.

[117] Albert Jircitano, and Daniel E. Dosch, "Gravity Aided Inertial Navigation System (GAINS)," *Proceedings of the 47th Annual Meeting of The Institute of Navigation (1991)*, Williamsburg, VA, June 1991, pp. 221-229. https://www.ion.org/publications/abstract.cfm?articleID=4955. Accessed November 23, 2024.

[118] C. Freier *et al,* "Mobile quantum gravity sensor with unprecedented stability." *J. Phys.: Conf. Ser.* **723** 012050 (2016). https://iopscience.iop.org/article/10.1088/1742-6596/723/1/012050/pdf. Accessed November 23, 2024.

[119] Jie Fang *et al.* "Classical and Atomic Gravimetry" *Remote Sensing* 16, no. 14: 2634 (2024). https://doi.org/10.3390/rs16142634. Accessed November 25, 2024.

prototypes. Within the United States, a high-performing gravimeter produced by the startup company Vector Atomic was recently fielded aboard a ship for a multi-week voyage during RIMPAC 2022, where their device's accuracy matched that of available maps.[120] Similar demonstrations have been performed by groups in the UK, France, Australia, and China, to name a few.[121] Given the success of these demonstrations, a substantial amount of funding is actively flowing to this area of technology, which will accelerate the process of development, ruggedizing, and scaled manufacturing.

Figure 6. Gravimeters developed for PNT by US-based startups Vector Atomic (left) and AOSense (right).[122]

There is still much work to be done on miniaturizing the laser systems and electronics for the interferometers, as well as software development for filtering out noise and extracting better measurements. However, even with the best sensor, GravNav's accuracy is currently limited to the best-resolved available gravimetric map of Earth, particularly over the oceans, which is about 1 nautical mile (1.852 km).[123] Creating higher-resolution maps of the oceans would require either

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[120] "Vector Atomic Validates Quantum Navigation Sensor at Sea," BusinessWire.
[121] University of Birmingham, "Quantum sensor for gravity gradiometry successfully validated at sea," (September 18 2023) https://www.birmingham.ac.uk/news/2023/quantum-sensor-for-gravity-gradiometry-successfully-validated-at-sea; Y. Bidel, N. Zahzam, C. Blanchard *et al*. Absolute marine gravimetry with matter-wave interferometry. *Nat Commun* **9**, 627 (2018). https://doi.org/10.1038/s41467-018-03040-2; Q-CTRL "Q-CTRL Sets Global Quantum Technology Fundraising Record, Increasing Series B to USD $113M, Led by GP Bullhound," https://q-ctrl.com/blog/q-ctrl-sets-global-quantum-technology-fundraising-record-increasing-series-b-to-usd-113m-led-by-gp-bullhound; B. Wang, Z. Ma, L. Huang, Z. Deng and M. Fu, "A Filtered-Marine Map-Based Matching Method for Gravity-Aided Navigation of Underwater Vehicles," in *IEEE/ASME Transactions on Mechatronics*, vol. 27, no. 6, pp. 4507-4517, Dec. 2022. https://ieeexplore.ieee.org/document/9744408. All accessed November 25 2024.
[122] Vector Atomic "Infinitesimal Forces. Enormous Impact"; "Gravimeter," AOSense. https://aosense.com/products/atom-optic-sensors/gravimeter/. Accessed January 11 2025.
[123] J. Kohler *et al.* "Performance Validation of a Strapdown Absolute Quantum Gravimeter for Gravity-aided Inertial Navigation;" World Gravity Map WGM2012. Bureau Gravimétrique International

more sophisticated satellite data or having thorough gravimetry measurements collected by all manner of nautical vessels and assembled into a database.[124]

Policy Options and Future Steps

- *The extensive GPS M-code upgrade will still be vulnerable to EW and space-based attacks.*
- *Startup companies are leading many alternate PNT quantum sensing R&D efforts; several prototypes were fielded during the Rim of the Pacific (RIMAC) Military exercise in 2022.*
- *The market dies without DOD: it should engage with quantum sensing startup companies developing alternate-PNT prototypes to ensure products traverse the "valley of death."*
- *If China surpasses the U.S in quantum sensing alternate PNT and eliminates the need for GNSS signals in combat first, it will gain a significant advantage in future conflicts.*
- *Dedicated DOD technical leadership, separate from the PNT Oversight Council, should be allocated to efficiently leverage the widespread domestic and allied quantum sensing PNT R&D efforts so it reaches a point of GNSS non-reliance before China does.*
- *DOD should leverage the GPS M-Code upgrade to enable infrastructure compatible with multiple PNT sources, ensuring seamless future integration of quantum sensing devices.*

DOD is currently investing most of its PNT-dedicated attention to a GPS upgrade that will make military-specific (M-Code) signals stronger and less susceptible to jamming and spoofing.[125] The project has been ongoing for more than two decades, is experiencing significant delays, and continues to run over-budget.[126] Once implemented, M-Code will still fail to address the Joint Force's vulnerability to GPS denial and will perpetuate GPS over-reliance. The updated system will remain susceptible to cyberattacks and anti-satellite warfare, possibly including Russia's nuclear-enabled satellite.[127] It may only be a matter of time before adversaries find a way to jam and spoof the new signals as well.

Greater attention is needed for a long-term solution that ensures mission success even when GPS signals are denied due to localized attacks or widespread outages. Having a fully resilient PNT capability would ensure an adversary's gain from initiating a widespread GPS outage or space-based attack would be small compared to the cost. While no single alternative can match GPS's

[124] Quantum Economic Development Consortium (QED-C). "Quantum Sensing for Position, Navigation, and Timing Use Cases"
[125] U.S. Government Accountability Office, *GPS Alternatives: DOD is Developing Navigation Systems but is Not Measuring Overall Progress,* GAO-22-106010 (August 5 2022). https://www.gao.gov/assets/d22106010.pdf. Accessed January 4, 2025.
[126] U.S. Government Accountability Office, *GPS Modernization: Delays Continue in Delivering More Secure Capability for the Warfighter,* GAO-24-106841 (September 9, 2024). https://www.gao.gov/assets/gao-24-106841.pdf. Accessed January 4, 2025.
[127] "Nuclear Threats and the Role of Allies: A Conversation with Acting Assistant Secretary Vipin Narang." Center for Strategic and International Studies.

ubiquity and accuracy, a combination of alternate sources could suffice for most missions. Creating a truly resilient PNT capability deserves greater attention from DOD, considering the substantial time, learning, and recourses it will require.

Developing Quantum PNT Technology

The revolution in quantum technology is fueling accelerated R&D in sensing applications for PNT, which opens significant new opportunities that were impractical even a few years ago. Improvements in sensor precision have enabled map-matching with Earth's gravity and magnetic fields, which are un-jammable, un-spoofable all-weather positioning methods. Other quantum sensing technologies such as inertial measurement and timing have also recently demonstrated orders of magnitude improvement in performance and SWaP, enabling longer and more accurate holdover periods when GPS signals are lost.

Each of these technologies is at a different stage of maturity and there are many disparate R&D efforts from startups, universities, national labs, defense contractors, and each branch of the military ongoing in the United States. As a result, the potential for inefficiency and redundancy is exceptionally high. DOD leadership is desperately needed to deliver these capabilities more quickly.

The market dies without DOD.

There is currently little use for many PNT-related quantum sensing products outside of the military.[128] Thus, DOD must leverage its position as the market for these technologies. A primary vehicle for bringing prototypes out of the lab and into the commercial space are startups. Startup success mandates that prototypes progress through acquisition, manufacturing, and fielding stages, also known as the "Valley of Death."

Many of these startups are either partially or fully funded by private investors who tend to expect returns on the scale of a few years. Getting such specialized technology to the point of profitability will take much longer without substantial help and funding from DOD, which puts the startups at risk of failing. The usual startup routes of using the Small Business Innovation Research and Technology Transfer (SBIR/STTR) programs to receive grants from DOD are too small to sustain a quantum startup through the Valley of Death.[129] To fill the gap, DOD agencies have recently been

[128] Atomic clocks are an exception.

[129] "Small Business Innovation Research (SBIR)/Small Business Technology Transfer (STTR)," Department of the Air Force Office of Small Business. https://www.airforcesmallbiz.af.mil/SBIR-STTR/. Accessed January 5, 2024. Heather R. Penney, "The Quantum Advantage: Why it Matters and Essential Next Steps, Part 3: Operationalizing a Quantum Advantage" Mitchell Institute for Aerospace Studies (January 30, 2024). https://mitchellaerospacepower.org/the-quantum-advantage-why-it-matters-and-essential-next-steps/. Accessed January 5, 2025.

stepping up as direct investors to the most promising startups.[130] Once backed, DOD must ensure their startups are protected from lapses in government funding, which could endanger their liquidity.

During a startup's prototype development stage, DOD should ensure equal emphasis on achieving performance metrics while encouraging low SWaP-C routes, so scaling can more easily be achieved. Once startups reach the scaling stage, their resource needs must be closely monitored. Many quantum sensing prototypes use lasers, gas cells, and other unusual components that may require unprecedented manufacturing systems to be built from the ground up. Scaling quantum manufacturing will be costly for the DOD but could strengthen the U.S. quantum economy and benefit future products. To support startups, the DOD must either allocate resources and personnel to maintain a direct connection or strongly signal intent to procure a startup's products, so private investment is sustained. Ultimately, the cost will fall to the DOD, but shaping the market could yield returns as commercial sectors adopt low-SWaP-C, high-performance navigation technology.

Expanding R&D

There are still substantial gains to be made from basic R&D for quantum sensing products, particularly for magnetometers. Unfortunately, the community of scientists who have relevant expertise is small. This issue is one part of an acute nationwide shortage of quantum talent. The situation may eventually be addressed by the Chips and Science Act of 2022, which aims to integrate quantum science into STEM curricula.[131] On timescales that would make a difference in the race to field current quantum sensing PNT technology, more immediate solutions are required.

A short-term approach is to integrate more established scientists into the QIST workforce. Quantum physics spans many areas of basic modern research, including QIST. As funding for basic research has flattened while defense R&D funding has grown, entrepreneurial scientists are attempting to migrate toward QIST. While these newcomers bring fresh perspectives, they lack the highly specialized experience of established QIST scientists. DOD program managers should maintain ties with QIST experts while engaging newcomers, fostering collaboration, and leveraging resources like the National Quantum Information Research Centers and the DOD Center of Excellence in

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[130] "Vector Atomic" Pitch Book. https://pitchbook.com/profiles/company/462249-19#overview. Accessed Jan 4, 2025.

[131] J. Dickson and E. Harding, "Unleashing Quantum's Potential" Center of Strategic and International Studies (October 25, 2024). https://www.csis.org/analysis/unleashing-quantums-potential. Accessed January 6, 2025.

Advanced Quantum Sensing to facilitate knowledge transfer and integration into the QIST community.[132]

A bigger picture than just Quantum

"Quantum" may be an effective buzz word for attracting attention, but the many R&D routes towards fielding these sensors lie outside the quantum physics package. Funding programs within DOD that are building ruggedized quantum sensing products at scale should ensure they are informed on where the greatest needs are, so resources can be allocated accordingly.

Ensuring that supporting electronics and hardware for quantum sensing devices have necessary performance levels while maintaining reasonable SWaP-C will be crucial for fielding these devices quickly. Many sensors outlined in this article require lasers to perform operations, which are themselves expensive and complicated to manufacture. Recent progress in integrated photonics research (engineering laser/optics systems), has enabled some of the suitcase-sized atomic clock and IMU prototypes shown previously. There is still substantial room for improvement so further miniaturization or cheaper assembly can be achieved. Even small R&D investments in integrated photonics could eventually yield millions of dollars in savings when scaled manufacturing begins. Similar R&D investing arguments could be made for many other high-performance electronics used in a quantum sensing device.

Sophisticated software, potentially including AI, is essential for the success of quantum sensing, as quantum sensors generate vast amounts of data due to their extreme sensitivity. Local software will be required to filter useful PNT information from environmental noise and vehicle activity while reducing data storage demands. Software is relatively cheap to create, requiring only knowledgeable programmers and some computers. However, high-performing algorithms, particularly those using AI, require large datasets to distinguish desired signals from noise. This data must be gathered through frequent field testing of prototypes on real military vehicles. For example, the 2023 MagNav flight demonstration was a positive step, but many more magnetometer flights across various U.S. military aircraft are needed to build a robust database, ensuring the software can reliably differentiate a plane's magnetic field from Earth's. [133]

Highly precise maps of the Earth's magnetic anomaly and gravitational fields are essential for MagNav and GravNav navigation. Once sufficient SWaP-C is achieved, quantum sensors currently in development could also be deployed to collect map data. To expedite mapping, commercial

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[132] "National Quantum Information Science Research Centers," U.S. Department of Energy Office of Science. https://nqisrc.org/; "Defense Department Launches Center of Excellence in Advanced Quantum Sensing," Quantum.gov (April 27, 2021). https://www.quantum.gov/defense-department-launches-center-of-excellence-in-advanced-quantum-sensing/. Both accessed January 6, 2025.
[133] Department of the Air Force-Massachusetts Institute of Technology AI Accelerator, "MagNav project successfully demonstrates real-time magnetic navigation."

partners like airlines and cruises could contribute data through the Federal Aviation Administration or Coast Guard, providing magnetic and gravitational information with accurate GPS positioning.[134] For global coverage, especially in adversary-controlled regions, LEO satellites equipped with next-generation quantum sensors may be needed to gather mapping data. Both approaches would require dedicated DOD resources and personnel to execute the data collection and assembly.

Dedicated DOD leadership is needed

Delivering quantum-based alternate PNT devices within the next few years will require funded leadership within DOD to guide development and track progress. Ongoing conflicts in Ukraine and the Middle East have heightened the military's awareness of GPS over-reliance. Meanwhile, the cost of a quantum sensing research project is small compared to other QIST technologies, with a startup investment requiring less than operating costs of a single F-35 aircraft for one year.[135] This internal pressure, in combination with a leadership vacuum and a low funding bar, has resulted in many scattered efforts to address the issue. The likelihood of reinventing the wheel, missing opportunities, and general inefficiency is astronomically high. While the PNT Oversight Council is responsible for managing DOD's PNT portfolio and has recently directed some attention to GPS alternatives, government accountability studies found its efforts disorganized, with unclear objectives and metrics. DOD claims to have since clarified its goals.[136]

Fortunately, The Defense Innovation Unit (DIU), known for its Replicator initiative, has assumed a leadership role in quantum sensing for alternate PNT.[137] In May 2024, they launched the Transition of Quantum Sensors (TQS) Program aimed at collecting commercial solution proposals for quantum-based IMUs and magnetometers.[138] The solicitation also established critical performance and SWaP requirements for the desired prototypes, which remedied a serious barrier towards

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[134] Quantum Economic Development Consortium (QED-C). "Quantum Sensing for Position, Navigation, and Timing Use Cases."

[135] U.S. Government Accountability Office, *F-35 Sustainment: Costs Continue to Rise While Planned Use and Availability Have Decreased,* GAO-24-106703 (April 15, 2024). https://www.gao.gov/assets/gao-24-106703.pdf. Accessed January 6, 2025.

[136] U.S. Government Accountability Office, *GPS Alternatives: DOD is Developing Navigation Systems but is Not Measuring Overall Progress;* U.S. Government Accountability Office, *GPS Modernization: Delays Continue in Delivering More Secure Capability for the Warfighter.*

[137] The DIU Replicator initiative was tasked with providing the military with a large supply of low-cost drones in preparation for future conflicts after observing their use in the Ukraine conflict; "Replicator" Defense Innovation Unit. https://www.diu.mil/replicator. Accessed January 7, 2024.

[138] "Defense Innovation Unit Launches First CSO Under New Emerging Technology Portfolio," Defense Innovation Unit (May 8, 2024). https://www.diu.mil/latest/defense-innovation-unit-launches-first-cso-under-new-emerging-technology. Accessed January 7, 2025.

measuring progress.[139] Led by Lieutenant Colonel Nicholas Estep, who holds a technical PhD, TQS is well-positioned to bring organization and efficiency to the alternate PNT quantum sensing field.

The current TQS program falls short of addressing DOD's leadership gap in developing and fielding alternative PNT methods. While a significant step forward, the program's three-week solicitation likely favored larger research groups who either knew it was coming or had the means to respond quickly. To address this, DOD should empower and fund the DIU to compile a comprehensive portfolio of quantum-based PNT R&D efforts across the U.S. This would enable DOD to better leverage its investments, combine the best prototypes into a high-performing product, and anticipate future upgrades efficiently.

Allies and Adversaries

The U.S. military is addressing GPS over-reliance amid heavy global competition, particularly with China. To compete effectively, the U.S. should collaborate with allies, many of whom are heavily investing in quantum technology and possess strong research ecosystems relative to their GDP.[140]

Studies indicate that China and the U.S. are on par in quantum sensing research, but China is outspending the U.S. and has a streamlined system to transition lab innovations to market.[141] Critics argue China's focus on mature tech and centralized investment is risky, as the chosen technology may not succeed.[142] Either way, were China to eliminate their reliance on GNSS signals in combat first, they could initiate a conflict with the United States with a significant advantage. To counter this, the U.S. and its allies should leverage their diverse research portfolio to exploit weaknesses in China's program. This strategy only works if:

- Stakeholders track quantum sensing R&D groups within both U.S. and allied countries.
- Quantum groups in U.S. and allied countries collaboratively learn from each other's research and innovation.
- The United States allows easier technical knowledge transfer between allies while preventing China from reaping substantial benefits from open literature.

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[139] "Transition of Quantum Sensors (TQS) Program," Defense Innovation Unit. https://www.diu.mil/work-with-us/submit-solution/PROJ00538. Accessed May 20, 2024.
[140] James Dargan, "Quantum Computing Poised to Transform Australia's Economy, Says Sector Expert," Quantum Insider (October 29, 2024). https://thequantuminsider.com/2024/10/29/quantum-computing-poised-to-transform-australias-economy-says-sector-expert/; Matt Swayne "Top Quantum Spenders Based on GDP — List Offers Surprising Changes in Leadership Status," Quantum Insider (February 28, 2023). https://thequantuminsider.com/2023/02/28/top-quantum-spenders-based-on-gdp-list-offers-surprising-changes-in-leadership-status/. Both accessed January 8, 2025.
[141] Hodan Omaar and Martin Makaryan, "How innovative is China in Quantum?"
[142] "China is catching up with America in quantum technology," *The Economist* (December 31, 2024). https://www.economist.com/business/2024/12/31/china-is-catching-up-with-america-in-quantum-technology. Accessed December 31, 2024.

DIU remains the best candidate to lead U.S. stewardship of alternate-PNT quantum sensing research given its extensive network of contacts within the field and its well-established relationships with startups and commercial industry. While their TQS solicitation was open to foreign submissions, non-U.S. prototypes are subject to International Traffic in Arms Regulations (ITAR), which is a known barrier to collaborating with foreign entities on military-related technology.[143]

Recent government initiatives are addressing the last two objectives. AUKUS Pillar II aims to "enhance joint capabilities and interoperability focusing on artificial intelligence [and] quantum technologies…" between the United States, United Kingdom, and Australia.[144] The treaty even included a dedicated AUKUS Quantum Arrangement (AQuA) for accelerating quantum technology development between the three nations, with an initial focus on PNT.[145] However, ITAR and similar restrictions remain significant barriers, particularly for small businesses.[146]

In accordance with Pillar II, the AUKUS nations aligned their export control systems in August 2024, which enabled all three nations to fully benefit from technology transfer exemptions.[147] The advancement should eventually have a direct and positive impact on quantum research collaboration.[148] However, the updated regulations introduce, at minimum, new reporting requirements, causing confusion among researchers, regulators, and partners.[149] Despite the initial challenges, decision-makers are optimistic about the potential benefits.[150]

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[143] John Schaus and Elizabeth Hoffman, "Is ITAR working in an Era of Great Power Competition?" Center for Strategic and International Studies (February 23, 2023). https://www.csis.org/analysis/itar-working-era-great-power-competition. Accessed January 7, 2025.
[144] "Joint Leaders Statement on AUKUS," The White House (September 15, 2021). https://www.whitehouse.gov/briefing-room/statements-releases/2023/03/13/joint-leaders-statement-on-aukus-2/. Accessed January 7, 2025.
[145] "FACT SHEET: Implementation of the Australia – United Kingdom – United States Partnership (AUKUS)," The White House (April 5, 2022). https://www.whitehouse.gov/briefing-room/statements-releases/2022/04/05/fact-sheet-implementation-of-the-australia-united-kingdom-united-states-partnership-aukus/. Accessed January 7, 2025.
[146] Tom Corben and William Greenwalt, "Breaking the barriers: Reforming US export controls to realize the potential of AUKUS," United States Studies Centre (May 17, 2023). https://www.ussc.edu.au/breaking-the-barriers-reforming-us-export-controls-to-realise-the-potential-of-aukus. Accessed January 7, 2025.
[147] "Chair Cardin Welcomes Adoption of Export Control Systems in AUKUS Agreement," U.S. Senate Foreign Relations Committee (August 15, 2024). https://www.foreign.senate.gov/press/dem/release/chair-cardin-welcomes-adoption-of-export-control-systems-in-aukus-agreement. Accessed January 7, 2025.
[148] Matt Swayne, "Updated AUKUS Pact Eases Export Controls on Quantum Among Member Nations," Quantum Insider (August 20, 2024). https://thequantuminsider.com/2024/08/20/updated-aukus-pact-eases-export-controls-on-quantum-among-member-nations/.
[149] "Department of Commerce Releases Export Controls on Quantum Technologies," Quantum.gov (September 6 2024) https://www.quantum.gov/department-of-commerce-releases-export-controls-on-quantum-technologies/. Accessed January 7, 2025.
[150] J. Dickson and E. Harding, "Unleashing Quantum's Potential."

Despite decisionmakers signaling a desire for quantum technology collaboration with allies, convincing program managers and researchers remains difficult. For PNT-related quantum sensing, the DOD still prefers working with U.S. researchers, especially those they fund directly. Small startups and research groups that might lack sufficient legal counsel often struggle to interpret complex export controls. The opaque policies and severe infraction penalties will deter change among researchers unless funders and program managers actively promote foreign collaboration. For example, at a recent international physics conference, a U.S.-based quantum startup employee was completely unaware that a foreign startup at a nearby booth was developing the same PNT technology.

Expanding the R&D pool is key to competing with China. Decisionmakers should continue employing every possible measure to enable and maintain quantum research collaboration across allied nations while fostering a culture of collaboration between scientists and the DOD.

Implementing PNT Resilience

Transitioning the military from GPS reliance to a resilient PNT posture is a challenging task. While historically slow to enact change, DOD has also faced internal resistance to alternate PNT due to GPS's entrenched influence.[151] Recognizing the urgency, Congress mandated in the 2021 National Defense Authorization Act (NDAA, section 1611) that DOD “mature, test, and produce…equipment to generate resilient and survivable alternative PNT signals” within two years of the bill’s passage, while consulting every possible source of expertise available.[152] Thanks to the congressional shove, DOD has driven significant progress in the past couple years, though much work remains.

To prepare the Joint Force for alternative PNT, DOD is using a modular open systems approach (MOSA).[153] This strategy involves installing modular receivers capable of integrating multiple PNT sources during the M-Code upgrade. Currently, the three services are pursuing four limited efforts to integrate multi-PNT receivers, all designed to use local IMUs and clocks, with the Air Force’s system explicitly allowing for future alternate PNT capabilities. Efforts are also underway to draft DOD-wide MOSA standards. These campaigns have cost nearly $1 billion from 2017 to 2025.[154] To meet Congress’s rapid timeline, the services are currently focusing on readily available technologies, such as LEO satellite signals, automated celestial navigation, and commercial clocks and IMUs. Once quantum sensing PNT prototypes are mature, they can easily supplement and replace the classical systems currently being deployed. Upgrading all PNT-relevant receivers to

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[151] U.S. Government Accountability Office, *Defense Navigation Capabilities*.
[152] William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021, H.R.6395 S.1611.
[153] U.S. Department of Defense, *Strategy for the Department of Defense Positioning Navigation and Timing (PNT) Enterprise,* (November 2018), https://rntfnd.org/wp-content/uploads/DOD-PNT-Strategy.pdf. Accessed January 8, 2025.
[154] U.S. Government Accountability Office, *GPS Alternatives: DOD is Developing Navigation Systems but is Not Measuring Overall Progress*.

multi-modal versions could eventually cost tens of billions. To avoid repeated upgrades, DOD should ensure all M-Code receiver upgrades include multi-modal capabilities.

DOD's rapid progress is promising. With sustained internal and congressional support, it can continue enhancing resilience and prepare for quantum sensing PNT as it matures. Due to the already-disruptive M-Code upgrade, the final step of fielding quantum sensors may be simplified.

Conclusion

Quantum sensing is a unique technology that will dramatically improve performance and open new capabilities for alternate PNT within the next few years. The U.S. military has allowed its over-reliance on GPS signals for timing and navigation to become a serious vulnerability in combat. Meanwhile, our adversaries are honing their skills at electronic and anti-satellite warfare, which could deny the Joint Force desperately needed GPS signals. With continued investment and DOD engagement, developments in quantum sensing have the capacity to nearly eliminate the PNT vulnerability and enable the Joint Force to fight tomorrow's war with resilience.

The ongoing revolution in quantum sensing technology has yielded high-stability clocks and IMUs that can continue providing precise PNT information for days without recalibrating to a GPS signal. Some of these prototypes are already entering the market. Similar breakthroughs on quantum gravimeters and magnetometry have enabled map-matching navigation, which would not have been practical even a few years ago. Ongoing R&D in quantum magnetometry may eventually yield chip-based sensors that could guide munitions and small drones, provided a sufficiently precise map exists. Every PNT-related quantum sensor currently under development can be used in nearly any location, in all weather, and is immune to jamming and spoofing.

In this era of global competition, China is investing heavily in quantum technologies and reports indicate that their research quality in quantum sensing is roughly equal to the United States.[155] China cannot be allowed to reach a point where it no longer needs GNSS signals in combat before the United States. Every effort must be made to leverage our domestic and allied quantum R&D portfolios to reach a point of clear PNT resilience. Once this capability is achieved, it must be protected. To accelerate the development and ruggedization of quantum prototypes across allied nations, strong technical leadership and guidance will be needed from DOD.

Congress has mandated that DOD incorporate alternate sources of PNT into its infrastructure. No single source of alternate PNT can replace GPS signals for accuracy and reliability, but using a combination of different sources will ensure missions can still be executed even in a GPS outage.

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[155] Hodan Omaar and Martin Makaryan, "How innovative is China in Quantum?"

With continued effort and the capabilities unlocked with from quantum sensing, this goal is achievable within the next decade.

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