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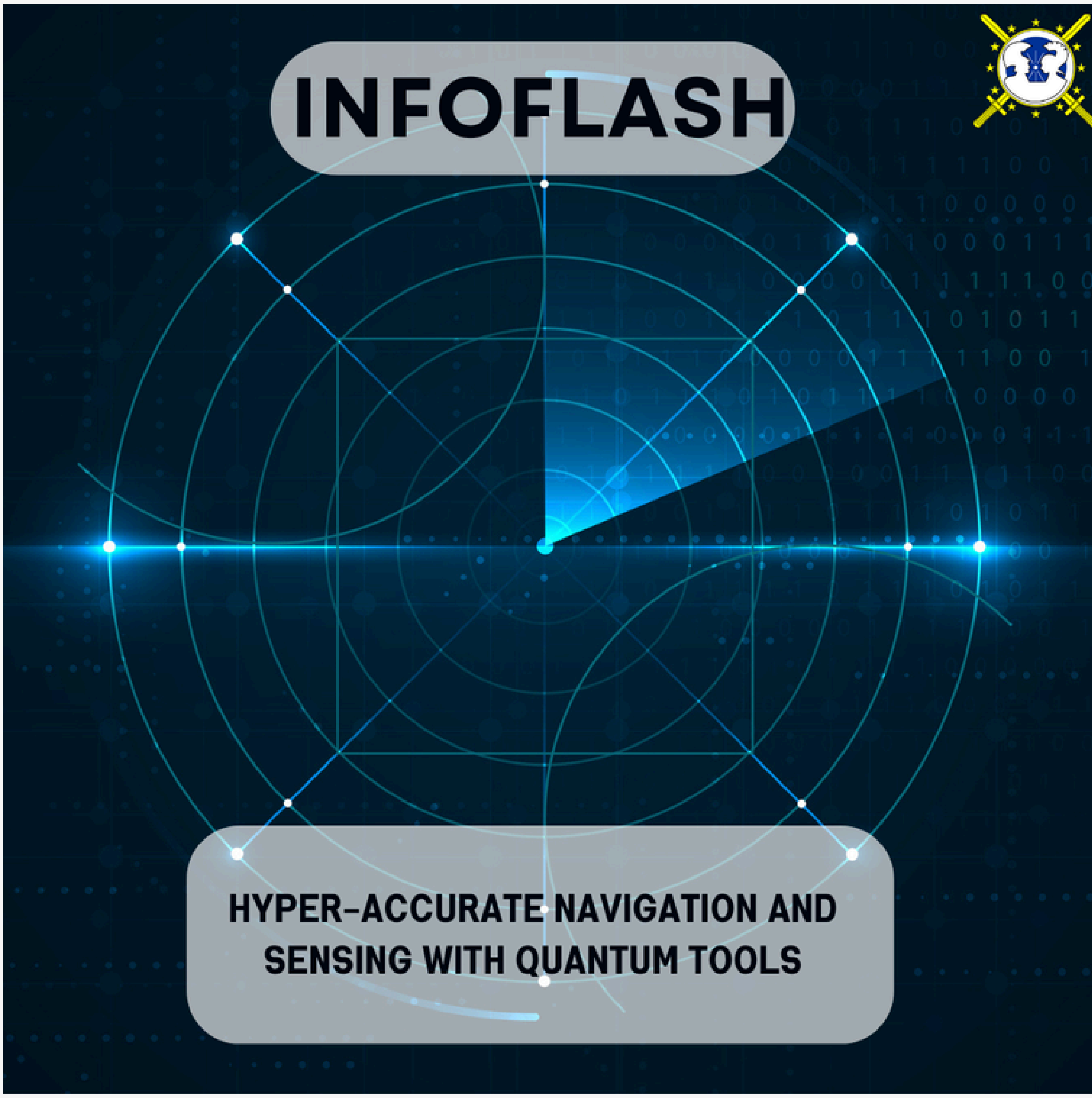

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Hyper-Accurate Navigation and Sensing with Quantum Tools

"If you think you understand quantum mechanics, you don't understand quantum mechanics." – Richard Feynman

1.Introduction

Nation-states and non-state actors use electronic warfare to prevent adversaries from using devices that require GPS, such as drones (NATO, 2025). GPS-degraded or denied environments (GPSDD) have become the norm in the battlefields of Ukraine and Gaza (Arraf, 2024; Slusher, 2025). In response, militaries rely on emerging technology such as artificial intelligence to circumvent GPS-jamming and ensure navigability in GPSDD environments (Khawaja et al., 2022).

Quantum positioning, navigation, and timing (PNT) rely on principles of nature to provide hyper-accurate information to users. Principles of superposition, entanglement, and interference enable users to measure minute differences in motion, acceleration, gravity and electromagnetic fields, allowing them to better navigate or detect foreign objects (van Amerongen, 2021). Quantum tools also facilitate better sensing. China claims to have built a quantum radar by measuring how entangled quantum particles in an electromagnetic storm can identify shapes and figures within that storm, regardless of their radar signature (Chen, 2021). Additionally, Chinese researchers successfully utilised a magnetometer to detect subtle variations in underwater electromagnetic readings, which could allow for more accurate detection of stealth submarines (Swayne, 2025a).

These developments in quantum technology have implications for navigation in GPSDD environments, the continued capabilities of stealth platforms, and mutually assured destruction (MAD). Hence, this paper – the second in a series of three on the impact of quantum technology on defence and security – will explore quantum PNT and sensing. Is Europe doing enough to improve its capabilities in quantum sensing? This paper argues that European agencies have conducted deep research into such capabilities and are moving towards deployment but must overcome issues of talent and supply chain resilience to ensure its military edge.

2.Issues in PNT and Sensing

PNT and sensing are affected by drift, GPS jamming, and high signal-to-noise ratios.
Firstly, Inertial Navigation Sensors (INS) are subject to "drift", or a tendency to erroneously measure PNT after prolonged use. For example, classical gyroscopes in aircraft drift and

produce incorrect readings due to friction as well as improper cleaning and maintenance (Federal Aviation Administration, 2023). Over time and without proper upkeep, classical INS instruments may provide incorrect information, reducing the accuracy of military PNT and affecting mission success.

Secondly, external actors may degrade or deny GPS in a battlespace, affecting both troops in combat and GPS-guided assets. Troops, for example, may be unable to orient themselves accurately or navigate quickly to their objective. Drones, rockets, artillery, and missiles that rely on GPS guidance may be unable to reach their target once their GPS systems are degraded. They may even be redirected to strike another less relevant or friendly target, leading to potential mission failure (Radsinger, 2018). Militaries already employ GPSDD techniques in conflict zones, especially in Ukraine and Gaza (Arraf, 2024; Slusher, 2025). For example, civilians in the Middle East have often experienced interference with navigation applications on cell phones due to GPS-spoofing originating from an Israeli Defence Force airbase (Arraf, 2024).

Thirdly, radars suffer from high signal-to-noise ratios. Currently, radars work by emitting radio frequencies at target areas and measuring the signals that return. However, the image is usually noisy: operators must differentiate between the radar picture, background noise and thermal radiation (Lloyd, 2008). In the case of stealth platforms or drones with small radar cross-sections, operators may be confused whether the reading is indeed a stealth platform or a small bird (Hutchinson, 2024; Robin Radar Systems, n.d.). Claims of quantum radar development, even if overblown (Karsa et. al., 2024; Krelina, 2025), mark the beginning of the end of stealth (Giles, 2019). China claimed to have deployed a quantum radar in 2021 alongside its deployment of a quantum-enabled magnetometer to measure underwater electromagnetic readings (Swayne, 2025a). While it is unclear if China possesses such a capability at scale, its implications are strategic. If a state can sense stealth platforms – such as stealth aircraft or submarines – MAD could be at risk, as it would be easier for states to eliminate an assured second-strike capability (Sayler, 2024).

3.Primer on quantum properties in Sensing

Quantum technologies rely on superposition, entanglement, and interference to provide answers to complex problems quickly. Its key problem is decoherence. Basic information on these principles is in the first article of this series, "The End of State Secrets with Quantum Cryptography".

In the context of sensing, militaries can use superposition, entanglement, interference, and quantum particles' hypersensitivity to environmental stimuli to measure the impact of such stimuli on quantum particles. For example, superposition allows for particles to exist in several states simultaneously. If environmental stimuli act on different states in distinct ways, that variance could provide valuable information, such as in nitrogen-vacancy centre tools and cold atom interferometry (CNRS, 2021). Entanglement allows one particle to provide information about its entangled partner, which can facilitate sensing at a distance, such as in quantum radar and quantum illumination (Krelina, 2021).

A key challenge in sensing is decoherence. It is difficult to maintain coherence when the precise aim of quantum sensors is to produce an output that must be measured. However, several techniques can be used to increase coherence time while still maintaining the readability of data. For example, quantum error correction mechanisms can stabilise qubits and provide reliable readings despite measurement attempts (Hecht et al., 2025). However, some challenges remain: several techniques covered in this paper require a specific set of circumstances to function well, such as super-cool temperatures and fast processing (Karsa et al., 2024). These considerations limit the immediate and short-term feasibility of some quantum sensing tools.

4.How do quantum sensors address current problems?

There are three major threats facing navigation and sensing: (i) INS drift; (ii) GPSDD; and (iii) limited capabilities of classical radars. Quantum tools address several of these issues. Natural drift and navigating in GPSDD can be addressed by quantum-powered accelerometers, gyroscopes, magnetometers and gravimeters that rely on the principles of nature to provide hyper-accurate PNT and navigation. While quantum illumination and radars have not been deployed at scale, it is theoretically possible for them to detect stealth platforms easily. This section discusses nitrogen-vacancy (NV) centres, cold atom interferometry (CAI), and quantum illumination to showcase the full range and varied Technology Readiness Levels (TRL) of quantum sensing tools.

4.1.Nitrogen-Vacancy Centre

An NV centre relies on the energy state of electrons in a diamond to provide precise measurements of gravitational fields. The vacancy is an empty slot in a nitrogen-doped carbon lattice of a diamond, which permits an unpaired electron in the nitrogen atom to become excited when a green laser is fired at it (Sanchéz-Toural et al., 2023). When excited, electrons can assume either a spin state of 0 or -1. When the electron returns to its unexcited state, it emits a red light of a particular intensity depending on the path it takes to return there: there is a bright red light in spin 0, but a dim red light in spin -1 (Wang et al., 2023). In the presence of magnetic fields, electrons in in spin -1 become less energetic proportional to the energy of the magnetic field, while spin 0 stays the same. Hence, we can use Optically Detected Magnetic Resonance to measure the difference in energy between the spin 0 and spin -1 particles to obtain an exact measurement of the magnetic field (CNRS, 2021).

NV magnetometers will help with both PNT and sensing. With regard to PNT, NV magnetometers could compare electromagnetic patterns with previous electromagnetic maps, providing an accurate location to the user (Graham et al., 2025; Krelina, 2025). For sensing, platforms could monitor discrepancies in magnetic fields underwater and on land to detect if potential adversary platforms are in the region (Small Business Innovation Research [SBIR], 2025). Infantry units could even use such technology to detect improvised explosive devices, especially where they have low metal content (US Army, 2025). These applications allow soldiers to navigate in GPSDD environments and allow for better sensing capabilities of enemy assets and potential threats.

NV centre technology is also easily deployable. Researchers have demonstrated the operability of NV centres at room temperature, reducing cooling needs (Yu et al., 2025). This makes the technology portable and eligible for integration into several platforms that operate in harsh terrain, such as tanks or artillery batteries. Second, the NV centre is not prone to “drift” or to jamming, as it relies on the properties of electrons and nature to derive a reading. Sensing platforms would be able to detect the presence of an enemy platform, regardless of GPSDD.

4.2.Cold Atom Interferometry

CAI relies on the wave-like properties of super-cooled atoms and their sensitivity to external forces (Krelina, 2021) to identify changes in acceleration and rotation. When atoms like rubidium are super-cooled close to absolute zero (0 Kelvin, or -273.15 degrees Celsius), they exhibit wave-like properties. These atoms are then put into superposition by a laser pulse, where an atom simultaneously occupies a ground state and an excited state. A second laser switches their paths, and a third laser pulse forces them to meet. When they meet, they create a pattern of interference that is compared to a no-movement pattern of interference to establish how much acceleration and spin are present. Ultimately, the technique allows instruments to rely on the behaviour of atoms under the influence of acceleration or rotation to generate a hyper-accurate reading (Bustamante, 2025).

This quantum measurement mechanism has direct applications to military operations. These measurements rely on the effects of forces of nature on the atoms in superposition to determine acceleration and rotation. Hence, they do not require recalibration and are not prone to the “drift” found in classical INS instruments. The hyper-accuracy of acceleration and rotation measurements enables the precise and timely delivery of missiles, especially in GPSDD environments (Travagnin, 2012). Submarines could also stay submerged for longer, as they would not need to surface to recalibrate their classical INS instruments with a Global Navigation Satellite System from time to time (Krelina, 2025). However, given that CAI technology is still too big to be installed in missiles or modern planes, more research must be done to miniaturise and scale CAI modules before the technology can be adopted widely (Travagnin, 2020).

4.3.Quantum Illumination

Quantum Illumination (QI) uses quantum entanglement to detect a target using entangled photons (Krelina, 2021). One photon – an 'idler' – is kept within the radar station, while the other – a 'signal' – is entangled and repeatedly sent toward a potential target. Some atoms may return, recombine with the 'idler' atom, and provide information on potential foreign platforms (Karsa, 2024). Given the entangled nature of the atoms, quantum radars can provide the advantage of a lower signal-to-noise ratio, which provides a clearer picture to radar operators of present threats (Lloyd, 2008).

Such technology can be useful for detecting stealth platforms in the air and sea. QI could eventually sense platforms regardless of advanced radar avoidance methodologies like radar reflective materials or small radar cross-sections. Hence, intelligence, surveillance, and reconnaissance platforms or close air support attempting to maintain stealth might be easily detected by QI.

Quantum radars are currently technologically infeasible, however, due to their many requirements (Karsa et. al., 2024; Krelina, 2025). These include high performance in challenging military environments, high range capabilities, and fast processing (Karsa et al., 2024). Additionally, an effective radar read requires that the 'signal' atoms of an entangled pair successfully probe a potential target area and recombine with the perfectly untouched 'idler' atoms (Karsa et al., 2025), which remains undemonstrated. Hence, quantum illumination requires further research and development until it can become integrated into contemporary military technology.

5.What is Europe doing?

Europe recognises the potential benefits of quantum sensing technology and has allocated money and developed policy frameworks for it. Several initiatives, such as the Quantum Technologies Flagship, Horizon Europe, and the European Defence Fund, have funded projects in quantum sensing.

European agencies are financially supporting attempts to gain an edge in quantum sensing. For example, Advanced, Disruptive, and Emerging Quantum Technologies for Defence (ADEQUADE) is a successor to the QuantaQuest initiative, which researched NV centre diamonds as magnetometers. ADEQUADE has received €27.4 million in funding from the European Defence Fund and oversees a 36-month project dedicated to providing a "breakthrough in different quantum-sensing domains" (European Defence Fund, 2021, p. 1). The project, which is coordinated by Thales, a French aerospace and defence company, brings together a consortium of 31 different entities, including defence groups, research centres, and private corporations, across eight countries. The project's goal is to improve quantum sensing capabilities, including through NV centre technologies and cold atom inertial sensors. The project hopes to commercialise the technology that enables navigation and reduces drift in GPSDD environments (European Defence Fund, 2021).

The Permanent Structured Cooperation (PESCO) platform has also embarked on a quantum sensing project to enable precise PNT and sensing. This includes, but is not limited to, using quantum technology to improve early warning systems for hypersonic weapons and improving sensing, computation, and communications. The project is led by Finland, with Germany, Denmark, Latvia, and Italy as partners (Permanent Structured Cooperation [PESCO], 2025). Sweden, Greece, and the Netherlands have also joined the project as observers (Swayne, 2025). As a leader in quantum technologies, Finland is hoping to pave the way for Europe to benefit from quantum technology's impact on the military (Finland Ministry of Defence, 2025).

5.1.Evaluation of Europe's efforts

Europe has done well by establishing the policy direction for quantum technologies in defence. It has also secured significant financial resources through dedicated and traditional defence technology funding and accelerator programs such as the EDF and Quantum Flagship. Such funding and coherent policymaking have supported long-term R&D programs that focus on the development of quantum sensing tools. For example, ADEQUADE is a follow-up project to QuantaQuest, which the European Defence Agency (EDA) funded €1.5 million for in 2017 (European Defence Agency, 2024). QuantaQuest, which was led by Thales, brought together nine defence companies and research institutes from France, Italy, and the Netherlands and was successful in experimenting with a "building block" of a quantum inertial measurement unit that used CAI (European Defence Agency, 2024). Hence, ADEQUADE – which was launched in 2025 – is expected to build on QuantaQuest's successes and suggests that EU policymakers are supporting successful research.

Europe should, however, pay attention to how resources and funding are split between various projects. Different projects are focusing on a variety of sensing instruments; however, the quantum technologies at their core involve many of the same principles, which only a limited cadre of experts are qualified in. Should there be too many projects across the continent, Europe's limited expertise may be stretched too thin to contribute meaningfully to various projects, above and beyond what the European Commission's European Quantum Talent Mobility Programme might provide (European Commission, 2025).[1] Generating expertise takes time, and Europe must publish a clear policy program and report on the state of quantum technology in Europe. Second, supply chain constraints may limit the

1. The initiative provides fellowships for EU and non-EU PhD holders and early career professionals

development of quantum technology. Building quantum sensors relies on specific materials including rare-earth materials like diamonds and rubidium. China dominates the rubidium export market (Mordor Intelligence, 2025) while Russia has rubidium supplies but has not invested in it due to investment reductions (SFA Oxford, 2025). Hence, raw material concerns are sensitive geopolitical issues that consortiums and research centres must navigate as they explore quantum sensing technologies. Finally, it is unclear if the research projects are developing particular quantum sensors with feedback from the military, which will require miniaturised sensors for their platforms. Collaboration between researchers and the military is a crucial step in ensuring that eventual products are fit for purpose.

6.Conclusion

The current threat picture is clear: GPS-denial and degrading are features of the current battlefield. Classical INS instruments are subject to drift and large inaccuracies over time. Radars struggle to differentiate between genuine enemy presence and signal noise. Together, these trends complicate operational necessities like PNT and sensing. Quantum technologies can resolve these issues by relying on the principles of nature to provide hyper-accurate readings and information regardless of wear-and-tear and GPSDD. NV centre magnetometry can detect electromagnetic waves and aid in navigation and sensing. CAI can detect changes in acceleration and rotation, aiding PNT and sensing. Quantum radar can detect potential adversary presence regardless of their size or radar cross-section, reducing the signal-to-noise ratio that current radar operators struggle with. These technologies, however, have their own strengths and weaknesses. While NV centre tools can operate at room temperature, allowing them to be deployed in harsh environments such as submarines or tanks, CAI requires atoms to be cooled to near absolute zero, which is not feasible in harsh environments. Similarly, Quantum radars require specific conditions to accurately function, limiting their effectiveness. So, what is the timeline for such quantum sensing technologies to be deployed in conflict? It depends on the success of ongoing R&D programs, which Europe has funded. Agencies like the EDF, PESCO, Horizon Europe, and the Quantum Flagship provide policy guidance and financing for projects that seek to improve Europe’s quantum PNT and sensing technology, including through enabling PNT in GPSDD environments and improving early-warning systems for missile attacks. Unfortunately, challenges remain. Europe should go further in building a steady pipeline of short-term and long-term talent in quantum technologies, which is currently severely limited. A second challenge is the supply chain. Many elements critical to the development of quantum technology, like rubidium, are rare-earth materials, the supply chain of which are controlled by non-European entities. Europe faces the additional challenge of ensuring supply chain security for such products, either through strong supply chain security agreements that function in wartime or through developing specific technologies that do not rely on materials outside of European control. Several challenges lie ahead for Europe’s researchers and militaries, but continued funding and enabling policy frameworks will enable the rapid deployment of quantum sensors.

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