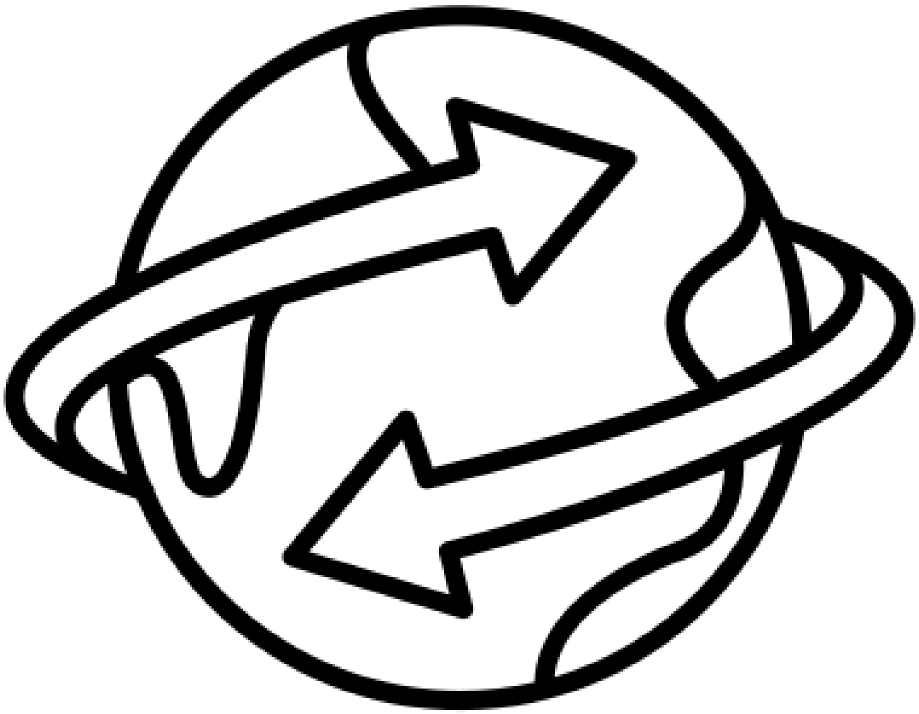
- Official Summary -



Critical Vulnerabilities in the Quantum Sensing Supply Chain within the NATO Alliance

HEIJMAN CONSULTANCY
Quantum & Deeptech Innovation

CJW
CJW Quantum Consulting, LLC

This summary contains the following (parts of) chapters from the report:

“Critical Vulnerabilities in the Quantum Sensing Supply Chain within the NATO Alliance”

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4. Discussion (shortened for clarity/brevity)
5. Vulnerabilities and Pathways for Solutions (shortened for clarity/brevity)
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Summary of the report written by Lukas Kingma, Freeke Heijman and Carl Williams

With input from Dr. Celia Merzbacher (QED-C), Dr. Thierry Botter (QuIC), Dr. Mike Larssen (Northrop Grumman), Dr. Jay Lowell (Boeing), Dr. Samuel Benz (NIST), Dr. John Kitching (NIST), Waseim Alfred (NATO STO), Dr. Phil Waldron (NRCC), NQS Secretariat Canada, Dr. Alex Maierean (Phantom Photonics), Julian Rabbie (TNO), Dr. Clara Osorio Tamayo (TNO).

Conducted in the context of the NATO Transatlantic Quantum Community (TQC)

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1. Executive Summary

As part of the agenda of the Transatlantic Quantum Community (TQC) a comprehensive analysis of critical gaps and vulnerabilities in the quantum technologies ecosystem within the Alliance has been conducted. This study focuses on the quantum sensing supply chain. As with our previous report on the quantum computing supply chain we use a systematic methodology based on the SRI model for Quantum Technologies Manufacturing Roadmap that is supplemented by our Reusable Quantum Enabling Supply Chain (ReQuEST™) tool that we have developed. The ReQuEST™ tool can be easily updated and used more broadly within the global quantum community. The scoping for this report has been coordinated with workstream 2 of the TQC.

Quantum sensing is rapidly emerging as a transformative capability in defense and national security. By exploiting the quantum properties of matter and light—superposition, entanglement, and coherence—these sensors offer performance far beyond classical technologies. Key advantages include enhanced sensitivity, precision, and resilience in contested environments, making them suitable for Intelligence, Surveillance, and Reconnaissance (ISR), Positioning, Navigation and Timing (PNT), and threat detection.

Leading NATO nations such as the UK, US, and France have prioritized quantum sensing as a near-term deployable technology. This reflects both its technological maturity and its critical value in scenarios where traditional sensors fail, such as GPS-denied environments, stealth detection, and underground facility mapping. This report provides a summary of the vulnerabilities in the quantum sensing supply chain and recommendations to address those vulnerabilities. We explore both quantum sensors and sensors that are enhanced by quantum technology (e.g. Rydberg atoms used as a microwave antenna).

Our analyses revealed several critical cross-cutting dependencies that pose significant risks to the quantum sensing ecosystem within the Alliance. These have many similarities to those for quantum computing but are further impacted by the requirements on size, weight and power (SWaP) and modest requirements on fieldability, including the ability to operate on a moving platform while undergoing modest temperature and humidity swings.

The most notable vulnerabilities the Alliance faces are substantial challenges related to semiconductor manufacturing supply chains and semiconductor fabrication facilities. There is also a heavy reliance on non-NATO sources for rare earth elements, such as Erbium and Ytterbium, and for exotic materials, compounds and isotopes such as Niobium, Strontium, Rubidium, Lithium Niobate, Thin Film Lithium Niobate, and numerous photonic crystals and materials that are often sourced from potentially unstable or non-allied regions. Finally, environmental requirements along with SWaP significantly reduced the number of vendors for lasers and vacuum technology.

In terms of technology-specific vulnerabilities, the study identified that over 90% of high purity material processing occurs outside the Alliance. The electronics sector shows considerable dependence on Asian fabrication facilities for advanced nodes, optical coatings and photonic integrated circuits (PICs).

Our study ignored the software to operate these sensors since this would require access to non-public, sensitive, or classified information. It is important to note that for defense applications such software includes data fusion and interoperability that makes it even more sensitive. We also ignored fieldable cryogenics, that are essential to operating superconducting quantum interferences devices (SQUIDs) since solutions exist within the defense and aerospace community, but such information is considered non-public or sensitive and may be subject to export controls.

Examining the R&D position and possibility to scale the technology within the Alliance, it is noted that the Alliance is reasonably solid, with the main exception being in non-silicon based photonic systems and MEMS related vacuum technology. This is further exacerbated by the fact that most lasers outside of the telecom region of the spectrum are not fieldable but are R&D instruments that operate only in controlled environments and in some cases do not meet even the meager SWaP requirements used within this study. As a result, NATO and member states needs to monitor the development of components such as environmentally stable laser systems, higher purity materials and more precise fabrication processes, especially for non-Si based photonics platforms.

Key Recommendations

Our recommendations come in three flavors: a) briefing documents that should inform relevant stakeholders within the Alliance; b) key studies aimed at helping to further clarify and define how best to resolve an identified vulnerability; and c) targeted programs aimed at further informing NATO and member states on potential solutions.

The three proposed set of briefing documents include: a) defining key fabrication facility requirements for quantum sensors; b) list of critical materials essential to quantum sensing technology; and c) a list of critical components that are typically sourced from suppliers outside the Alliance within the quantum sensing supply chain.

The three proposed key studies are:

- Explore and prioritize the appropriate fabrication infrastructure needed to guarantee that NATO nations have access to silicon carbide (SiC) and III-V semiconductor[1] capabilities appropriate to Photonic Integrated Circuits (PICs) and photonics.

[1] III–V semiconductors are compounds made from elements in groups III and V of the periodic table, such as gallium arsenide (GaAs) and indium phosphide (InP), used to produce high-speed, high-efficiency electronic and optical devices.

- Perform an econometric study on the appropriate balance in investment between quantum system integrators and the nascent quantum supply chain for environmentally robust and low-SWaP systems and components.
- Explore options for interventions to balance the investment landscape in North America and Europe for the quantum technologies sector.

Finally, we proposed a set of targeted programs. This included a pilot program for producing small quantities of qubit materials required to support primarily neutral atom and ion-trap based quantum sensors. We also made the recommendation to follow through the study on SiC and III-V semiconductor capabilities mentioned above to actually provide an appropriate solution. Additional targeted programs included: a) developing testbeds to help accelerate both the development and interoperability of quantum sensing technology and provide realistic requirements for SWaP and interoperability; b) creating R&D programs aimed at support companies in both the quantum supply chain and quantum sensor developers to create environmentally robust systems and components, that are both fieldable and have low SWaP; and c) utilize NATO innovation program aimed at incentivizing new commercial activity to increase competitiveness for specific quantum supply chain vulnerabilities.

A complete list and description of these vulnerabilities can be found in Chapter 5 and the conclusions and recommendations in Chapter 6.

2. Introduction

Goal
The findings of these analyses aim to serve as an input to workstream 1 of the Transatlantic Quantum Community to allow for conclusions and potential follow-up actions to address identified gaps and vulnerabilities. In the case of this study on quantum sensors, the findings will also be used as input to inform workstream 2 and their analyses.

This study focuses on quantum sensing; a similar study has already been carried out for quantum computing and a more qualitative study for quantum communication and networking is in draft final form.

Approach
We have set up a Transatlantic team of CJW Quantum Consulting (Maryland) and Heijman Consultancy (Delft) to carry out the study, with the purpose of unlocking as much knowledge and expertise from both North America and Europe as possible. To contribute to the long-term development of the field and the NATO intelligence position, we have developed ReQuEST™ - a Reusable Quantum Enabling Supply Chain Tool, that can be updated and revised on a regular basis. This report contains the key findings of the model filled in for quantum sensing. ReQuEST, the reusable framework itself, is a separate tool in Excel designed by Lukas Kingma and owned and managed by Heijman Consultancy and CJW Quantum Consulting.

One key difference from the Quantum Computing report is that workstream 2 suggested that we include modes Size, Weight, and Power (SWaP) constraints such that the systems were *at least* fieldable. This meant that the final system was typically no more than 8U, 12 U maximum, and that the power was no more than 250 W, 1 kW maximum. The system should also have some ability to run 24/7 in a non-ideal environment with temperature and humidity swings along with modest vibration. These SWaP constraints were not meant to be what would be required for deployment but enough for field testing.

3. Supply Chain Mapping for Quantum Sensing

In this section, the results of the ReQuEST™ analysis for the quantum sensing supply chain are presented.

The primary objective of this analysis is to identify and clarify which parts of the quantum sensing ecosystem are missing or underdeveloped within the Alliance. Consequently, this study focuses on critical dependencies—specifically, those components of the supply chain that require attention. Technologies or elements deemed to be "good enough" fall outside the scope, as they do not represent areas of concern or opportunity for improvement. Therefore, elements assessed as sufficiently developed or stable are not highlighted in the subsequent conclusions, allowing this study to maintain a targeted focus on areas in need of strategic improvement.

This approach is identical to our previous report "Critical Vulnerabilities in the Quantum Computing Supply Chain within the Alliance."

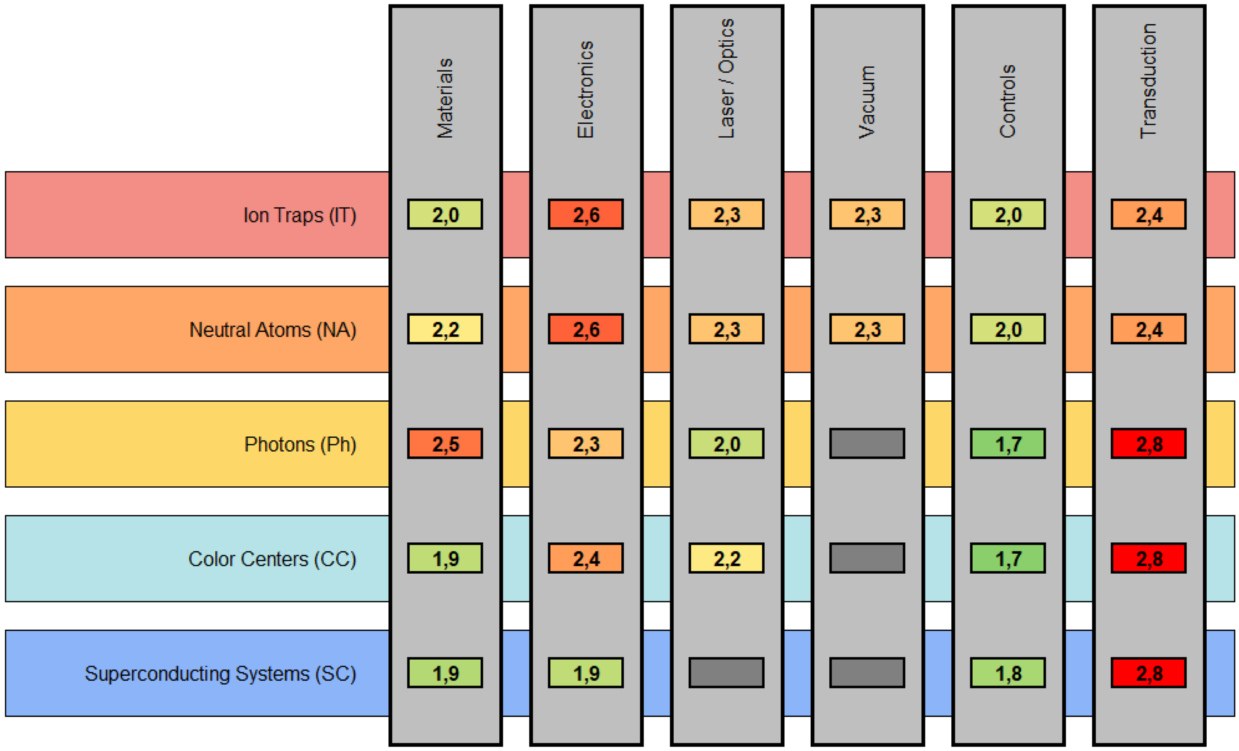

Figure 1. Main matrix output for Quantum Sensing from the ReQuEST™ Tool. A score of 1.9 or less implies reasonable risk, a score of 2.0-2.4 implies moderate risk, and a score above 2.5 implies significant risk. Compared to our Quantum Computing matrix, the Quantum Sensing one has more orange and red (higher scores), primarily due to the *modest* SWaP and fieldability requirements that significantly reduces the number of suppliers within NATO and thereby increases the risk.

4. Discussion

Enabling Conditions

In addition to the supply chain for the enabling technologies for the Quantum Sensing modalities described in chapter 3, there are several facilities and conditions needed for the successful development and deployment of quantum sensors within the Alliance. We have identified the following non-limitative list of important enabling conditions, with a qualitative assessment of the status within the Alliance. Follow-on studies of Workstream 1 of the TQC should allow these aspects to be more thoroughly investigated.

- Testbeds and Use Case Development
- Fabrication Facilities
- Talent Development

- Ethical and Regulatory Frameworks
- Investments
- Standardization and Interoperability
- Awareness and Readiness

Comparison of the North American and European Ecosystem

A detailed assessment of each of the technology pillars has been performed, combined for all qubit modalities, with a comparison between NA and Europe. Overall, the ecosystems are fairly balanced, with equal strengths and weaknesses. Most importantly, vulnerabilities are largely shared.

Materials & Processing

Both regions are exposed to geopolitical risks, especially for materials dominated by China and Russia, and neither is fully self-sufficient for all quantum-grade materials.

Electronics

The Europe's strength lies in equipment and R&D, while NA excels in chip design and system integration. However, both face bottlenecks due to single-source suppliers for critical subcomponents and dependencies on Asian supply chains for specialty gases, rare earths, and advanced packaging.

Vacuum

The European nations have a slight advantage in vacuum R&D and custom solutions, but NA offers more scalable production for certain components. Overall, both regions are exposed to similar vulnerabilities and neither is fully independent.

Control Electronics

Both regions have strong R&D in control systems, but scaling is limited by dependencies on fabs outside of the Alliance, rare earths, and specialty materials.

Laser & Optics

Europe excels in R&D and specialty optics, while NA offers broader manufacturing scale. Both are exposed to Asian supply chain risks for key materials and subcomponents.

Transduction

Scaling is limited by single-source risks and external dependencies, making both regions equally vulnerable.

5. Vulnerabilities and Pathways for Solutions

Here we have grouped the individual flagged vulnerabilities from our results section into a set of critical vulnerabilities that occur multiple times within individual cells of the ReQuEST risk matrix. These are:

1. **Semiconductor manufacturing supply chain and semiconductor manufacturing fabrication facilities**: As Europe and NA have recognized during the past decade, we have inadequate redundancy and capabilities in the semiconductor manufacturing space. This impacts the capability to scale, along with the required

electronics and control systems required for each qubit modality. It also impacts the suppliers' supply chain for control systems and for lasers. While there are some variations in control systems for various qubit modalities this remains a common risk.

2. **Lack of III-V semiconductor suppliers:** There is a lack of III-V semiconductor suppliers essential to emerging and next generation photonic platforms for lasers, optics, and photonic devices including Photonic Integrated Circuits (PICs) that are essential to everything from imaging and high-speed operation to creating very low-SWaP quantum sensors, including the lasers necessary to drive these systems. The frequency of the operation and the wavelength of the light determines whether these are GaAs, GaN, GaP, InGaAs, InP or other related materials along with SiC. Except for Si and InP, the Western ecosystem has limited ability to produce next generation devices which impacts quantum sensors especially photon-based modalities and the low-SWaP lasers and optics required for almost all modalities of quantum sensors. Note R&D leadership, in InP devices is being challenged by China.
3. **Dependency on rare earth elements:** Rare earth elements such as Erbium (Er) and Ytterbium (Yb) relevant to photonic materials and neutral atoms.
4. **Dependency on exotic materials:** Exotic materials are found in materials, electronics, and, on occasion, laser/optics and cryo/vacuum. Some of these transition metals are relevant to the fabrication of superconducting qubits along with Aluminum (Al); Alkali Metals and Alkaline Earths such as Strontium (Sr) and Rubidium (Rb) relevant to neutral atom and ion trap quantums sensors; and other materials essential to ion pumps. Most of these exotic materials are sourced from the Global South or non-friendly countries.
5. **Dependency on photonic and nonlinear materials:** This includes compounds such as lithium niobate ($LiNbO_3$) and thin-film lithium niobate which are typically produced in Japan and China. Increasingly, photonic materials and nonlinear crystals are sourced from China. In many cases, the high-quality materials required are refined in China creating serious problems even when they are mined in a friendly country.
6. **Limited capability to scale MEMS Vacuum Chambers production**, due to a manufacturing on R&D scale production along with extremely long lead times for critical subcomponents for hermetic seal production creates risks for all ion-trap and neutral atom based quantum sensor modalities.
7. **Investment Landscape:** As described above, the imbalance in the investment landscape including venture capital and internal investments by big tech create an imbalance in both the startup scene and in the location of system integrators.

The main difference from our quantum computing supply chain study is the inclusion of SiC and III-V semiconductor capabilities.

6. Conclusion and recommendations

The chapter synthesizes the preliminary findings to identify overarching trends and critical areas of concern across qubit modalities and technologies. This synthesis highlights strategic priorities for policy and investment, helping to shape future initiatives in Quantum Sensing.

The primary objective of this analysis is to identify and clarify which parts of the quantum sensing ecosystem are missing or underdeveloped within the Alliance. Consequently, this study focuses on critical dependencies—specifically, those components of the supply chain that require attention. Technologies or elements deemed to be "good enough" fall outside the scope, as they do not represent areas of concern or opportunity for improvement. Therefore, elements assessed as sufficiently developed or stable are not highlighted in the conclusions, allowing this study to maintain a targeted focus on areas in need of strategic improvement.

The analysis, like our quantum computing supply chain study, has revealed several critical cross-cutting dependencies that pose significant risks to the quantum sensing ecosystem within the Alliance. As with our quantum computing study, the Alliance faces substantial challenges regarding semiconductor manufacturing supply chains and fabrication facilities. The heavy reliance on non-Allied sources for rare earth elements, such as Erbium and Ytterbium, is essential for various quantum components. The dependence on exotic materials, compounds, and isotopes presents another significant vulnerability, as these materials are often sourced from potentially unstable or non-allied regions.

In terms of technology-specific vulnerabilities, the study identified that more than 90% of high-purity material processing occurs outside NATO territories. The electronics sector shows considerable dependence on Asian fabrication facilities for advanced nodes, optical coatings, ASICs, FPGAs, and PICs.

However, the analysis also found several risks that were either new or significantly more pressing. Among these were the need to have SiC and III-V semiconductor fabrication facilities that are essential to highly integrated quantum sensor systems and that are essential to low-SWaP laser and photonic systems including PICs. This also brought a heavier emphasis on photonic crystals and other photonic systems including thin film lithium niobate. Increasingly the photonic industry is dominated by both our Asian allies and our strategic competitor, China. This is especially critical with respect to the nascent PIC industry and its relevance to broader technologies.

Looking at the R&D position and possibility to scale the technology within the Alliance, it is noted that the position in quantum sensing is less solid, with some fields in which non-Allied competitors are dominant, such as photodetection systems, lithium niobate processes, and both the refining of III-V materials and their fabrication facilities. Finally, when it comes to environmentally robust laser systems with low-SWaP the West is underperforming in part because the existing laser systems for quantum computing are aimed at an R&D environment and thus have neither the size nor the ruggedness required for fieldable quantum sensors.

Based on these vulnerabilities, a few recommendations are proposed to workstream 2 of the TQC to help inform their analysis. While these include proposed briefing documents to share within the Alliance to aid with coordination on common problems, a few key studies, and a larger number of targeted programs, it is felt that workstream 2 will be most informed to make final recommendations and prioritization to the TQC.

Briefing Documents:

- Key fabrication facility requirements for quantum sensors
- List of critical materials needed for various quantum systems, whether rare earths, superconducting materials, or materials required for photonic systems, PICs, and/or lasers and optics.
- List of critical components (e.g. hermetic seals, MEMS vacuum devices, ion pumps, photodetectors) sourced from suppliers outside the Alliance within the quantum sensing supply chain.

The goal of these briefing documents is to explain the problem with the goal of coordination with other ongoing NATO efforts to address semiconductor fabrication facilities and rare-earths or other exotic materials within the Alliance. Each briefing should consist of a 2-page synopsis and a handful of slides.

Key Studies:

- Explore and prioritize the appropriate fabrication infrastructure that must be invested in to help guarantee that the Western ecosystem has access to SiC and III-V semiconductor capabilities appropriate to PICs and photonics. This should include packaging facilities, flip-chip bonding, and other capabilities essential to both a robust R&D community and early manufacturing capabilities.
- Perform an econometric study on the appropriate balance in investment between quantum system integrators and the nascent quantum supply chain for environmentally robust and low-SWaP systems and components.
- Explore options for interventions to balance the investment landscape in the US with the investment landscape in the EU and Canada specifically for the quantum technologies sector, as well as the possible interventions to avoid additional trade and export restrictions.

The goal of these studies is to provide NATO and member states with either potential solutions or possible paths forward.

Targeted Programs:

- Explore and support a pilot program focused on producing the small quantity (less than 10 kg/year and probably less than 1 kg/year) qubit material needed to support neutral-atom and/or ion-trap quantum sensing efforts, with a goal of understanding the feasibility and path toward technological independence. TQC workstream 2 may have an identified list of plausible atoms.
- Use the results of the study aimed at appropriate fabrication infrastructure required for the Western ecosystem to have access to SiC and III-V semiconductor capabilities appropriate to PICs and photonics. Work across the Western ecosystem to support the study and make new investments in infrastructure that reduces risks, creates competition where most needed, while creating complementarity in capabilities across the Western ecosystem.
- Prioritize coordination between NATO allies with strong capabilities and testbeds in the Quantum Sensing domain, including the US, France, Germany, Netherlands and the UK. By developing interoperability between the various testbeds and technologies and exchange of best practices, deployment of quantum sensing within the Alliance will be accelerated.
- Create R&D programs aimed at supporting both the quantum supply chain and the system developers to create environmentally robust systems and components, that are both fieldable and have low SWaP.
- Build a NATO innovation program aimed at incentivizing new commercial activity to increase competitiveness within the Alliance for hermetic seals, MEMS vacuum devices, ion pumps, and photodetectors.
- Implement targeted interventions to balance the investment landscape in the US with the investment landscape in the EU and Canada within the quantum technologies sector, and to avoid additional trade and export restrictions – based on the results of the key study on this subject.