

# QUANTUM SENSING LANDSCAPE

Quantonation Whitepaper — 2026 Edition

MALO LE GALL

FEBRUARY 2026

# QUANTONATION

# QUANTUM SENSING LANDSCAPE

## EXECUTIVE SUMMARY

Quantum sensors include diverse technologies leveraging quantum states to achieve performance beyond conventional sensors:

- Superconducting devices have offered record sensitivities since the 1960s, but they have faced field deployment constraints.
- Atomic and ion devices have recently achieved record performance. They have been undergoing an important miniaturization effort in the 21st century.
- Solid-state spin defects – NV centers in diamond and beyond – provide unique access to nanoscale and multimodal sensing.
- Photonics is undergoing renewal with integrated platforms, optomechanics and quantum states of light.

Each technology has distinct sensitivity, robustness or form factor advantages. The key to quantum sensing success is therefore a careful match between technology and applications.

Some industries will be more impacted:

- Quantum sensors will offer access to new measurement regimes in body imaging (including human-machine interface) and molecular biosensing.
- Quantum sensing in industry focuses on high-value use cases like chip inspection and non-destructive testing. Mastering integration into manufacturing workflows is essential for adoption.
- For navigation, they provide alternatives or complements to GNSS through magnetic, gravitational, inertial and timing measurements, with military and spatial as important drivers. Resilience, portability and sensitivity are equally required, along with new accurate maps.
- In the energy domain, quantum gravimetry and magnetic sensing can improve subsurface characterization and infrastructure monitoring. But robustness and form factor are critical.
- Quantum detectors bring sensitivity and stealth advantages in security and defense, with an important willingness to pay.
- Many quantum sensors originate from fundamental matter, particle and astrophysics experiments, which continue to push towards extreme sensitivity.

The quantum sensing commercial ecosystem has remained relatively small compared to computing and communication: despite their technological readiness, translation of laboratory performance into field operation and market adoption have been the main roadblocks so far. Yet the military and sovereignty stakes explain important public funding.

Quantum sensing is therefore a fragmented field, where matching technologies specificities to market needs requires expertise for significant value creation. Informed surveys will also be key to spot the next major sensing paradigms stemming from material science, qubits development or quantum states manipulation.

# QUANTUM SENSING LANDSCAPE

## PREFACE – DAVID ROY-GUAY

Still in its early days, the new wave of quantum technologies holds potential that extends far beyond raw performance gains. Its true promise lies in redefining how we address important and complex societal challenges, expanding the range of “jobs to be done” that technology can meaningfully tackle. While early discourse around quantum computing largely emphasized computational power, quantum sensing has followed a markedly different trajectory—one defined by the identification of novel, field-deployable problems with the capacity to directly impact end-user workflows. As a result, the value created by quantum sensors is limited less by technical limits than by our imagination, fueled by the ability to align breakthrough capabilities with real-world use cases.

The sensing landscape thus finds itself at a crossroads. One path follows incremental innovation—smaller, faster, and more precise devices achieved by continuously pushing performance frontiers. The alternative path focuses on identifying acute value-creation points, where quantum capabilities can be combined with conventional sensing solutions to unlock entirely new, game-changing commercial opportunities. The latter shifts the focus from isolated component performance to system-level impact.

In this context, the most impactful quantum sensors of the future are likely to emerge from unforeseen “unfair advantages” that can only be uncovered through sustained, rigorous problem-market fit efforts. In many applications, realizing this potential will require the fusion of multiple sensing modalities, blending classical and quantum approaches to deliver robust, deployable solutions that outperform either paradigm alone. There, algorithmic approaches that unify multiple sensing methods within a single quantum sensor can preserve size, weight, and power requirements, while delivering true “Swiss Army knife”-style versatility.

The coming years will therefore see the rise of companies built at the intersection of deep domain expertise and quantum technology. These ventures will be led by entrepreneurs who intimately understand a problem space and work hand-in-hand with quantum experts to identify, validate, and iterate on concrete value-creation opportunities. By engaging directly with end users, gathering expert knowledge in the field, and rapidly refining solutions, these teams will deliver integrated systems that abstract away the technical subtleties of quantum physics, offering products that are simply “powered by quantum.”

In a world that has long taken the availability of natural resources for granted, assumed stable geopolitics, and relied on ubiquitous high-precision positioning, navigation, and trustworthy data to fuel increasingly complex healthcare and industrial insights, quantum sensing opens the door to unforeseen opportunities. It is now up to the next generation of quantum-literate, problem-driven entrepreneurs to come together and turn these possibilities into reality—to deliver what was once unthinkable.

# QUANTUM SENSING LANDSCAPE

## INTRODUCTION

Quantum sensors are setups that make use of fundamental quantum properties to achieve better measurement performance than classical systems. A definition given in a reference paper on quantum sensing<sup>1</sup> encompasses technologies using the phenomena of energy quantization – like the discrete levels in an atom or the two levels in a qubit –, quantum coherence – superposition and interference of states in the wave-like behavior of light and matter – and quantum entanglement. This definition is broad, as it does not limit to entanglement-enhanced systems which often define the stricter class of “quantum-enhanced” metrology, still narrow and mainly limited to scientific research.

The diversity of quantum sensors is often mentioned: when compared to quantum computing or communications, sensors exhibit a wide diversity, both in technologies and in applications. This often makes them difficult to compare with each other, each application having its own precise requirements and each sensor having its own specifications, ranging from physical parameters such as sensitivity, bandwidth, stability, dynamic range, and many more, to practical considerations such as size, weight, power, and cost (SWaP-C), robustness, ease of use, etc. A thorough understanding of sensor specifications and application requirements for identifying product-market fit is therefore a strong added value in quantum sensing. This whitepaper tries to bring together knowledge from both perspectives by reviewing the historical evolution, recent advances, and ongoing exploratory efforts in quantum sensing technologies in relation to current market trends.

<sup>1</sup>C. L. Degen et al., « Quantum sensing », Reviews of Modern Physics 89, no 3 (2017): 035002, <https://doi.org/10.1103/RevModPhys.89.035002>.

<sup>2</sup>« Quantum sensing’s potential: Insights for leaders | McKinsey », consulté le 9 octobre 2025, <https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/quantum-sensings-untapped-potential-insights-for-leaders>.

# QUANTUM SENSING LANDSCAPE

## INTRODUCTION

Some quantum sensors have already been in use since the 20th century: atomic clocks are essential to GPS, and superconducting quantum interference devices are the core of magnetoencephalography in hospitals and research centers. Over the past two decades, a new generation of research outputs has proven many advantages, either in sensitivity or in practical considerations. However, while the core quantum sensing principles are relatively mature compared to quantum computing or communications, many quantum sensors have remained in niche markets, often in specific defense applications. The quantum sensor ecosystem has remained relatively small, with 48 quantum sensing startups launched in 2022–2024, five times fewer than quantum computing startups and with much less growth in valuations<sup>2</sup>. The whitepaper is thus driven by this problem statement: what has been lacking so far for quantum sensing to become an economic success?

Part of the answer lies in the R&D needed to drive engineering reliability, SWaP-C improvements, and boost quantum sensing applications into larger commercial markets. As an indicator of this ongoing effort, quantum sensing R&D has accelerated significantly, with a 10x increase in quantum sensing patent applications over the last decade. In the following, we outline how recent progress translates into opportunities.

# 1) PILLAR TECHNOLOGIES

Quantum sensing technologies can be categorized into several main pillars: superconducting devices, atomic and ion-based systems, solid-state spin defects, and photonics. We review each category with a focus on their promises and challenges.

## 1.1. Superconducting technology

Superconducting sensors are a good starting point for a broader commercialization analysis of quantum sensors. Studied since the 1960s as devices with record sensitivity, they have been proposed and explored in most of the major fields of application of today's quantum sensors. Examining these sensors and understanding why they succeeded in some applications, and what was lacking for broader deployment, is thus an insightful first case study.

### 1.1.1 The SQUID

The Superconducting Quantum Interference Device (SQUID) dates back to the 1960s<sup>3</sup>. It works by the interaction of the magnetic field with a superconducting current in a cryogenically cooled device. This sensor still reaches the best magnetic field sensitivities down to the  $fT/\sqrt{Hz}$ , enables broadband working from DC to MHz, and has a good dynamic range. Its main disadvantage is that this device needs to be cooled below a very low critical temperature  $T_c$  to have its superconducting properties and work. It therefore requires a cryocooler, which is often bulky (tens of liters), costly and requires maintenance and refills. Two categories of superconductors can be distinguished by their critical temperature:

-Low- $T_c$ , often operated with liquid 4He cryocooler at  $\leq 4.2K$ . They are used where high sensitivity is required.

-High- $T_c$ , often operated with a liquid nitrogen cryocooler at  $\leq 77K$ , which is a simpler device than 4He cryocooler. High- $T_c$  superconducting materials are more complicated to manipulate and noisier than low- $T_c$ . They are used in applications requiring lower SWaP-C and reduced performance requirements.

<sup>3</sup>R. C. Jaklevic et al., « Quantum Interference Effects in Josephson Tunneling », Physical Review Letters 12, no 7 (1964): 159-60, <https://doi.org/10.1103/PhysRevLett.12.159>.

Since the 1960s, a broad range of applications have been explored. The handbooks by Prof. Clarke and Braginsky<sup>4</sup> list many proposals; some of which were further developed, as cryogenic devices became easier to operate. Looking at their current scope provides insight into the challenges of SQUIDs.

One of their applications is in biomedicine, especially magnetoencephalography (MEG) and magnetocardiography (MCG) for noninvasive mapping of brain and heart activity. These very sophisticated, room-sized devices have been commercialized globally for two decades. However, the commercialization has remained limited to a few hundred devices, which can be mainly understood as being due to their high cost and low flexibility. We review this application in more detail in the second part of this paper. SQUIDs were also proposed in magnetic immunoassays and for monitoring iron or tracer movement in organs.

In industry, SQUIDs were proposed for nondestructive testing of aircraft, reactors, infrastructure and microelectronics circuits by revealing cracks or inclusions through passive or induced magnetic responses. They have the advantages of excellent sensitivity which makes them suitable for detection of buried cracks, and a wide dynamic range. Demonstrations and industrial prototypes have been built for these applications<sup>5 6</sup>. However, their poor spatial resolution and bulkiness may explain their very limited deployment, as detection of small defects is critical and ease of use is required for field operation.

In geophysics, high-Tc SQUIDs were proposed to detect subsurface conductivity anomalies to locate mineral and oil deposits or buried ordnance and submarines. Here too commercial devices were developed since the 2000s<sup>7 8</sup> but with limited use. For these applications, field portability is necessary and the competition of much easier-to-use classical sensors with lower performance may have hindered their deployment.

<sup>5</sup><https://www.wesdyne.com/wp-content/uploads/2018/06/PWR-Type-Nozzle-Inspection-system-SQUID-NS-FS-0149.pdf>

<sup>6</sup><https://neoceramagma.com/semiconductor-failure-analysis-tools/semiconductor-failure-analysis-capabilities>

<sup>7</sup><http://www.supracon.com/de/unternehmen.html>

<sup>8</sup><https://sustec.jp/usecase.html>

Besides magnetic field sensing, SQUIDs also act as amplifiers and transducers. They have interesting advantages for low-frequency nuclear magnetic resonance, which is finding applications in accessible ultralow-field MRI, discussed later in this paper. They also found applications in bolometers and X-ray detectors for astrophysics and particle physics. X-ray detection has important commercial applications for semiconductor anomaly detection, security scanning and medical imaging, where more sensitive detectors can enable the use of less damaging X-ray power. Yet SQUIDs did not find broad use in these applications, again probably because of their SWaP-C. SQUID transducers were also proposed in precision accelerometers and gravity sensors, without noticeable deployment.

Beyond these early proposals and commercial attempts, the SQUID story is also continuing in research laboratories. Miniaturized nanoSQUIDs have been invented to image magnetic and thermal properties with sub-micron resolution<sup>9</sup> <sup>10</sup>. They are also widely employed in superconducting circuit quantum computers, as detection elements or as qubits themselves.

### 1.1.2. Superconducting qubits

Conversely, the research in superconducting qubits has led to new quantum sensors. Qubits have been proposed as magnetic field sensors at  $\text{pT}/\sqrt{\text{Hz}}$  level<sup>11</sup> or as single microwave photon detectors with record sensitivity<sup>12</sup>, with initial applications in particle physics. Such single-photon counters have recently enabled the microwave detection of single spins for the first time<sup>13</sup>, with expected applications in spectroscopy/biosensing at unprecedented levels as well as in quantum computation.

### 1.1.3. Transition edge sensors and beyond

Superconductors can also be used in another approach as transition edge sensors<sup>14</sup>, for the very sensitive detection of massive particles or photons, from X-ray to THz radiation. The working principle makes use of the superconducting transition: below their critical temperature, superconductors exhibit no resistivity, whereas above this temperature they sharply develop a finite resistivity. Operating just below this temperature makes them very sensitive to any incident energetic particle. They are used in astronomy and particle physics, but also as prototypes in biology and in nondestructive chip testing, notably in work at NIST. Other superconducting sensors include microwave kinetic inductance detectors<sup>16</sup> and superconducting nanowire single-photon detectors.

<sup>9</sup>Denis Vasyukov et al., « A Scanning Superconducting Quantum Interference Device with Single Electron Spin Sensitivity », *Nature Nanotechnology* 8, no 9 (2013): 639-44, <https://doi.org/10.1038/nnano.2013.169>.

<sup>10</sup>D. Halbertal et al., « Nanoscale Thermal Imaging of Dissipation in Quantum Systems », *Nature* 539, no 7629 (2016): 407-10, <https://doi.org/10.1038/nature19843>.

M. Bal et al., « Ultrasensitive Magnetic Field Detection Using a Single Artificial Atom », *Nature Communications* 3, no 1 (2012): 1324, <https://doi.org/10.1038/ncomms2332>.

<sup>12</sup>L. Balembois et al., « Cyclically Operated Microwave Single-Photon Counter with Sensitivity of  $10 - 22 \text{ W} / \text{Hz}$  », *Physical Review Applied* 21, no 1 (2024): 014043, <https://doi.org/10.1103/PhysRevApplied.21.014043>.

<sup>13</sup>« All-Microwave Spectroscopy and Polarization of Individual Nuclear Spins in a Solid », <https://doi.org/10.1126/sciadv.adu0581>.

<sup>14</sup>Mario De Lucia et al., « Transition Edge Sensors: Physics and Applications », *Instruments* 8, no 4 (2024): 47, <https://doi.org/10.3390/instruments8040047>.

<sup>15</sup>Zachary H. Levine et al., « A Tabletop X-Ray Tomography Instrument for Nanometer-Scale Imaging: Reconstructions », *Microsystems & Nanoengineering* 9, no 1 (2023): 47, <https://doi.org/10.1038/s41378-023-00510-6>.

<sup>16</sup>Day, P.K.; LeDuc, H.G.; Mazin, B.A.; Vayonakis, A.; Zmuidzinas, J. A broadband superconducting detector suitable for use in large arrays. *Nature* 2003, 425, 817-821.

#### 1.1.4. Superconducting gravimeters

Superconductivity is also used in the most precise relative gravimeters, making use of another physical phenomenon: a superconducting sphere is magnetically levitated using persistent currents in superconducting coils. This allows extremely stable measurement of relative gravity variations. Both their bulkiness and sensitivity to handling and their ability to measure only gravity differences – not absolute gravity measurements – may explain why these record devices have not found widespread application in gravity navigation or geophysical exploration.

#### 1.1.5. Superconducting devices: conclusion

Superconducting devices are thus a prominent example of quantum sensors with a strong advantage in performance, for which many applications were expected, but that have remained constrained to high-grade scientific applications and niche commercial use cases with limited extent. The example of SQUIDs speaks to the complexity of fitting the value proposition of quantum sensors in the right use case: ultralow-field SQUID-MRI is an example where a technology brick developed in the 1960s is currently finding an interesting application. This reinforces how valuable a thorough understanding of device capabilities and market requirements is when assessing sensing technologies. Encumbrance issues were the main limit of superconducting technologies, which provides insight for analyzing new quantum sensors with a very diverse range of SWaP-C and value propositions.

## 1.2. Atomic & ion sensors

Atomic sensors are an example of versatile devices with a broader value proposition: some of them reach record sensitivities while others bring better SWaP. They have been employed since the second half of the 20th century in space applications, as they can sense time, electromagnetic fields, and motion with excellent precision. But they have also been an active research field in the 21st century with the miniaturization of vapor cells and the development of cold atom trapping. Some key properties are reviewed, while their use in magnetoencephalography, navigation and clocks are further discussed in the applications section.

At a fundamental level, these devices use the core properties of atoms and ions as quantum systems with discrete, well-defined energy levels. The key advantage is that atomic properties are identical for a given species and depend only on fundamental physical constants, providing inherent calibration stability.

### 1.2.1. OPM

An early use of atomic properties under a magnetic field is in proton-precession magnetometers, where protons in hydrogen-rich species precess under an applied magnetic field. They have been used since the 1950s in space applications<sup>17</sup>, but were soon replaced by Optically Pumped Magnetometers (OPMs), a particular form of thermal atomic vapors.

In hot neutral atomic vapors, alkali atoms – often rubidium – are contained in glass cells and manipulated and read out by microwave fields and optical beams. They can be designed to serve as magnetometers, gyroscopes or clocks.

OPMs are such vapor cells used as magnetometers. In these devices, a light source is used to manipulate the quantum state of atoms and effectively pump the atomic ensemble into a desired state sensitive to the magnetic field – in a process called optical pumping. A magnetic field then causes the spins to precess and this precession is read out optically. Theorized in the 1950s, these devices were improved to reach 30 fT/ $\sqrt{\text{Hz}}$  in the 1970s, limited by collisions between atoms. Strongly increasing the collision rate between atoms by working with dense heated vapors surprisingly proved to average out the collision effect – in a spin exchange relaxation free (SERF) regime. In the 2000s, SERF reached sensitivities rivaling and even surpassing superconducting magnetometers<sup>18</sup>, reaching a record of 160 aT/ $\sqrt{\text{Hz}}$ <sup>19</sup>. However, in this regime they need to work at near-zero magnetic field, in a magnetically shielded environment – while coherent population trapping (CPT) and “Mx” magnetometers are less sensitive OPM variants but can work in an ambient field.

<sup>17</sup>I. R. Shapiro et al., « The Vector Field Proton Magnetometer for IGY Satellite Ground Stations », *Journal of Geophysical Research* (1896-1977) 65, no 3 (1960): 913-20, <https://doi.org/10.1029/JZ065i003p00913>.

<sup>18</sup>Budker D., Kimball D.F., Rochester S.M., Yashchuk V.V., Zolotarev M. Sensitive magnetometry based on nonlinear magneto-optical rotation. *Phys. Rev. A: At., Mol., Opt. Phys.* 2000;62(4):7. doi: 10.1103/PhysRevA.62.043403.

<sup>19</sup>H. B. Dang et al., « Ultrahigh Sensitivity Magnetic Field and Magnetization Measurements with an Atomic Magnetometer », *Applied Physics Letters* 97, no 15 (2010): 151110, <https://doi.org/10.1063/1.3491215>.

## 1.2.2. Chip-scale vapor cells

OPMs were predicted to be suitable for some applications previously studied for SQUIDs, with the advantage of being an absolute measurement reference, requiring no cryogenics and offering emerging miniaturization. Indeed, OPMs saw increasing interest following the successful realization of chip-scale atomic vapor cells in the 2000s<sup>20</sup>, enabled by silicon micromachining and the invention of Vertical-Cavity Surface-Emitting Lasers (VCSEL), a semiconductor laser technology. Chip-scale OPMs demonstrated the advantage of centimeter- to millimeter-scale size and mW-scale low-power operation. Their sensitivities were also very good: about 10 fT/ $\sqrt{\text{Hz}}$  for SERF operating at zero field in magnetically shielded environments, and 10 pT/ $\sqrt{\text{Hz}}$  for ambient field CPT and Mx magnetometers<sup>21</sup>. However, they have not yet achieved industrial-scale production. Moreover, increasing their reliability is one of their challenges. This encompasses reducing gas leakage and extending their lifetime which is typically a few years. Further research is also expected to extend their capabilities, with for example new cell architectures, or further integration with photonics to replace free-space beams. These chip-scale cells also find applications in clocks and gyroscopes.

## 1.2.3. Vapor cells as gyroscopes

Vapor cells can be used as gyroscopes because rotation influences the precession of the atomic spins, which can then be measured. For this application, it is important to suppress the effect of the magnetic field to be more sensitive to pure rotation. As opposed to magnetometers, the electron spin of alkali atoms cannot be used directly because it is very sensitive to the magnetic fields. Instead, we make use of the nuclear spins in a noble gas for their lower sensitivity to magnetic field and longer lifetime, whereas alkali atoms are only used to communicate with the noble gas. Moreover, two atomic species are often used to subtract the influence of the magnetic field, and additional magnetic shielding is required – for a total chip volume of a few cm<sup>3</sup>.

<sup>20</sup>John Kitching, « Chip-Scale Atomic Devices », *Applied Physics Reviews* 5, no 3 (2018): 031302, <https://doi.org/10.1063/1.5026238>.

Ricardo Jiménez-Martínez et Svenja Knappe, « Microfabricated Optically-Pumped Magnetometers », in *High Sensitivity Magnetometers*, éd. par

<sup>21</sup>Asaf Grosz et al., vol. 19, *Smart Sensors, Measurement and Instrumentation* (Springer International Publishing, 2017), [https://doi.org/10.1007/978-3-319-34070-8\\_17](https://doi.org/10.1007/978-3-319-34070-8_17).

#### 1.2.4. Vapor cells as clocks

Vapor cells are also used as clocks. In this design, a given atomic transition between two energy levels within the atom serves as an absolute timing reference – since an energy difference corresponds to a well-defined frequency which is the inverse of a time. Probing this transition with a laser or microwave source enables one to obtain this highly accurate frequency reference. These clocks currently dominate applications where timing accuracy over hours to days is important, such as in base stations for cellular telephone systems. A miniaturized version was similarly developed in the 2000s, with much lower SWaP, but also lower time accuracy. Depending on the application, it can outperform bulkier or less precise clocks.

#### 1.2.5. Cesium beam clocks

Conversely, higher-precision applications – where stability or accuracy over months is needed, such as high-speed telecommunications systems – mainly employ cesium beam clocks. They are based on the same principle, with the atoms moving along a collimated beam instead of being contained in a cavity. However, the devices are larger and more expensive.

#### 1.2.6. Hydrogen maser clocks

For high short-term precision but niche applications, hydrogen maser clocks are used, also making use of atomic transitions: hydrogen atoms stored in a resonant cavity are stimulated to emit microwaves at a given frequency, on a principle similar to that of a laser. Their size and cost limit them to Earth-based scientific applications.

#### 1.2.7. Atomic fountain clocks

Besides these established clock technologies and the breakthroughs in miniature vapor cells, other clocks have emerged. Progress in cold atom trapping has recently enabled the emergence of cold atom clocks. Fountain clocks work on the same atom interrogation principle as vapor cells and cesium beams, but with laser-cooled atoms, extending unperturbed interaction time for better accuracy.

#### 1.2.8. Optical clocks

Even more precise are optical clocks, which currently achieve the highest performance. While all previous clock types interrogated a microwave transition, optical clocks are based on the interrogation of an optical transition, which is higher in frequency and thus oscillates faster, improving time measurement as it is averaged over more oscillation events. Two implementations have achieved record accuracy: single trapped ions<sup>22</sup> and cold neutral atoms trapped in an optical lattice<sup>23</sup>.

<sup>22</sup>Huntemann, N., C. Sanner, B. Lipphardt, C. Tamm, and E. Peik (2016), Phys. Rev. Lett. 116, 063001.

<sup>23</sup>Bloom, B. J., T. L. Nicholson, J. R. Williams, S. L. Campbell, M. Bishof, X. Zhang, W. Zhang, S. L. Bromley, and J. Ye (2014), Nature 506 (7486), 71.

### 1.2.9. “Quantum-enhanced” clocks

Further versions of atomic clocks may achieve even better accuracy by using so-called “quantum-enhanced” states such as spin squeezing or entanglement. Spin squeezing overcomes the quantum noise that appears at a fundamental limit, by reducing the uncertainty in the measurement direction (while increasing it in the other direction, as stated by fundamental quantum principles). Spin squeezing can also be understood as a form of entanglement, which makes use of quantum correlations between the atoms to be measured, to extract more information from the system than from each atom individually. If such states have already led to remarkable scientific demonstrations, their use in clocks has been demonstrated with too few particles to increase clock accuracy for now<sup>24</sup>. But much research is ongoing and such phenomena could lead to new state-of-the-art “quantum-enhanced” optical clocks.

### 1.2.10. Cold-atom interferometers

If cold atoms make excellent clocks, they can also be used as gravimeters, gyroscopes, and accelerometers, when employed in an interferometric protocol where atoms behave as matter waves. In the interferometer, light pulses act like beam splitters separating the atomic wavepacket in two different trajectories that undergo a phase difference related to the field to be measured. For instance, the gravimeter interferometer throws the atoms into a parabolic trajectory, free-falling under gravitational acceleration. A few laser pulses imprint phases dependent on the trajectory of the atoms, and the interferometry protocol thus serves as a way to measure the curvature of this parabola, which gives the value of the gravity field.

Gyroscopes and accelerometers are based on similar protocols. Experimental demonstrations have been made since the 2000s<sup>25</sup>, and they are being developed into portable devices. The commercial state of these devices is discussed in more detail in the applications section.

<sup>24</sup>Ricardo Jiménez-Martínez et Svenja Knappe, « Microfabricated Optically-Pumped Magnetometers », in High Sensitivity Magnetometers, éd. par Asaf Grosz et al., vol. 19, Smart Sensors, Measurement and Instrumentation (Springer International Publishing, 2017), [https://doi.org/10.1007/978-3-319-34070-8\\_17](https://doi.org/10.1007/978-3-319-34070-8_17).

<sup>25</sup>A. Peters, K. Y. chung, S. chu, high-precision gravity measurements using atom interferometry. Metrologia 38, 25–61 (2001).

### 1.2.11. Trapped ions

We also mentioned trapped ions as record-accuracy optical clocks, when trapped in vacuum by electric or magnetic fields. But like neutral atoms, they can also be employed as field sensors. Indeed, their spin states are similarly sensitive to magnetic fields, and they have been demonstrated as magnetic sensors<sup>26</sup>. They are also sensitive to rotation and have been proposed as gyroscopes<sup>27</sup>. Additionally, the motion of these ions couples strongly to electric fields or forces to be sensed. However, sensing with trapped ions is often limited to single ions, compared to the many atoms used in vapor cells, which makes them not competitive in terms of sensitivity level. This limits their advantage to extreme resolution applications, leveraging their high sensitivity per unit volume. But to exploit this high resolution they need to be operated near the surface to be sensed, which is complicated with ion traps. Many-ion trapping and entanglement may yet increase the sensitivity of such sensors or clocks in practical applications<sup>28</sup>, which is driven by ion-trap quantum computing<sup>29</sup>.

### 1.2.12. Rydberg atoms

Like trapped ions, Rydberg atoms can act as remarkable electric field sensors, since their loosely bound electron in a large orbit is easily displaced by electric fields. This has enabled fundamental quantum physics demonstrations, for example the detection of single microwave photons without destroying them<sup>30</sup>, later enhanced by the use of non-classical Schrödinger-cat superpositions<sup>31</sup>. From an applications perspective, atomic vapor cells of Rydberg atoms have already been demonstrated<sup>32</sup>, but not broadly commercialized. They could be used for example in communication, an application pursued for ten years by Rydberg Technologies<sup>33</sup>. These devices are still under active research as they face some intrinsic bandwidth challenges<sup>34</sup>.

<sup>26</sup>Baumgart, I., J.-M. Cai, A. Retzker, M. B. Plenio, and C. Wunderlich (2016), Phys. Rev. Lett. 116 (24), 240801.

<sup>27</sup>Campbell, W. C., and P. Hamilton (2017), Journal of Physics B: Atomic, Molecular and Optical Physics 50 (6), 064002.

<sup>28</sup>Kevin A. Gilmore et al., « Quantum-enhanced sensing of displacements and electric fields with two-dimensional trapped-ion crystals », *Science* 373, no 6555 (2021): 673-78, <https://doi.org/10.1126/science.abi5226>.

<sup>29</sup>Bohnet, J. G., B. C. Sawyer, J. W. Britton, M. L. Wall, A. M. Rey, M. Foss-Feig, and J. J. Bollinger (2016)

<sup>30</sup>Haroche, S. (2013), Reviews of Modern Physics 85 (3), 1083.

<sup>31</sup>Facon, A., E.-K. Dietsche, D. Grosso, S. Haroche, J.-M. Raimond, M. Brune, and S. Gleyzes (2016), Nature 535 (7611), 262.

<sup>32</sup>Jonathon A. Sedlacek et al., « Microwave Electrometry with Rydberg Atoms in a Vapour Cell Using Bright Atomic Resonances », *Nature Physics* 8, no 11 (2012): 819-24, <https://doi.org/10.1038/nphys2423>.

<sup>33</sup><https://www.rydbergtechnologies.com/resources?offset=1514039220817&reversePaginate=true>

<sup>34</sup><https://anr.fr/Project-ANR-20-ASTQ-0002>

### 1.2.13. Atomic and ion sensors: conclusion

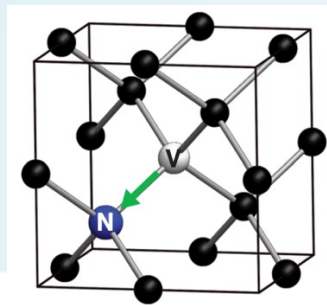
Atomic and ion sensors are therefore a good example of a highly versatile use of a given platform for sensing very different physical quantities. Importantly, the wide diversity and recent progress of these platforms provide a tunable range of sensitivities and SWaP-C for applications with different requirements. Moreover, this brief overview shows how the landscape of atomic clocks is evolving in research laboratories, despite a slower commercial deployment. The breakthroughs in optical clocks show that record sensitivities are still regularly beaten, while the history of chip-scale atomic devices speaks to the possibility for major disruption in the dimensions of quantum sensors. Two key points should be closely monitored: the commercial deployment of chip-scale atomic devices and the many research paths discussed in this section.

Additionally, we explored some examples of single-particle versus many-particle sensors which lay emphasis on this key difference: many particle sensors act as many repetitions of the same experiment, thus yielding higher accuracy; whereas single particles have the advantage of being smaller and can therefore provide better spatial resolution. This distinction is also important to understand “quantum-enhanced” protocols using non-classical states: they are often easier to demonstrate and find use with few particles, but their implementation in enhancing many-atom sensors has not yet been demonstrated in significant applications. This difference is also key in the physics of solid-state spin defect sensors.

### 1.3. Solid-state spin defects

Spin-defects are a recent class of sensors that were proposed<sup>35</sup> and soon demonstrated<sup>36 37</sup> in the late 2000s. Their main differentiating advantage compared to previously discussed sensors is the small size of the sensitive part that enables record spatial resolution. A second major advantage is the possibility to operate them under ambient conditions, but also in harsh temperature and pressure environments. A third asset is that they are multisensors of magnetic, electric, strain and temperature fields. Many applications were thus proposed for these sensors, alongside a continuous research effort to improve their properties.

These sensors are based on a crystalline material, where all atoms occupy well-defined lattice positions, but in which some defects are intentionally created. The nitrogen-vacancy (NV) defect in diamond, for instance, is created by the addition of a nitrogen atom substituting a carbon atom, adjacent to a carbon vacancy. As in atomic sensors, this system exhibits spin levels sensitive to the ambient field to be sensed and can be manipulated and read out with lasers and microwaves.



*Representation of the NV defect in diamond, where a nitrogen and a vacancy replace carbon atoms at their lattice positions.*

<sup>35</sup>Degen, C. L., 2008, Appl. Phys. Lett. 92, 243111.

<sup>36</sup>Balasubramanian, G., et al., 2008, Nature (London) 455, 648.

<sup>37</sup>Acosta, V. M., et al., 2009, Phys. Rev. B 80, 115202.

### 1.3.1. Ensemble- vs. single-defect sensors

The number of such defects can be tuned during fabrication, from isolated ones to a large ensemble of defects, which gives rise to two distinct regimes:

- Ensemble spin defect sensors use many spins, by means of a densely doped crystal, to enhance the signal strength. This gives them better sensitivity to tiny signals. For instance, NV ensembles in diamond demonstrated sub-pT/ $\sqrt{\text{Hz}}$  magnetic field sensitivities in laboratories<sup>38</sup>. This is not as good as SQUIDs or SERF OPMs, but they have other advantages already mentioned: they are multisensors, they can be operated under ambient and harsh conditions, and they can be very close to a sample, enabling high spatial resolution. This is intuitive: the closer a sensor can be placed to the sample, the better it can resolve its details.

However, it turns out that ensembles of defects in diamond are not the sensors with highest spatial resolution. Indeed, the ensemble-to-sample distance is limited to tens of micrometers, as defect ensembles face issues when they are placed closer: they are very sensitive to noise at the surface of the diamond, which adds inhomogeneously across many spins. Therefore, they must be positioned tens of micrometers away from the surface, inside the bulk of the diamond.

- Single defect sensors are based on isolated defects individually addressable. They can be placed at nanometers from the surface of the sensor, thus closer to the material to be sensed. This enables record resolution. The drawback is that single spins produce weaker signals than ensembles.

### 1.3.2. NV centers in diamond

Diamond has been the most widely studied spin-defect material, achieving the best sensitivities. It was rapidly developed into laboratory demonstrations as an ensemble defect magnetic microscope<sup>39</sup> or single defect scanning probe tip<sup>40</sup> for diverse applications in biology, chemistry, rock studies and condensed matter physics among others. Biology applications have so far found limited uptake, but they may be unlocked by better regimes of sensitivity and resolution; they are still attracting much interest in research, with the advantage of diamond being chemically inert, hence not perturbing the sample. Other applications include magnetometry and device monitoring in harsh conditions, where diamond has the advantage of broad working range; or distant field vector magnetometry, for instance in magnetic navigation or in remote weapon detection, as the four axes of the diamond lattice structure makes it intrinsically sensitive to the three-dimensional orientation of a magnetic field.

<sup>38</sup>John F. Barry et al., « Sensitive Ac and Dc Magnetometry with Nitrogen-Vacancy-Center Ensembles in Diamond », Physical Review Applied 22, no 4 (2024): 044069, <https://doi.org/10.1103/PhysRevApplied.22.044069>.

<sup>39</sup>Edlyn V. Levine et al., « Principles and Techniques of the Quantum Diamond Microscope », Nanophotonics 8, no 11 (2019): 1945-73, <https://doi.org/10.1515/nanoph-2019-0209>.

<sup>40</sup>Vincent Jacques et al., « Microscopie magnétique à spin unique », Photoniques, no 108 (mai 2021): 32-35, <https://doi.org/10.1051/photon/202110832>.

Another interesting proposal is nano-diamonds, that can be integrated inside the biological or chemical sample to be at the nearest contact with the molecules to be sensed<sup>41</sup> or used in wide-field imaging<sup>42</sup>. They can also be used in levitation as rotation sensors – leveraging the Berry phase accumulated by the spin during its rotation<sup>43 44</sup>.

More generally, research on diamond-based quantum sensors continues to focus on pushing fundamental sensitivity limits, with the dual objective of improving current device performance and enabling new applications, notably in biosensing. A landmark review published in 2020 showed that experimentally achieved sensitivities were still four to five orders of magnitude above fundamental physical limits, and outlined concrete pathways for sensitivity improvements<sup>45</sup>, some of which have already begun to materialize<sup>46</sup>. Prof. Ronald Walsworth, co-author of this influential roadmap, highlights the central role of materials science in this progress: “The number one thing that has to be done – and there has been progress since that 2020 paper – is improving material properties. This is the most important factor for enhancing coherence times (and hence sensitivity) by improving charge stability, charge state ratio, strain... There has been steady improvement over the past 15 years. But, as with silicon in the 1960s and 1970s, or any technologically important material, material improvement is a long and expensive road with no shortcuts – yet it almost always pays off. If the material is important enough, it is worth the investment.”

Another research path for diamond is on-chip integration for important SWaP reduction. Although a proof of concept was demonstrated in 2019<sup>47</sup>, most of the work is still to be done. For instance, Element Six and Bosch recently partnered to develop such sensors.

The most advanced industrial application of diamond sensors is non-destructive analysis of semiconductors, where single-defects sensors can detect smaller cracks and ensemble-defect sensors can detect buried cracks. Beyond the sensitivity optimization strategies on which many researchers have been working for two decades, engineering of industrial devices appears to be the main challenge for broad market deployment. In particular, managing the high quality diamond resource and its integration into the sensors is challenging. SWaP-C improvements are within reach for the horizon of startups, but they require a technological development effort somehow decoupled from the fundamental sensitivity improvements made by researchers<sup>48</sup>.

<sup>41</sup>Adrish Sarkar et al., « High-Precision Chemical Quantum Sensing in Flowing Monodisperse Microdroplets », Science Advances 10, no 50 (2024): eadp4033, <https://doi.org/10.1126/sciadv.adp4033>.

<sup>42</sup>Saravanan Sengottuvel et al., « Wide-Field Magnetometry Using Nitrogen-Vacancy Color Centers with Randomly Oriented Micro-Diamonds », Scientific Reports 12, no 1 (2022): 17997, <https://doi.org/10.1038/s41598-022-22610-5>.

<sup>43</sup>Yuanbin Jin et al., « Quantum Control and Berry Phase of Electron Spins in Rotating Levitated Diamonds in High Vacuum », Nature Communications 15, no 1 (2024): 5063, <https://doi.org/10.1038/s41467-024-49175-3>.

<sup>44</sup>Zhang, H. & Yin, Z.-Q. « Highly sensitive gyroscope based on a levitated nanodiamond », Opt. Express 31, 8139 (2023).

<sup>45</sup>John F. Barry et al., « Sensitivity Optimization for NV-Diamond Magnetometry », Reviews of Modern Physics 92, no 1 (2020): 015004, <https://doi.org/10.1103/RevModPhys.92.015004>.

<sup>46</sup>John F. Barry et al., « Sensitive Ac and Dc Magnetometry with Nitrogen-Vacancy-Center Ensembles in Diamond », Physical Review Applied 22, no 4 (2024): 044069, <https://doi.org/10.1103/PhysRevApplied.22.044069>.

<sup>47</sup>Donggyu Kim et al., « A CMOS-Integrated Quantum Sensor Based on Nitrogen-Vacancy Centres », Nature Electronics 2, no 7 (2019): 284-89, <https://doi.org/10.1038/s41928-019-0275-5>.

<sup>48</sup>Interview with Mathieu Munsch, CEO of Qnami

### 1.3.3. Silicon carbide

Beyond diamond, several materials are emerging as promising hosts for spin defects, though with lower sensitivity. Silicon carbide (SiC) has sensitivities orders of magnitude lower, but it is easily compatible with semiconductor processing and photonic integration, and it is already widely produced industrially for other applications. Giovanni Scuri, a researcher at Stanford, explains: “Silicon carbide uniquely combines strong photonic and quantum capabilities. It supports ultra-low-loss photonics, is CMOS-compatible and therefore highly scalable. The qubits themselves exhibit excellent performance, with T2 coherence times reaching tens of milliseconds, and even longer in bulk structures or when coupled to nuclear spins. In short, the qubits are high quality, the photonic integration is robust, and the platform is inherently scalable.”

### 1.3.4. Hexagonal boron nitride

Hexagonal boron nitride (hBN) is a promising new material for sensing, that has attracted significant interest from the research community since the 2020s. Indeed, as opposed to diamond and SiC, it is not a bulk material but rather a two-dimensional platform for quantum sensing directly at surfaces. In an interview, Prof. Vincent Jacques, specialist in the domain of spin-defect sensors, tells the interest of researchers for this material: “I believe that there is a real possibility of doing something that we cannot do with diamonds, even if we have not done it yet, because the field is very young. But it has been shown that these defects can be stable even in hBN layers thinner than 1nm. It was a real question, and now we have measured it. We are now trying to carry out NMR detection experiments in a regime inaccessible to NV centers, thanks to the proximity effect.”

hBN also has the potential to be a better in-situ sensor thanks to its two-dimensional and elastic properties: its shape can adapt to the underlying structure of the sample, enabling it to have better spatial resolution for complex surfaces, and to sense the strain at the surface of the material. This material is still very recent and further analysis is needed to find its best market application. Prof. Chong Zu, from Washington University in St. Louis, emphasizes the diverse potential of hBN:

**“ WE COULD ENVISION OTHER DIRECTION FOR HBN, BEYOND MAGNETIC FIELD SENSING. WE THINK THAT ITS RESPONSE TO TEMPERATURE IS MUCH STRONGER THAN DIAMOND: WE COULD USE IT FOR HEATMAPPING. IT IS ALSO MUCH MORE SENSITIVE TO STRAIN, WHICH CAN BE VERY IMPORTANT IN 2D MATERIALS. I THINK THERE IS DEFINITELY A POTENTIAL FOR STARTUPS TO WORK ON THIS AND LOOK FOR APPLICATIONS.”**

### 1.3.5. Other spin defect sensors

Other semiconductors such as GaN, ZnO, AlN, and  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> are also being explored. These are known as “wide-bandgap” and “ultrawide-bandgap” materials, as their semiconductor energy gap is wide, which enables the spin defects to be well isolated inside this gap and have fewer interactions with surrounding energy bands thereby reducing noise and improving sensitivity. Transition-metal dichalcogenides (TMDs) and noble-TMDs are also under consideration<sup>49</sup>. Prof. Chong Zu, relates the state of this research:

**“PEOPLE ARE STARTING TO LOOK FOR DEFECTS IN TMD, THERE HAS BEEN MULTIPLE PAPERS PREDICTING THEM. BUT THERE HAS NOT YET BEEN EVIDENCE OF SPIN POLARIZATION, THAT WOULD BE NECESSARY FOR SENSING PROTOCOLS.”**

<sup>49</sup>Yinhua Hu et al., « Noble-Transition-Metal Dichalcogenides-Emerging Two-Dimensional Materials for Sensor Applications », *Applied Physics Reviews* 10, no 3 (2023): 031306, <https://doi.org/10.1063/5.0150018>.

### 1.3.6. Comparative table (1)

The main pros and cons of these platforms are described in the following table, mainly inspired from<sup>50</sup>.

Platform	Pros	Cons
<b>Diamond (NV<sup>-</sup> centers)</b>	<ul style="list-style-type: none"> <li>• Very high sensitivity to magnetic fields.</li> <li>• Also better sensitivity in electrometry and thermometry than other spin defect platforms.</li> <li>• Broad working conditions :up to 8.3 T, 4–625 K, 60 GPa<sup>51</sup>.DC to several GHz.</li> <li>• There is already a small-scale industry for diamond sensors production<sup>52</sup>. <ul style="list-style-type: none"> <li>• Nanodiamonds (tens of nm to μm) enable versatile use on many substrates and in liquids.</li> <li>• Potential for multimodal sensing: magnetic, electric, strain, pressure, temperature fields.</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Current production methods are costly, size-limited, and require complex lift-off. The core technology patents are also mainly possessed by a unique company, Diamond Six.</li> <li>• Loss of sensitivity when placing ensembles near the surface (best sensitivities 20μm deep in the bulk).</li> <li>• Loss of sensitivity when using single defects.</li> </ul>
<b>Silicon Carbide (SiC)</b>	<ul style="list-style-type: none"> <li>• Easy fabrication.</li> <li>• Industrially developed: CMOS-compatible semiconductor widely used in high-power, high-temperature, and high-frequency electronics.</li> <li>• Recent advances on SiC-oninsulator platform. <ul style="list-style-type: none"> <li>• Telecom-band NIR emission.</li> <li>• There is room for lesser studied but promising defects (NV and transition metal ions).</li> </ul> </li> <li>• Opportunity for multimodal sensor of both temperature and magnetic fields with VSi – defect.</li> </ul>	<ul style="list-style-type: none"> <li>• Loss of sensitivity when placing spins near the surface.</li> <li>• Low sensitivities in magnetometry (10<sup>4</sup>-10<sup>5</sup>x lower than diamond) and electrometry (50x lower than diamond).</li> </ul>

<sup>50</sup>D. R. Glenn et al., « Micrometer-Scale Magnetic Imaging of Geological Samples Using a Quantum Diamond Microscope », *Geochemistry, Geophysics, Geosystems* 18, no 8 (2017): 3254-67, <https://doi.org/10.1002/2017GC006946>.

<sup>51</sup>John F. Barry et al., « Sensitivity Optimization for NV-Diamond Magnetometry », *Reviews of Modern Physics* 92, no 1 (2020): 015004, <https://doi.org/10.1103/RevModPhys.92.015004>.

<sup>52</sup>Mathieu Munsch et al., *Deck Qnami* 2023, s. d.

### 1.3.6. Comparative table (2)

<p><b>Hexagonal Boron Nitride (hBN)</b></p>	<ul style="list-style-type: none"> <li>• Atomically thin hBN allows spin defects to be placed extremely close to the target, enabling highly localized measurements.</li> <li>➔ Proximity of spin defects to sample increases sensitivity and spatial resolution. This feature is only relevant when sample is nm-scale near to the probe.</li> <li>• Widely used in low-dimensional devices, so its fabrication technology is mature for research purposes.               <ul style="list-style-type: none"> <li>• As a VdW material, it has good heterostructure stacking capability. Thin hBN layers' elasticity allows them to conform to surfaces, making it promising for strain sensing.</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• No ready industrial facilities or large-scale production method.</li> <li>• Low sensitivities in magnetometry (<math>10^4</math>-<math>10^5</math>x lower than diamond) and thermometry (100x lower than diamond).</li> </ul>
<p><b>(Noble) Transition-Metal Dichalcogenides (TMD/NTMD)</b></p>	<ul style="list-style-type: none"> <li>• Operates at telecom wavelengths for low-loss fiber transmission<sup>53</sup>.</li> <li>• Thickness of 2D NTMD makes them promising for strain sensing<sup>54</sup></li> </ul>	<ul style="list-style-type: none"> <li>• There are less studies of these platforms for quantum sensing.</li> <li>• The material gap is not so wide, which makes them less promising.</li> </ul>
<p><b>Other wide-band-gap and ultrawide-band-gap semiconductors including GaN, ZnO, AlN, and <math>\beta</math>-Ga<sub>2</sub>O<sub>3</sub></b></p>	<ul style="list-style-type: none"> <li>• Potentially promising coherence times, hence sensitivities.</li> <li>• Compatibility with existing semiconductor fabrication processes.               <ul style="list-style-type: none"> <li>• Suitability for extreme environment applications.</li> </ul> </li> <li>• Maturity of GaN as a material platform for optoelectronics.</li> </ul>	<ul style="list-style-type: none"> <li>• More study is required to develop and assess their properties as a sensor.</li> <li>• No widely developed industries.</li> </ul>

<sup>53</sup>Yeonghun Lee et al., « Spin-Defect Qubits in Two-Dimensional Transition Metal Dichalcogenides Operating at Telecom Wavelengths », *Nature Communications* 13, no 1 (2022): 7501, <https://doi.org/10.1038/s41467-022-35048-0>.

<sup>54</sup>Yinhua Hu et al., « Noble-Transition-Metal Dichalcogenides-Emerging Two-Dimensional Materials for Sensor Applications », *Applied Physics Reviews* 10, no 3 (2023): 031306, <https://doi.org/10.1063/5.0150018>.

### 1.3.6. Comparative table (3)

application	platform	defect	sensitivity
magnetometry	diamond	NV <sup>-</sup>	$10^{-6}-1 \mu\text{T}/\sqrt{\text{Hz}}^{17a}$
	4H-SiC	V <sub>Si</sub> <sup>-</sup> (V2)	$0.05 \mu\text{T}/\sqrt{\text{Hz}}^{236}$
	hBN	V <sub>B</sub> <sup>-</sup>	$2.55 \mu\text{T}/\sqrt{\text{Hz}}^{383}$
electrometry	diamond	NV <sup>-</sup>	$0.9 \pm 0.1(\text{V}/\text{cm})^2/\sqrt{\text{Hz}}^{27}$
	4H-SiC	VV <sup>0</sup>	$41 \pm 8(\text{V}/\text{cm})^2/\sqrt{\text{Hz}}$ (ac power) <sup>61</sup> (ac)
	hBN		
thermometry	diamond	NV <sup>-</sup>	$5 \text{ mK}/\sqrt{\text{Hz}}^{254}$
	4H-SiC	VV <sup>0</sup> (PL6 ensemble)	$13.4 \text{ mK}/\sqrt{\text{Hz}}^{253}$
	hBN	V <sub>B</sub> <sup>-</sup>	$0.37 \text{ K}/\sqrt{\text{Hz}}^{327}$
strain/pressure	diamond	NV <sup>-</sup>	$2 \times 10^7 \text{ Pa}/\sqrt{\text{Hz}}^{103}$ (pressure)
	4H-SiC	VV <sup>0</sup> (PL1-PL4)	$<10^{-6}/\sqrt{\text{Hz}}^{170}$ (ac strain)
	hBN	V <sub>B</sub> <sup>-</sup>	$10^7/10^6 \text{ Pa}/\sqrt{\text{Hz}}^{40b}$ (pressure)
	hBN	V <sub>B</sub> <sup>-</sup>	$10^{-5}/10^{-4345,346b}$ (strain)

<sup>a</sup>Varies greatly depending on the experimental parameters: sensor volume, NV concentration, sensing protocol, etc. <sup>b</sup>In-plane/Out-of-plane.

*Comparison of sensitivities achieved in laboratory settings, from<sup>55 56</sup>*

<sup>55</sup>Henry Roberts et al., « Quantum Sensing with Spin Defects Beyond Diamond », ACS Nano 19, no 25 (2025): 22528-75, <https://doi.org/10.1021/acsnano.5c00802>.

<sup>56</sup>Error in the electrical sensitivity units, see instead V·cm<sup>-1</sup>·Hz<sup>-1/2</sup>

### 1.3.7. Laboratory vs field

An important point to note is that there is often a difference of at least three orders of magnitude between laboratory state-of-the-art results, which are often uniquely fabricated and require entire laboratories for control or impractical operating conditions, and their integration into practical, small-footprint industrial systems. This can be seen in the following table.

Platform		Magnetic field sensitivity	Distance spin-surface
NV centers in diamond	Ensemble of NV centers	$210 \text{ fT}/\sqrt{\text{Hz}}^{57}$	
	Single NV center	$\text{nT}/\sqrt{\text{Hz}}^{58}$	5nm
	Ensemble of NV centers	$400 \text{ pT}/\sqrt{\text{Hz}}^{59}$ (vectorial)	
	Microscope	$1 \text{ }\mu\text{T}/\sqrt{\text{Hz}}^{60}$	10nm <sup>61</sup>
	Fiber-integrated	$\mu\text{T}/\sqrt{\text{Hz}}^{62}$	
<b>V<sub>B</sub> in hBN</b>	Tabletop	$10\text{-}138 \text{ nT}/\sqrt{\text{Hz}}^{63}$	10nm
<b>SiC</b>	Tabletop	$50 \text{ nT}/\sqrt{\text{Hz}}$ (DC) <sup>64</sup>	
	Fiber-integrated	$12.3\mu\text{T}/\sqrt{\text{Hz}}^{65}$	

*Comparison of magnetic field sensitivities between laboratory and industrial setups*

This last point is of critical importance, as it applies to many quantum sensing platforms: transitioning from proof-of-concept laboratory experiments – characterized by high SWaP-C, individually fabricated devices, and highly controlled environmental conditions – to lower-SWaP-C, industrially produced devices integrated into noisy environments is challenging and often results in the loss of a significant part of the initial performance advantage. Importantly, for certain classes of applications, this reduction in sensitivity is not necessarily limiting, as overall performance is dominated by environmental noise constraints – for example, when sensors are deployed on mobile platforms such as vehicles.

<sup>57</sup>Barry et al., « Sensitive Ac and Dc Magnetometry with Nitrogen-Vacancy-Center Ensembles in Diamond ».

<sup>58</sup>T. Rosskopf et al., « Investigation of Surface Magnetic Noise by Shallow Spins in Diamond », Physical Review Letters 112, no 14 (2014): 147602, <https://doi.org/10.1103/PhysRevLett.112.147602>.

<sup>59</sup>Vincent Halde et al., « Who Let the Diamonds Out? », arXiv:2509.19179, prépublication, arXiv, 10 octobre 2025, <https://doi.org/10.48550/arXiv.2509.19179>.

<sup>60</sup>Interview of Mathieu Munsch, CEO of Qnami

<sup>61</sup>« Qnami\_WhitePaper1\_NV\_magnetometry-5.pdf », s. d., consulté le 24 septembre 2025, [https://qnami.ch/wp-content/uploads/2020/07/Qnami\\_WhitePaper1\\_NV\\_magnetometry-5.pdf](https://qnami.ch/wp-content/uploads/2020/07/Qnami_WhitePaper1_NV_magnetometry-5.pdf).

<sup>62</sup>Interview of Remi Geiger, CEO of KWAN-TEK

<sup>63</sup>Biswas et al., « Quantum sensing with a spin ensemble in a two-dimensional material ».

<sup>64</sup>John B. S. Abraham et al., « Nanotesla Magnetometry with the Silicon Vacancy in Silicon Carbide », Physical Review Applied 15, no 6 (2021): 064022, <https://doi.org/10.1103/PhysRevApplied.15.064022>.

<sup>65</sup>Wei-Ke Quan et al., « Fiber-Integrated Silicon Carbide Silicon-Vacancy-Based Magnetometer », Optics Letters 48, no 6 (2023): 1423, <https://doi.org/10.1364/OL.476305>.

### 1.3.8. Spin defect sensors : conclusion

Spin defect sensors illustrate the wide range of variations stemming from a single concept, that enable sensing of several fields at different working ranges, enabled by the coexistence of multiple architectures. Only a subset of their broad capabilities may find a market fit, therefore significant effort is required to spot and assess the applications where they can find a major competitive advantage.

Matthieu Munsch, CEO of Qnami, emphasizes the need for a sensing startup to concentrate on a specific application, after initially pursuing a 'quantum foundry' approach – where the focus is on developing a very good technology and targeting diverse applications:

**“A QUANTUM SENSOR PROJECT REMAINS HIGHLY VERTICAL FOR A STARTUP, AS THE MARKET RISK IS QUITE LARGE. THERE ARE TWO POSSIBILITIES: EITHER YOU SHOW THAT YOU CAN DEPLOY SOMETHING AT VERY LARGE SCALE AND THAT WORKS AT A GIVEN PERFORMANCE AND SWAP LEVEL. ENGAGEMENT WITH BUSINESS UNITS TYPICALLY COMES LATER. FOR HAVING BEEN IN THE SENSOR DOMAIN FOR DECADES, BOSCH KNOWS VERY WELL THAT IF THE SENSOR IS CHEAPER AND HAS GOOD SPECS, IT WILL BE ADOPTED. FOR A STARTUP IT IS QUITE COMPLICATED. OTHERWISE, YOU HAVE TO VERTICALIZE COMPLETELY.”**

## 1.4. Photonics

Optics can be considered the most widespread sensing modality; it is also the field in which the distinction between classical and quantum sensors becomes less clear. The coherence of light, considered as a wave, predates 20th-century quantum theories. A prominent example is light interferometry, which splits light into two paths, one of them going through the medium to be sensed, and their tiny difference is measured by recombining them and observing the resulting interference. This can measure small relative displacements or refractive index change for instance. These principles underpin many widely used devices in imaging, telecom, navigation... Another widespread use of light is its interaction with matter: in that case, semiclassical description is often employed, where light is described classically and matter is treated with quantized energy levels. Such phenomena also describe important technologies like Raman scattering, where a molecule illuminated with light at a given wavelength transfers energy and scatters light at another wavelength, revealing how the atoms in the molecule vibrate: this is for instance used in biology to detect the presence of a given species, but also in chemistry or material analysis.

### 1.4.1. Nano and integrated photonics

These phenomena, among others, have attracted renewed interest over the past decades with advances in nanophotonics<sup>66</sup>. These platforms exploit nanoscale quantum-confinement effects to enhance light-matter interaction. They originated from the physics of quantum dots developed in the 1980s, a field recognized by the 2023 Nobel Prize in Chemistry<sup>67</sup>. In quantum dots, the nanoparticle size is comparable to the de Broglie wavelength of electrons, making their optical properties strongly size-dependent. Quantum dots can be addressed individually in quantum physics experiments, or used collectively in deposited films; in the latter case, they are generally not considered quantum technologies, as individual quantum states are not manipulated, but rather as a specialized class of semiconductors. Such semiconductor quantum dot films find widespread applications as emitters in display technologies, but also in photovoltaics, photodetectors, and bioimaging among others.

More generally, integrated photonics are promising for large-scale deployment, primarily for health and biology, as they can enable smaller devices probing the properties of biomolecules with good sensitivity. For instance, surface plasmons (a phenomenon of electron resonance at an interface) are often used to confine light in a small volume around the surface, and strongly enhance the interaction of the sample with the sensor in this volume. Current development paths include the use of 2D materials, active quantum dots, metasurfaces, in-situ nanostructures, advanced coating, data analysis and coupling to microfluidics – as demonstrated in fiber-coupled waveguide-enhanced Raman spectroscopy which led to the startup InSpek<sup>68</sup>. Combining these research directions with the development of spin-defect sensors could lead to promising cross-domain applications.

<sup>66</sup>Hatice Altug et al., « Advances and Applications of Nanophotonic Biosensors », *Nature Nanotechnology* 17, no 1 (2022): 5-16, <https://doi.org/10.1038/s41565-021-01045-5>.

<sup>67</sup>The Nobel Committee for Chemistry, *Scientific Background to the Nobel Prize in Chemistry 2023*

<sup>68</sup>Derek M. Kita et al., « A Packaged, Fiber-Coupled Waveguide-Enhanced Raman Spectroscopic Sensor », *Optics Express* 28, no 10 (2020): 14963, <https://doi.org/10.1364/OE.392486>.

This is a very active research domain where many proofs of concept are proposed. Broad market applications are promising as progress in integrated photonics is enabling integration and miniaturization. However, bringing these devices to market requires industrial-scale nanostructure production and additional engineering to ensure reliability in harsh conditions. This engineering can be far from the initial patent concept, for instance requiring efforts in packaging. Jérôme Michon, CEO of InSpek, emphasizes it: “Our environment is complex: it is a bioreactor, with its sterility constraints, where it sticks, it grows... Sensor integration is very important. In a room there are not too many constraints, but you have to think about it carefully for an industrial environment.” While this challenge requires additional R&D effort for a startup, it also endows them with stronger IP differentiation.

#### 1.4.2. “Quantum-enhanced” photonics

In photonics as well, quantum-enhanced sensing could be the next paradigm. This is actually the first domain in which quantum enhancement has led to a major scientific application. Since 2019, a measurement regime inaccessible by classical light was unlocked, with a useful application: in LIGO gravitational-wave detectors<sup>69</sup>, squeezed light is employed to see black hole mergers much farther in space. In these detectors, all classical sources of noise are so strongly reduced by precise engineering that fundamental quantum noise becomes the limiting factor. This noise comes from the fundamental quantum uncertainty principle, which states that until a measurement has been done, quantum objects are in a superposition of states within an uncertainty region which has a minimal size. Squeezed light is a quantum state where the shape of this fundamental uncertainty zone is squeezed – reduced in the direction of measurement, and increased in the other, leaving the total uncertainty unchanged.

<sup>69</sup>W. Jia et al., “Squeezing the quantum noise of a gravitational-wave detector below the standard quantum limit”

Other advanced and non-classical states of light are proposed to enhance the sensitivity of optical sensing. For instance, entangled photons have been shown to enhance resolution since the early Hanbury-Brown-Twiss experiments<sup>70</sup> in 1956. Since then, notable achievements with quantum states have been demonstrated. However, these states of light are complicated to produce in large numbers, or very sensitive to decoherence – similarly to qubits in quantum computers – and thus need highly controlled experimental conditions to bring a quantum advantage. As in quantum computing, it is more complicated to produce quantum states of many particles. There is therefore a trade-off between working with states of many classical or few quantum photons; and in many situations it is often better to work with higher classical beam powers to enhance sensitivity. Only the extremely low-noise environment of gravitational-wave detectors has enabled to reach a regime<sup>71</sup> where we could not increase the beam power, and where one could gain significant sensitivity with quantum states. A niche demonstration in biology has also reached this regime, but no broadly applicable advantage has been demonstrated that would justify broad market deployment; more work is needed to find use cases and market opportunities where such improvements would be significant. This could nevertheless become an important future sensing paradigm, that could benefit from future on-chip quantum-state generation<sup>72</sup>.

### 1.4.3. Optomechanics

Quantum optomechanics is another active research direction related to photonics, where the quantized motion of a mechanical resonator (so-called phonons) is coupled to light: displacements of the mechanical element modulate the size of a cavity, which modifies the resonance of the light inside. This field attracts significant research interest<sup>73 74 75</sup> to demonstrate quantum control of phonons, to perform fundamental tests of gravity, or to develop transducers. Beyond quantum mechanics demonstrations, these devices have proven to be very sensitive to pressure, acceleration, masses and electromagnetic fields. Further development toward practical sensors should be closely followed<sup>76</sup>, that could, for instance, lead to a new generation of MEMS accelerometers. Quantum-enhanced sensing may also unlock additional advantages in this domain.

<sup>70</sup>Hanbury Brown, R., and R. Q. Twiss (1956), *Nature* 178 (4541), 1046.

<sup>71</sup>Catxere A. Casacio et al., « Quantum-Enhanced Nonlinear Microscopy », *Nature* 594, no 7862 (2021): 201-6, <https://doi.org/10.1038/s41586-021-03528-w>.

<sup>72</sup><https://www.darpa.mil/news/2025/new-frontiers-signal-detection>

<sup>73</sup>Yu Yang et al., « A mechanical qubit », *Science* 386, no 6723 (2024): 783-88, <https://doi.org/10.1126/science.adr2464>.

<sup>74</sup>Kyrylo Gerashchenko et al., « Probing the quantum motion of a macroscopic mechanical oscillator with a radio-frequency superconducting qubit », arXiv:2505.21481, prépublication, arXiv, 28 mai 2025, <https://doi.org/10.48550/arXiv.2505.21481>.

<sup>75</sup>Lorenzo Dania et al., « High-Purity Quantum Optomechanics at Room Temperature », *Nature Physics* 21, no 10 (2025): 1603-8, <https://doi.org/10.1038/s41567-025-02976-9>.

<sup>76</sup><https://www.leti-cea.com/cea-tech/leti/english/Pages/Industrial-Innovation/Demos/optomechanical-sensor.aspx>

## 1.5. Other sensors

Some sensors do not fit into the previous categories and still require attention. We list a few here; this overview is not intended to be exhaustive as many more sensors could appear along research discoveries.

### 1.5.1. Spintronics

Spintronics, which exploits both the spin and charge of electrons in microelectronics, has found applications in magnetic field sensors since the late 20th century with giant magnetoresistance (GMR), anisotropic magnetoresistance (AMR) and tunneling magnetoresistance (TMR) devices<sup>77</sup>. They achieve sub-nT/ $\sqrt{\text{Hz}}$  in a few mm<sup>2</sup> area<sup>78</sup> and are CMOS-compatible. They are widely used in automotive and industrial applications and are also considered in emerging biomedical applications.

### 1.5.2. Single-electron transistors

Single-electron transistors are another sensor type, based on electron tunneling through a submicron island, which is extremely sensitive to electric fields or charges. This physics developed in the 1990s has been used by condensed matter researchers to do imaging of electric fields at the nanoscale – in a complementary approach to magnetic imaging with spin-defects, that we discussed earlier. They are also interesting as detectors in some quantum computer architectures<sup>79</sup>.

### 1.5.3. Sensing with muons

Muon spin rotation uses positively charged muons, which behave like electrons with a spin that precesses in magnetic fields. They can be used by direct implantation into the material to be sensed and are manipulated in a very similar way as spin defects. They can therefore be in-situ sensors for magnetic field, for which they have found established scientific use since the late 20th century<sup>80</sup>.

<sup>77</sup>B. Dieny et al., « Opportunities and Challenges for Spintronics in the Microelectronics Industry », *Nature Electronics* 3, no 8 (2020): 446-59, <https://doi.org/10.1038/s41928-020-0461-5>.

<sup>78</sup>James G. Deak et al., « Tunneling Magnetoresistance Sensor with pT Level 1/f Magnetic Noise », *AIP Advances* 7, no 5 (2017): 056676, <https://doi.org/10.1063/1.4978465>.

<sup>79</sup>Morello, A., Pla, J., Zwanenburg, F. et al. Single-shot readout of an electron spin in silicon. *Nature* 467, 687–691 (2010). <https://doi.org/10.1038/nature09392>

Jeff E. Sonier et al., «  $\mu$ SR Studies of the Vortex State in Type-II Superconductors », *Reviews of Modern Physics* 72, no 3 (2000): 769-811, <https://doi.org/10.1103/RevModPhys.72.769>.

In a related but technologically distinct approach, cosmic-ray muons are used as passive probes to sense large-scale structures through their interaction with matter. By detecting the angular distribution and attenuation of naturally occurring muon flux after it traverses geological formations, this technique enables the reconstruction of integrated density along each trajectory. Often referred to as muon tomography, it relies on large-area particle detectors and statistical reconstruction methods, which is more related to deep physics than strictly quantum sensing. The penetration depth of muons makes this sensing modality suited for imaging dense or deeply buried structures, and it has been established as a measurement technique since the early 21st century<sup>81</sup>. Ideon is an example of startup using this technology for mining<sup>82</sup>.

#### 1.5.4. Sensing with neutrons

We previously discussed proton-precession magnetometers as ancestors of OPMs. Neutrons also exhibit useful properties for sensing. In neutron spin echo spectroscopy, for instance, the precession of a neutron's spin acts as a clock recording its time of flight, enabling the measurement of minute energy exchanges with materials, which impact the velocity of the neutrons. Neutrons can also sense the gravity field<sup>83</sup>, in a similar way as we described for cold atoms, for fundamental gravity testing; yet with lower sensitivity and higher complexity than cold atoms when it comes to other use cases.

#### 1.5.5. Nuclear quantum physics

New physics may also emerge, unlocking new regimes of quantum sensing, nuclear clocks<sup>84</sup> or nuclear qubits being an example of possible future physics enabled by the precise determination of the thorium-229 nuclear transition<sup>85</sup>.

<sup>80</sup>Jeff E. Sonier et al., «  $\mu$ SR Studies of the Vortex State in Type-II Superconductors », *Reviews of Modern Physics* 72, no 3 (2000): 769-811, <https://doi.org/10.1103/RevModPhys.72.769>.

<sup>81</sup>Nolwenn Lesparre, " Mise au point d'une méthode de tomographie utilisant les muons d'origine cosmique." PhD thesis (2011) <https://www.ipgp.fr/~lesparre/Ecrits/TheseLesparre.pdf>.

<sup>82</sup><https://ideon.ai>

<sup>83</sup>Jenke, T., Goldenbort, P., Lemmel, H. et al. Realization of a gravity-resonance-spectroscopy technique. *Nature Phys* 7, 468-472 (2011). <https://doi.org/10.1038/nphys1970>

<sup>84</sup>John Kitching, « Chip-Scale Atomic Devices », *Applied Physics Reviews* 5, no 3 (2018): 031302, <https://doi.org/10.1063/1.5026238>.

<sup>85</sup>Benedict Seiferle et al., « Energy of the  $^{229}\text{Th}$  Nuclear Clock Transition », *Nature* 573, no 7773 (2019): 243-46, <https://doi.org/10.1038/s41586-019-1533-4>.

## 2) APPLICATION DOMAINS & IMPACTED INDUSTRIES

The second part of this report studies quantum sensing in applications. We review some key use cases in the sectors most impacted: healthcare and life sciences, industry, positioning-navigation-timing (PNT), geology and energy, security and defense, fundamental science, and other quantum technologies. For each use case, we try to highlight the actual position of quantum propositions within the competition landscape, and to give an overview of the trends. We also provide a mapping of companies by application area<sup>86</sup>. The following table summarizes this analysis.

Sector	Use case	Value proposition	Challenges	Overall opportunity
Healthcare & life sciences	Medical MEG	A new MEG paradigm enabled by OPM operating without cryogenics	Data acquisition, magnetic shielding	Currently a niche market, but quantum technologies could expand and transform it
	MEG-BCI	Accurate, non-invasive brain-computer interfaces	Magnetic shielding, BCI software maturity	Potential to become a competitive solution in a market with very high potential
	New MRI	More accessible and potentially lower-cost MRI systems	Commercial deployment	Quantum technologies could unlock growth in a market constrained by bulky and expensive devices
	Nano-MRI for healthcare and biology	Ultra-sensitive biological sensing down to the single-cell level	Ongoing research to circumvent materials limitations	Still research-grade, but with very high prospective impact
	Integrated optical sensors for bioscience	On-chip sensors enabling large-scale deployment	Device reliability in real-world conditions	Potential for broad deployment after additional R&D stage
	Quantum optics microscopes	Quantum-enhanced sensitivity beyond classical limits	Need for clearer quantum advantage and better alignment with use cases	Research progress should be closely monitored
	Industry	NDT for microelectronics	Detection of hidden defects in advanced components	Device cost, timeline for integration into production lines
Industrial NDT and monitoring		Defect detection and monitoring in harsh environments	SWaP-C constraints	Good market potential, provided further technological maturation

<sup>86</sup>As the boundaries of quantum sensing are not sharply defined, we do not claim this overview to be exhaustive.

<b>PNT</b>	MagNav	Sensors with high-sensitivity and small size, or operable in harsh environments	CSAC reliability, on-chip diamond integration, strong competition from classical sensors; limited magnetic cartography	Still narrow quantum advantage; clear defense interest, feasibility to be monitored
	GravNav	Portable, high-performance gravimeters	Reliability improvements; limited availability of gravimetric maps	Proven quantum advantage, but near-term market likely restricted to military use
	Inertial sensors (cold atoms)	Superior sensitivity for space and military applications	SWaP reduction, reliability	Niche, high-end market requiring substantial further R&D
	Inertial sensors (NMR gyroscopes)		Cost and performance competition with improving classical sensors; reliability	Potentially large market, provided reliability developments
	Clocks (cold atoms)	Performance competitive with hydrogen masers	Important SWaP reduction needed for satellite deployment	Potential for disruption in niche markets, provided size reduction
	Clocks (CSAC)	Advantage in military GNSS communication and in assisting GPS	Reliability; competition from MEMS and higher-performance satellite clocks	Clear advantage in some niche use cases, provided reliability improvements
	<b>Geology &amp; energy</b>	Geophysical exploration (gravity & magnetics)	Portable, high-precision gravity and magnetic mapping for subsurface imaging	Instrument size, operational robustness, data interpretation
Battery diagnostics		High-resolution non-invasive current and field sensing across wide dynamic range	Robustness in noisy, mobile environments	Promising niche if reliability improves
<b>Security &amp; defense</b>	Security screening	Remote, discreet security scan	Hardware and software R&D for object reconstruction	Market with clear unmet needs and willingness-to-pay, especially for non-intrusive screening
	Military remote detection	Discreet long-range object detection	Additional proofs of concept required	High strategic value
<b>Science applications</b>	Fundamental physics experiments	Ultimate sensitivity for tests of fundamental laws and discovery of new physics	Long development cycles, limited direct commercial market	Key driver of quantum sensor innovation: research should be closely monitored
<b>Quantum technologies</b>	Enabling components for quantum computing and communication	Shared high-performance sensors and components across platforms	Integration with emerging quantum systems, evolving standards	Strategic enabler with early revenue potential

## 2.1. Healthcare & Life Sciences



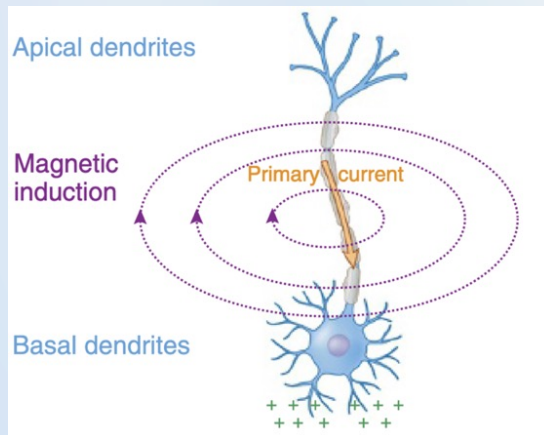
Healthcare and life sciences rely heavily on precise measurements: to access clinical information from human organs, or to study biological samples for diagnosis and drug design. Quantum sensing can offer advantages at both macroscopic and microscopic scales, as some platforms enable record-level sensitivities while others enable measurements at sub-micron scales. We highlight use cases in clinical magnetoencephalography (MEG), brain-computer interfaces (BCIs) and other biomagnetism techniques, magnetic-resonance imaging (MRI), and multi-sensor monitoring of biological samples.

### 2.1.1. Biomagnetism and brain-computer interfaces

Magnetoencephalography (MEG) is a technology based on the detection of the tiny magnetic fields produced by the neurons in the living brain to monitor neuronal activity. Early research in this area was enabled by the invention of SQUIDs, with the first measurement of brain magnetic waves a decade later, in 1972<sup>87</sup>. MEG relies on the fact that the synaptic discharge of a neuron transports charged ionic species and thus produces currents when the neuron is activated. This current generates a magnetic field according to Maxwell's equations, about a billion times smaller than Earth's magnetic field. Recording the distribution of the magnetic field at the surface of the head at the level of  $10 \text{ fT}/\sqrt{\text{Hz}}$  enables reconstruction of the firing activity of neurons inside the brain, via inverse solution of Maxwell's equations. The resolution currently achieved by MEG is of sub-microsecond and sub-millimeter<sup>88</sup>, detecting the activity of ensembles of neurons.

<sup>87</sup>David Cohen, « Magnetoencephalography: Detection of the Brain's Electrical Activity with a Superconducting Magnetometer », *Science* 175, no. 4022 (1972): 664-666, <https://doi.org/10.1126/science.175.4022.664>.

<sup>88</sup>Holly Schofield et al., Towards a 384-Channel Magnetoencephalography System Based on Optically Pumped Magnetometers, s. d.



*Magnetic field induced by a neuron firing<sup>89</sup>.*

This technique was commercialized for about three decades with over one hundred systems sold worldwide. Commercialization has been limited because of the size, fixed geometry and cost of the machines, as SQUIDs require cryogenic systems. The safety risk associated with several tens of liters of liquid helium in the vicinity of the head, the constraint of remaining immobile in a large system inside a shielded room, as well as the maintenance cost and uncertainty of helium supply, have limited MEG to neuroscience research.

The emergence of new practical sensors competing with SQUIDs in the last two decades has been changing the landscape for MEG. As OPMs have reached the levels of sensitivity of SQUIDs while being miniaturized at the centimeter- to millimeter-scale, they have been employed in practical MEG demonstrations reaching the resolution level of SQUID-MEG<sup>90</sup>. The possibility to operate the OPM sensors closer to the head, as opposed to the 2 cm distance dictated by SQUID cryogenics, compensates for their intrinsically higher noise level<sup>91</sup>. Despite their early development stage, they are currently available at upfront and operating costs of \$1.4M and \$70k respectively, lower than the \$3.5M and \$200k costs of SQUID-MEG<sup>92</sup>. These high upfront and operating costs and the early stage of OPM-MEG have been limiting their use to niche research and clinical applications. Initial demonstrations of OPM-MEG were recent so their industrialized cost may decrease, while becoming increasingly practical to allow subject motion during measurements.

<sup>89</sup>Sulvain Baillet, « Magnetoencephalography for Brain Electrophysiology and Imaging », *Nature Neuroscience* 20, no 3 (2017): 327-39, <https://doi.org/10.1038/nn.4504>.

<sup>90</sup>Elena Boto et al., « Moving Magnetoencephalography towards Real-World Applications with a Wearable System », *Nature* 555, no 7698 (2018): 657-61, <https://doi.org/10.1038/nature26147>.

<sup>91</sup>Holly Schofield et al., « A Novel, Robust, and Portable Platform for Magnetoencephalography Using Optically-Pumped Magnetometers », *Imaging Neuroscience* 2 (septembre 2024): imag-2-00283, [https://doi.org/10.1162/imag\\_a\\_00283](https://doi.org/10.1162/imag_a_00283).

<sup>92</sup>Holly Schofield et al., « A Novel, Robust, and Portable Platform for Magnetoencephalography Using Optically-Pumped Magnetometers », *Imaging Neuroscience* 2 (septembre 2024): imag-2-00283, [https://doi.org/10.1162/imag\\_a\\_00283](https://doi.org/10.1162/imag_a_00283).



Comparison of SQUID (left) and OPM (right) based MEG in 2018, from <sup>93</sup>

However, the shielded room accounts for a quarter of the upfront cost of SQUID-MEG<sup>94</sup> and is also required in OPM-MEG<sup>95 96</sup>. Shielding alkali-based OPM-MEG systems from external magnetic noise is an additional challenge as these devices have very low dynamic range on the order of a few nT, and are thus more affected by environmental field fluctuations. Additional protection against the ambient magnetic field is required within the shielded room. For instance, active shielding with electromagnetic coils (whereby electromagnetic fields are generated to effectively counter unwanted ones) is a promising field of research<sup>97</sup>. Another research path and startup direction<sup>98</sup> is to use helium instead of alkali atoms, as it has a larger dynamic range of 200 nT<sup>99</sup>.

MEG complements other neuroimaging techniques employed in neuroscience. It is often compared to electroencephalography (EEG) as both are non-invasive methods to access, in real time, the activity of neuronal ensembles. EEG detects the electrical potential of the neurons while MEG detects the current flowing between them. EEG has intrinsically poorer resolution because the electrical signal is attenuated by the head tissues; yet it remains the leading neuroscience tool for its relative affordability and portability and has seen the emergence of consumer-grade products notably for brain-computer interfaces (BCI)<sup>100</sup>. These devices leverage users' ability to learn how to control the computer interface thanks to their neural plasticity<sup>101</sup>, and have demonstrated rehabilitation of paralysis and tetraplegia since 2012<sup>102 103 104</sup>.

<sup>93</sup>Elena Boto et al., « Moving Magnetoencephalography towards Real-World Applications with a Wearable System », *Nature* 555, no 7698 (2018): 657-61, <https://doi.org/10.1038/nature26147>.

<sup>94</sup>Sylvain Baillet, « Magnetoencephalography for Brain Electrophysiology and Imaging », *Nature Neuroscience* 20, no 3 (2017): 327-39, <https://doi.org/10.1038/nn.4504>.

<sup>95</sup>Holly Schofield et al., « A Novel, Robust, and Portable Platform for Magnetoencephalography Using Optically-Pumped Magnetometers », *Imaging Neuroscience 2* (septembre 2024): imag-2-00283, [https://doi.org/10.1162/imag\\_a\\_00283](https://doi.org/10.1162/imag_a_00283).

<sup>96</sup>Costs are evolving: <https://qusp.in.com/a-small-low-cost-magnetically-shielded-room/>,  
<sup>97</sup>« QTFM Gen-2 - QuSpin », consulté le 13 octobre 2025, <https://qusp.in.com/qtfm-gen-2/>.

<sup>98</sup>The startup Mag4Health for instance is developing He-based MEG: <https://www.mag4health.com>

<sup>99</sup>Yidan Ding et al., « EEG-Based Brain-Computer Interface Enables Real-Time Robotic Hand Control at Individual Finger Level », *Nature Communications* 16, no 1 (2025): 5401, <https://doi.org/10.1038/s41467-025-61064-x>.

<sup>100</sup>Sylvain Baillet, « Magnetoencephalography for Brain Electrophysiology and Imaging », *Nature Neuroscience* 20, no 3 (2017): 327-39, <https://doi.org/10.1038/nn.4504>.

<sup>101</sup>Ranganatha Sitaram et al., « Closed-Loop Brain Training: The Science of Neurofeedback », *Nature Reviews Neuroscience* 18, no 2 (2017): 86-100, <https://doi.org/10.1038/nrn.2016.164>.

<sup>102</sup>C. Ethier et al., « Restoration of Grasp Following Paralysis through Brain-Controlled Stimulation of Muscles », *Nature* 485, no 7398 (2012): 368-71, <https://doi.org/10.1038/nature10987>.

<sup>103</sup>Leigh R. Hochberg et al., « Reach and Grasp by People with Tetraplegia Using a Neurally Controlled Robotic Arm », *Nature* 485, no 7398 (2012): 372-75, <https://doi.org/10.1038/nature11076>.

<sup>104</sup>Yidan Ding et al., « EEG-Based Brain-Computer Interface Enables Real-Time Robotic Hand Control at Individual Finger Level », *Nature Communications* 16, no 1 (2025): 5401, <https://doi.org/10.1038/s41467-025-61064-x>.

Although MEG accounts for only 5% of neuroscience research within non-invasive brain analysis, this technology is following the path of EEG in research and clinical use, catching up in flexibility while offering superior resolution. Data are beginning to be shared to enable broad development of analysis of MEG brain signals<sup>105</sup>. And data accumulation is expected to accelerate as OPM-MEG helmet flexibility – as opposed to old SQUID-MEG rigidity – will enable reproducible data to be acquired as in EEG<sup>106</sup>. Moreover, better software analysis pipelines should make MEG analysis less time-consuming, unlocking broader use of time-constrained medical use cases like presurgical functional mapping of brain tumors. MEG is also expected to have significant impact in the treatment of epilepsy by replacing current invasive methods<sup>107</sup>. MEG is already being prescribed and reimbursed in some countries for these cases; clinical demands should increase deployment of these devices, enabling access for researchers and improvement of their use. These critical use cases should facilitate entry of new MEG systems in the medical market despite the high upfront costs, allowing them to benefit from the structured validation cycles and business models in medtech. Many more applications of hospital-based and portable medical BCIs are expected, such as autism diagnosis, limb impairment rehabilitation or depression treatment.

Beyond medical, BCI may find applications in warfare, neurogaming or longevity – with Neuralink implants being tested for war neurogaming<sup>108</sup> and EEG being experimented with for robot control by soldiers<sup>109</sup>. Consumer-grade MEG-based BCI has the key advantage of non-invasiveness over implanted BCI, and better resolution than EEG-based BCIs which enable much faster control of the device. It will nevertheless require further cost reductions, as invasive BCI selling price can be estimated in the range of \$30k-\$60k upfront acquisition cost<sup>110</sup>. As for home applications in medical rehabilitation or neurogaming, the need for a shielded room should restrict them to wealthy people. Today, active magnetic noise cancellation is being developed to work inside shielding rooms and therefore does not yet remove the need of shielding rooms<sup>111</sup>. However, developing active shielding techniques that would eliminate the need of shielding rooms entirely – a much bigger challenge – would be a game changer for the wider use of precise and non-invasive BCI.

<sup>105</sup>Hong Gi Yeom et al., « A Magnetoencephalography Dataset during Three-Dimensional Reaching Movements for Brain-Computer Interfaces », *Scientific Data* 10, no 1 (2023): 552, <https://doi.org/10.1038/s41597-023-02454-y>.

<sup>106</sup>Sylvain Baillet, « Magnetoencephalography for Brain Electrophysiology and Imaging », *Nature Neuroscience* 20, no 3 (2017): 327-39, <https://doi.org/10.1038/nn.4504>.

<sup>107</sup>Sylvain Baillet, « Magnetoencephalography for Brain Electrophysiology and Imaging », *Nature Neuroscience* 20, no 3 (2017): 327-39, <https://doi.org/10.1038/nn.4504>.

<sup>108</sup>Neuralink Update, Summer 2025 : [https://youtu.be/FASMejN\\_5qs?si=VVsKL\\_xte5dgrnA7](https://youtu.be/FASMejN_5qs?si=VVsKL_xte5dgrnA7).

<sup>109</sup>ASME, « AI Helps Soldiers Bark Orders Telepathically to Robot Dogs », <https://www.asme.org/topics-resources/content/ai-helps-soldiers-bark-orders-telepathically-to-robot-dogs>

<sup>110</sup>Morgan Stanley et al., *Brain Computer Interface Primer: The Next Big MedTech Opportunity?*, s. d.

<sup>111</sup>Niall Holmes et al., « A Lightweight Magnetically Shielded Room with Active Shielding », *Scientific Reports* 12, no 1 (2022): 13561, <https://doi.org/10.1038/s41598-022-17346-1>.

MEG and BCI appear in market analyses with sometimes contradictory or surprising TAM estimates. MEG market was estimated at \$255M in 2024 by Global Market Insight. They forecast \$700M in 2034<sup>112</sup>. These market sizes would traditionally be considered too small for a VC investment, and are likely to vary significantly depending on technological advances and competition with other BCI technologies. The brain-computer interface market could reach \$5Bn by 2030 according to CitiBank sources<sup>113</sup>, while Morgan Stanley estimates \$400Bn for invasive BCI by 2045. Though Morgan Stanley's reference paper is well known in the space, it lacks the nuance needed to understand how the market will evolve from a mere potential \$5Bn in 2030, to \$400Bn in 2045. There are still significant commercialization questions as to what is needed for these numbers to be reached in that timeline. Organizational challenges for medical implantation of brain chips and associated patient follow-up, or the reluctance of people to receive a brain implant, need closer consideration. Non-invasive MEG-BCI is based on a very different commercial model, with more costly but also much more user-friendly devices, without the associated risk, implantation complexity, maintenance burden and ethical considerations of permanently implanted brain probes.

Recent market transactions underscore the increasing traction of BCI. Technology is becoming increasingly accurate<sup>114</sup>, a decade after first arm control demonstrations. Development of better hardware happens in parallel with increasing market confidence in software potential after recent AI breakthroughs. BrainCo, a Chinese company in non-invasive EEG-BCI -which has lower precision than MEG-BCI- seeks pre-IPO at \$1.3bn<sup>115</sup>, while Neuralink raised \$650M series E in 2025 for its invasive electrode-BCI<sup>116</sup>, Precision Neuroscience raised \$102M in 2024 for its invasive ECoG-BCI<sup>117</sup>, INBRAIN Neuroelectronics raised \$50M in 2024 for invasive electrode-BCI<sup>118</sup>. Comind raised \$102.5M in 2025 for non-invasive infrared light-based brain medical analysis<sup>119</sup>. This technology indeed has the advantage of non-invasiveness and relative technological simplicity, despite being unfavored for brain-computer communication: it is based on the detection of brain vascular response, which only occurs seconds after neuronal activity, a thousand times slower than real-time neuronal firing. Compared to these technologies, OPM-MEG has a combination of flexibility, high resolution and non-invasiveness.

<sup>112</sup><https://www.gminsights.com/industry-analysis/magnetoencephalography-market>

<sup>113</sup><https://www.strategicmarketresearch.com/market-report/brain-computer-interface-market>

<sup>114</sup>Idan Ding et al., « EEG-Based Brain-Computer Interface Enables Real-Time Robotic Hand Control at Individual Finger Level », *Nature Communications* 16, no 1 (2025): 5401, <https://doi.org/10.1038/s41467-025-61064-x>.

<sup>115</sup><https://www.bloomberg.com/news/articles/2025-08-05/china-neuralink-rival-seeks-pre-ipo-funds-at-1-3-billion-value>

<sup>116</sup><https://neuralink.com/updates/>

<sup>117</sup><https://precisionneuro.io>

<sup>118</sup><https://inbrain-neuroelectronics.com>

<sup>119</sup><https://www.comind.io/news/comind-announces-102-5m-funding-to-redefine-clinical-monitoring-of-the-brain>

The historical companies in SQUID-MEG are MEGIN as the top player, followed by Ricoh, Compumedics and CTF MEG. The OPM-MEG market is younger and comprises distinct actors, for the different technologies of the value chain. They sometimes work on common projects with for example Quspin OPM production company working with Cerca Magnetics producing MEG and with Magnetic Shields for construction of shielded rooms<sup>120</sup>. Twinleaf, FieldLine, Mag4Health and QSensato are companies based on alternative technologies. QSensato has versatile vapor cell configurations that could boost MEG development while targeting many other applications. MEG software was identified early as a key missing asset<sup>121</sup>, which has been confirmed by a partnership between MYndspan MEG-software startup and MEGIN SQUID-MEG company in 2025<sup>122</sup>, followed by strategic investment by EEG company Emotiv into MYndspan to develop MEG-EEG combined clinical analysis<sup>123</sup>. Like MRI scanners, MEG systems are expensive devices needing a shielding room and required for specific clinical cases, so these machines are expected to first follow the same business models as MRI.

As OPM-MEG currently require a magnetically shielded room, it can be assumed that they will first be installed in hospitals and research institutions. Some R&D will be necessary to overcome the remaining magnetic shielding challenges among others and enable large-scale production of devices. OPM-MEG could then replace SQUID-MEG first in research settings, and then in clinical setups after obtaining regulatory clearance, as higher maintenance costs of SQUID-MEG make replacement economically attractive in a few years. The main roadblock is the high cost requiring researchers or hospitals to have enough funding upfront. As a point of comparison, MRI systems similarly cost a few million dollars with about 50,000 scanners installed worldwide. A similar market penetration would imply \$70bn TAM for hospital-based OPM-MEG – though this is a purely financial comparison and the use cases are not the same for the two devices. In a second phase, further industry-driven cost reduction and research in magnetic field effects mitigation could enable targeting patients and broader consumer markets with a much larger TAM.



Worldwide distribution of the 120 MEGIN SQUID-MEG sorted by applications<sup>124</sup>

<sup>120</sup>Niall Holmes et al., « A Lightweight Magnetically Shielded Room with Active Shielding », *Scientific Reports* 12, no 1 (2022): 13561, <https://doi.org/10.1038/s41598-022-17346-1>.

<sup>121</sup>Sylvain Baillet, « Magnetoencephalography for Brain Electrophysiology and Imaging », *Nature Neuroscience* 20, no 3 (2017): 327-39, <https://doi.org/10.1038/nn.4504>.

<sup>122</sup>« MYndspan and MEGIN Partner to Make MEG Brain Scans More Accessible\_MEGIN », <https://megin.com/2025/02/myndspan-and-megin-partner/>  
<sup>123</sup><https://www.prnewswire.com/news-releases/myndspan-secures-strategic-investment-from-emotiv-to-advance-consumer-brain-health-technology-302424837.html>

<sup>124</sup><https://megin.com>

Looking forward, diamond quantum sensors could theoretically achieve sensitivities in the tens of fT/ $\sqrt{\text{Hz}}$  enabling potential use in BCI. An additional 1–2 orders of magnitude in sensitivity are required to achieve the threshold for neuron signal measurement with tabletop research diamond sensors. Integration into practical devices is an additional hurdle. It is worth noting that progress has been made in non-human tests. Thanks to their spatial resolution and ability to be placed close to a sample, they have enabled single-neuron monitoring in a living worm<sup>125</sup> or in a mouse brain slice<sup>126</sup>, and research projects on diamond sensors for surgical applications are ongoing<sup>127</sup>.

Beyond neurons, biomagnetism has applications in cardiac monitoring. The sensitivity requirements are less stringent, with 10 pT/ $\sqrt{\text{Hz}}$  needed<sup>128</sup>. SQUIDs were first employed but this is also achievable by tunneling magnetoresistors (TMRs)<sup>129</sup><sup>130</sup>, OPMs, and NV centers in diamonds. The market was estimated to be \$1.3bn in 2023 and expected to reach \$3.1bn in 2030 in some analysis<sup>131</sup>. This market is small by VC standards, largely due to the operational complexity of SQUID magnetometers requiring magnetically shielded rooms, until the recent emergence of alternatives. We expect the market sizing to grow as technology ease of use and clinical habits develop hand in hand<sup>132</sup>.

### 2.1.2. Accessible MRI

Magnetic resonance imaging (MRI) is another healthcare domain impacted by advances in quantum sensing. Current MRI scalability is constrained by the engineering complexity of generating high magnetic fields, which makes systems bulky and expensive, and by the requirement for magnetically shielded rooms. Owing to its excellent magnetic field sensitivity and broad bandwidth, SQUID technology is a promising candidate for ultra-low-field MRI that could be about an order of magnitude cheaper and portable<sup>133</sup>. Product-market fit remains challenging, however, as SQUID-based MRI delivers lower image resolution than conventional MRI. They require practitioner adaptation and the identification of clinical use cases where reduced resolution is acceptable and where a wide adoption would be highly relevant, such as intensive care monitoring, stroke diagnosis, or Alzheimer's disease follow-up.

<sup>125</sup>« Optical Magnetic Detection of Single-Neuron Action Potentials Using Quantum Defects in Diamond », <https://doi.org/10.1073/pnas.1601513113>.

<sup>126</sup>Nikolaj Winther Hansen et al., « Microscopic-Scale Magnetic Recording of Brain Neuronal Electrical Activity Using a Diamond Quantum Sensor », *Scientific Reports* 13, no 1 (2023): 12407, <https://doi.org/10.1038/s41598-023-39539-u>.

<sup>127</sup>Johannes Gutenberg University Mainz, « Using Quantum Sensor Technology to Improve Brain Tumor Operations | Press and Public Relations », Johannes Gutenberg University Mainz, 15 novembre 2022, <https://press.uni-mainz.de/using-quantum-sensor-technology-to-improve-brain-tumor-operations/>.

<sup>128</sup>Felix M. Stürner et al., « Integrated and Portable Magnetometer Based on Nitrogen-Vacancy Ensembles in Diamond », *Advanced Quantum Technologies* 4, no 4 (2021): 2000111, <https://doi.org/10.1002/qute.202000111>.

<sup>129</sup>Kosuke Fujiwara et al., « Magnetocardiography and Magnetoencephalography Measurements at Room Temperature Using Tunnel Magnetoresistance Sensors », *Applied Physics Express* 11, no 2 (2018): 023001, <https://doi.org/10.7567/APEX.11.023001>.

<sup>130</sup>James G. Deak et al., « Tunneling Magnetoresistance Sensor with pT Level 1/f Magnetic Noise », *AIP Advances* 7, no 5 (2017): 056676, <https://doi.org/10.1063/1.4978465>.

<sup>131</sup>Valuate Reports, « Global Magnetocardiograph System Market Research Report 2024 », <https://Reports.Valuates.Com/Market-Reports/QYRE-Auto-2U17972/Global-Magnetocardiograph-System>, s. d.

<sup>132</sup>D. Brisinda et al., « Clinical Magnetocardiography: The Unshielded Bet—Past, Present, and Future », *Frontiers in Cardiovascular Medicine* 10 (août 2023): 1232882, <https://doi.org/10.3389/fcvm.2023.1232882>.

<sup>133</sup>Dimitri Labat, Chipiron High-Quality 1 mT MRI, s. d.

Hyperfine, a US pioneer, received FDA clearance in 2021, reported \$3M in sales in Q3 2024 for approximately ten installed units, and recently raised \$17.5M through a public offering. Chipiron, a French startup, closed a \$17M Series A in 2025, is currently in the R&D phase, and targets FDA clearance in 2028. These two companies currently dominate a still-nascent market; their scale-up should be closely monitored, and additional entrants based on SQUIDs or alternative technologies are expected<sup>134 135</sup>.

Business models may include direct hardware sales, leasing to hospitals and research institutions, and imaging or data-as-a-service offerings. Portability makes leasing and service models more plausible than for conventional MRI. The US market is likely to be addressed first, followed by Europe and Asia. Lower cost and portability also make these systems attractive for regions with limited access to conventional MRI infrastructure.

Quantum algorithms provide an additional lever for accessible MRI through algorithmic cooling. This software-based approach polarizes nuclear spins in the target material (e.g., brain tissue), effectively cooling them, which enhances sensitivity<sup>136</sup>. Foqus is commercializing such quantum algorithmic solutions combined with AI. Its CEO, Sadegh Raesi, explains: “We target a 20–30% improvement in sensitivity through spin polarization. In some cases, we achieve even higher gains, but this already exceeds what others in the field deliver. Many NMR (nuclear magnetic resonance) and MRI labs upgrade from 5 T to 6 T systems, corresponding to a 20% improvement, while spending millions of dollars on hardware. By contrast, this software-based approach is significantly cheaper and easier to deploy.” These algorithms are applicable not only to MRI but also to NMR chemistry and ultra-low-field MRI as a sensitivity enhancement layer.

Overall, these approaches are expected to broaden access to MRI by offering alternatives to costly and bulky tesla-scale field increases. Two challenges remain critical: regulatory clearance, with its inherent timelines and uncertainties, and market inertia in healthcare, where adoption requires funding, training, and organizational change. These constraints also constitute significant entry barriers, reinforcing the defensibility of successful startups.

<sup>134</sup>Yilong Liu et al., « A Low-Cost and Shielding-Free Ultra-Low-Field Brain MRI Scanner », *Nature Communications* 12, no 1 (2021): 7238, <https://doi.org/10.1038/s41467-021-27317-1>.

<sup>135</sup>Emil Ljungberg et al., « Characterization of Portable Ultra-Low Field MRI Scanners for Multi-Center Structural Neuroimaging », *Human Brain Mapping* 46, no 8 (2025): e70217, <https://doi.org/10.1002/hbm.70217>.

<sup>136</sup>Sebastian Zaiser et al., « Cyclic Cooling of Quantum Systems at the Saturation Limit », *Npj Quantum Information* 7, no 1 (2021): 92, <https://doi.org/10.1038/s41534-021-00408-z>.

### 2.1.3. Nanoscale biosensing

Quantum sensing based on spin defects has emerged as a novel approach for probing biological systems at the nanoscale. These quantum sensors enable non-invasive detection of magnetic fields, electric fields, temperature variations, strain, and pressure in living cells, combining excellent sensitivity with biologically relevant spatial resolution and biocompatibility.

One key objective of researchers is to achieve NMR and MRI sensitivity down to a few nuclear spins. Both techniques rely on the same physical principle: nuclear and electronic spins interact resonantly with the electromagnetic field, allowing their detection and mapping. NMR is used to analyze the chemical composition of samples, while MRI provides three-dimensional maps of molecular distributions, for instance in brain imaging. To date, these methods have been limited to macroscopic scales, where large ensembles of identical spins enhance the detected signal. This advantage disappears when studying individual biological objects containing only a few nuclear spins, where signal levels become extremely weak. As a result, sensing techniques with both excellent electromagnetic sensitivity and high spatial resolution are required.

NV centers in diamond could offer capabilities in this context, as ensemble sensors can achieve  $\text{sub-pT}/\sqrt{\text{Hz}}$  magnetic sensitivity when located tens of micrometers away from the diamond surface. Recent advances have demonstrated optical wide-field NMR microscopy using NV centers, in which NMR signals are converted into optical signals detectable by high-speed cameras. This approach enables rapid imaging of microfluidic structures with approximately  $10 \mu\text{m}$  resolution<sup>137</sup>. However, spatial resolution is limited by surface-induced electric noise in diamond, which necessitates positioning NV ensembles inside the bulk, tens of micrometers away the surface. This distance between the NV ensembles and the targeted spins limits the measurement resolution.

Atomically thin van der Waals materials offer a potential route to push spatial resolution toward the nanometer scale. However, current implementations suffer from much lower sensitivities, typically in the  $10\text{--}100 \text{ nT}/\sqrt{\text{Hz}}$  range—more than three orders of magnitude worse than NV-based sensors. Further research is also required to overcome the micrometer-scale diffraction-limited readout and to fully exploit their intrinsic nanoscale proximity<sup>138</sup>. Other promising approaches include invasive placement of nanodiamonds inside living cells, or direct microwave coupling to spins within the target material by use of superconducting qubits, enabling improved signal quality, nanometer-scale resolution, and volumetric imaging of chemical and biological samples<sup>139</sup>.

This field remains at an early stage of development, with potential spin-outs emerging from academic laboratories, such as projects originating from the Q-CAT portfolio<sup>140</sup>, from TUM

<sup>137</sup>Karl D. Briegel et al., « Optical Widefield Nuclear Magnetic Resonance Microscopy », *Nature Communications* 16, no 1 (2025): 1281, <https://doi.org/10.1038/s41467-024-55003-5>.

<sup>138</sup>Kento Sasaki et al., « Magnetic field imaging by hBN quantum sensor nanoarray », *Applied Physics Letters* 122, no 24 (2023): 244003, <https://doi.org/10.1063/5.0147072>.

<sup>139</sup>« All-Microwave Spectroscopy and Polarization of Individual Nuclear Spins in a Solid », <https://doi.org/10.1126/sciadv.adu0581>.

<sup>140</sup><https://q-cat.io/portfolio>

(QTAS)<sup>141</sup>, or from Harvard (QDTI)<sup>142</sup>. Initial applications could be in chemistry and fundamental biomedical research, followed by clinical diagnostic use cases after regulatory approval processes.

Raman biosensing represents another active and rapidly evolving domain. Based on Raman scattering—a phenomenon discovered a century ago and widely adopted in laboratory spectroscopy in the late 20th century—Raman sensing is now moving toward broad deployment thanks to advances in miniaturization and integration. The emergence of on-chip and CMOS-compatible Raman platforms is increasing accessibility and enabling new use cases.

Historically, the Raman spectroscopy market has been dominated by established incumbents such as Thermo Fisher Scientific, Horiba Scientific, MKS Instruments, Bruker, Renishaw, and WITec (Oxford Instruments). The global Raman spectroscopy market is currently estimated at below one billion dollars, with an annual growth rate of around 7%<sup>143</sup>, driven by the availability of more compact and affordable instruments. Recent advances in CMOS-integrated Raman systems and on-chip photonic Raman sensors have led to the emergence of startups such as Sensorium and InSpek. These companies aim to outperform incumbent solutions by enabling more practical devices and addressing new application spaces. For example, InSpek targets automated analysis of liquid bioreactors, while Sensorium focuses on semiconductor characterization. Both companies pursue a verticalized strategy, positioning themselves as reference suppliers for specific applications, while retaining the potential to expand into adjacent markets.

Raman sensing is an example of the benefits of sensor integration, but it is only one instance among many integrated photonics-based sensors under development for biological applications. These technologies address a rapidly growing biosensor market, estimated at approximately \$32 billion in 2024 and projected to reach \$68 billion by 2034, driven largely by increased adoption in medical applications such as diabetes monitoring<sup>144</sup>.

These photonic technologies are not usually considered quantum sensing, since they rely on classical states of light and semi-classical description of light-matter interactions. Looking ahead, research efforts also explore quantum-enhanced Raman sensing, aiming to surpass classical sensitivity limits using non-classical light states such as squeezed light. However, such enhancements are only effective in quantum-noise-limited systems, where classical noise sources are already negligible. To date, the demonstrated gains – such as a 14% improvement in concentration sensitivity using squeezed-light Raman microscopy<sup>145</sup> – remain insufficient to justify the complexity of the required experimental setups. For practical adoption in research laboratories or healthcare environments, sensitivity improvements of at least an order of magnitude would likely be necessary.

<sup>141</sup>Karl D. Briegel et al., « Optical Widefield Nuclear Magnetic Resonance Microscopy », *Nature Communications* 16, no 1 (2025): 1281, <https://doi.org/10.1038/s41467-024-55003-5>.

<sup>142</sup>David R. Glenn et al., « Single-Cell Magnetic Imaging Using a Quantum Diamond Microscope », *Nature Methods* 12, no 8 (2015): 736-38, <https://doi.org/10.1038/nmeth.3449>.

<sup>143</sup><https://www.marketsandmarkets.com/Market-Reports/raman-spectroscopy-market-23875879.html>

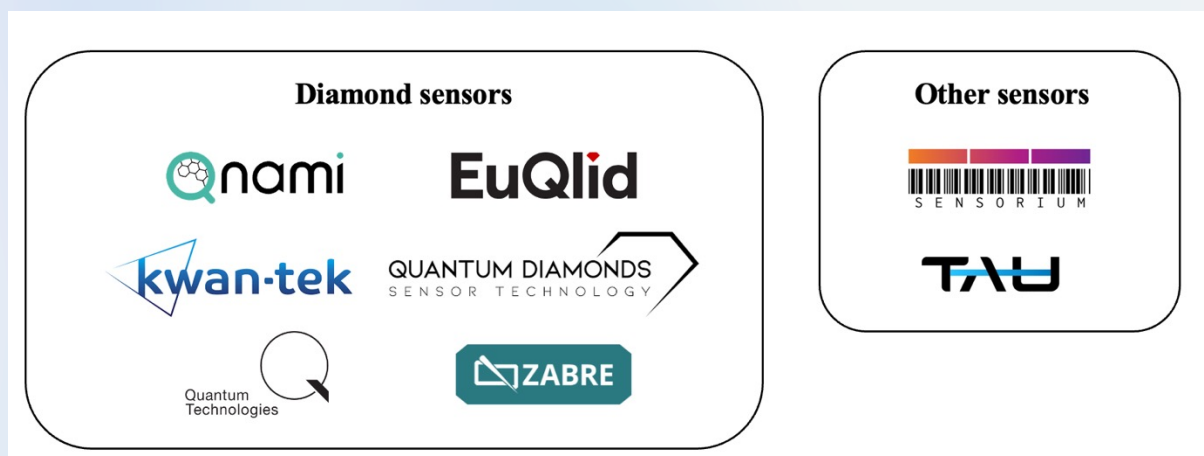
<sup>144</sup><https://www.gminsights.com/industry-analysis/biosensors-market>

<sup>145</sup>Catxere A. Casacio et al., « Quantum-Enhanced Nonlinear Microscopy », *Nature* 594, no 7862 (2021): 201-6, <https://doi.org/10.1038/s41586-021-03528-w>.

---

Beyond Raman spectroscopy, other imaging modalities could also benefit from quantum states of light, including techniques based on bright squeezed light, two-photon states, undetected photons, or single-photon illumination, potentially enabling sensitivity and resolution beyond classical limits. For the time being, demonstrated advantages over classical approaches remain modest and largely confined to specialized experiments. From a commercial perspective, the field is still at an early stage, with broader investment likely awaiting the emergence of a clearly compelling application.

## 2.2. Industry



Industry also faces applications requiring the detection of weaker signals or measurements at smaller scales, where quantum sensors offer clear added value. The main use case is non-destructive testing (NDT).

NDT refers to techniques that evaluate the physical condition of materials and components without causing damage or altering their functional properties<sup>146</sup>. NDT techniques work by applying various forms of energy to materials and analyzing how these energies interact with the material properties and any discontinuities present. For over 50 years, many different methods have been developed ranging from visual inspection, radiographic testing with X-rays and gamma-rays, Raman spectroscopy, thermography, terahertz, ultrasonic, acoustic, functional tracers through to electromagnetic testing. Each technique can probe a diverse range of material properties, with distinct advantages and limitations in terms of detectable defect size, shape, and depth, as well as accuracy, operational speed, and SWaP-C.

The diversity of applications makes it difficult to compare two NDT sensors: the quality of a given sensor has to be proven on a given application. For instance, large-scale critical infrastructure such as nuclear plants or wind turbine blades sometimes demand screening of a wide area in complex geometry and outside environments, whereas semiconductor industry requires detection of smaller defects in a production line; metallic or polymeric materials respond differently to each technique; and defect types and depth of penetration require different sensors to be detected. The value of a given sensor therefore lies in its ability to detect cracks that other sensors cannot, or to do so in a more practical way. A key performance metric is the ability to detect smaller cracks: it enables early detection of damage in infrastructures, and is necessary for NDT in semiconductors. Most NDT techniques are suitable to image defects of minimal size from tens of micrometers to millimeters, whereas semiconductor miniaturization has been increasing the requirement for smaller-scale defect detection. Semiconductors are becoming increasingly smaller with defects in size from sub-micrometer down to tens of nm, while some stacked architectures require detecting buried defects within complex structures.

<sup>146</sup>Maria Inês Silva et al., « Review of Conventional and Advanced Non-Destructive Testing Techniques for Detection and Characterization of Small-Scale Defects », *Progress in Materials Science* 138 (septembre 2023): 101155. <https://doi.org/10.1016/j.pmatsci.2023.101155>.

### 2.2.1. Semiconductor inspection

Quantum sensing based on spin defects has emerged as a novel approach for probing biological systems at the nanoscale. These quantum sensors enable non-invasive detection of magnetic fields, electric fields, temperature variations, strain, and pressure in living cells, combining excellent sensitivity with biologically relevant spatial resolution and biocompatibility.

A promising approach in the NDT landscape combines infrared (IR) thermography with Raman spectroscopy, offering strong potential for disruptive newcomers. Infrared thermography detects and maps temperature variations at a surface by measuring emitted infrared radiation, thereby revealing subsurface defects or irregular heat flow. It enables relatively high-speed scanning with sub-micrometer spatial resolution. When combined with Raman spectroscopy, the technique can achieve resolutions down to ~50 nm, making it well suited for defect analysis in semiconductor devices.

Sensorium is an example of a newcomer developing disruptive technology in this space. The company leverages the versatility of its platform, which can be adapted through inverse hardware design using closed-loop optimization algorithms. Such versatility is particularly valuable in semiconductor production lines, where multiple sensors must be deployed at different manufacturing steps, each with distinct operating constraints and performance requirements. However, entering the semiconductor NDT market requires a carefully planned strategy. Established Raman and IR instrumentation providers—such as Thermo Fisher Scientific, Horiba Scientific, MKS Instruments, Bruker, Renishaw, and WITec—have decades of experience in semiconductor analysis. This long-standing presence has given them deep integration within fabrication facilities, extensive domain knowledge, and access to large datasets, enabling continuous optimization of their instruments.

The integration of NDT equipment into production lines operating at full capacity represents a major entry barrier. Chip manufacturers are generally reluctant to interrupt high-throughput manufacturing processes, as the cost of halting a production line to replace inspection equipment is high. As a result, even NDT systems offering superior sensitivity or improved form factors may struggle to displace incumbent solutions. New entrants must therefore align with major industry transitions and engage early in strategic discussions. One such transition may occur over the coming decade, as future semiconductor devices could shift from silicon wafers to glass substrates<sup>147</sup>.

A second major barrier is limited access to proprietary manufacturing processes and inspection data. Chip producers rarely disclose detailed process information, placing newcomers at a disadvantage in two ways: they lack both the information needed to optimally design their hardware, and the datasets of functional and defective chips required to train their inspection models.

<sup>147</sup>« The growth of advanced semiconductor packaging | McKinsey », consulté le 30 octobre 2025, <https://www.mckinsey.com/industries/semiconductors/our-insights/advanced-chip-packaging-how-manufacturers-can-play-to-win>.

---

Prof. Simone De Liberato, CTO of Sensorium, explains this challenge:

**“AT THE BEGINNING, WE SURVEYED SEVERAL APPLICATION AREAS AND FOCUSED ON SEMICONDUCTORS, AS OUR MANAGEMENT TEAM HAD STRONG CONTACTS IN THE FIELD. THE SEMICONDUCTOR INDUSTRY IS HIGHLY CONFIDENTIAL, AND WITHOUT BEING AN INSIDER, IT IS EXTREMELY DIFFICULT TO IDENTIFY CONCRETE NEEDS.”**

Sensorium has addressed the abovementioned challenges by forming early partnerships with manufacturers, enabling access to real production data and positioning itself ahead of the next major transformation in the semiconductor industry, expected between 2030 and 2035.

Quantum magnetic sensors are also a promising platform for chip defect inspection. While former magnetic sensors typically enabled inspection at length scales of 10–100  $\mu\text{m}$ , spin-defect sensors offer access to the sub-micrometer regime. Qnami and EuQlid, for example, are two companies developing solutions based on NV centers in diamond.

Qnami uses arrays of single NV centers to achieve sample-to-NV distances of a few tens of nanometers<sup>148 149</sup>, enabling spatial resolutions in that range. In contrast, EuQlid’s Quantum Diamond Microscope employs an ensemble of NV centers, allowing wide-field imaging with sub-micrometer resolution. These two approaches target complementary defect types: scanning with single NV centers provides superior near-surface resolution, enabling the detection of very small defects, while ensemble-based imaging offers faster screening and higher sensitivity, making it better suited for identifying buried defects.

For this application, the sensitivity advantage of SQUIDs or atomic vapor cell sensors does not compensate for their inferior spatial resolution at these scales. For similar reasons, microelectronics testing is also a potential application domain for hBN spin-defect sensors, whose ability to operate in close proximity to the sample could enable high spatial resolution. However, their significantly lower sensitivity compared to diamond-based sensors currently limits their competitiveness.

<sup>148</sup>Vincent Jacques et al., « Microscopie magnétique à spin unique », *Photoniques*, no 108 (mai 2021): 32-35, <https://doi.org/10.1051/photon/202110832>.

<sup>149</sup>« Qnami\_WhitePaper1\_NV\_magnetometry-5.pdf », s. d., consulté le 24 septembre 2025, [https://qnami.ch/wp-content/uploads/2020/07/Qnami\\_WhitePaper1\\_NV\\_magnetometry-5.pdf](https://qnami.ch/wp-content/uploads/2020/07/Qnami_WhitePaper1_NV_magnetometry-5.pdf).

Market growth and ongoing transformation underscore the increasing importance of new non-destructive testing (NDT) technologies for semiconductor manufacturing. The traditional packaging market is expected to reach approximately \$16 billion by 2031 for wire bonding and \$45 billion by 2030 for flip-chip packaging, while advanced packaging is projected to reach the tens-of-billions-of-dollars range in 2026, driven by high-performance computing<sup>150</sup>. This structural shift in semiconductor manufacturing is likely to favor new NDT modalities, where quantum sensors have an opportunity.

According to Future Market Insights, the semiconductor inspection market was valued at approximately \$10 billion in 2025 and is expected to reach \$20 billion by 2035. Recent investment activity further reflects this demand, including Onto Innovation's acquisition of Semilab International for \$545 million in 2025<sup>151</sup>, aimed at expanding its advanced optical materials analysis capabilities. Collectively, these trends confirm the semiconductor industry's growing need for more advanced NDT solutions.

### 2.2.2. Infrastructure NDT

Beyond semiconductor inspection, NDT plays a critical role in infrastructure monitoring, with oil and gas representing the largest market segment, followed by aerospace, which is expected to grow at the fastest CAGR. Other significant sectors include energy, manufacturing, and transportation infrastructure, according to MarketsandMarkets<sup>152</sup>. The firm estimates that the global NDT market will grow from approximately \$15 billion in 2025 to \$22 billion by 2030.

Quantum technologies were early candidates for magnetic defect detection, with the record sensitivity of SQUIDs identified decades ago as a potential advantage for detecting buried cracks. Wesdyne is an example of a commercial product based on this approach ; however, the technology did not achieve widespread adoption. SQUID-based systems typically offer spatial resolutions on the order of ~50  $\mu\text{m}$  and require bulky cryogenic infrastructure, which limits their practical deployment.

NV centers in diamond were proposed later as a promising alternative, offering lower absolute sensitivity but enabling more compact and operationally convenient devices. For example, Kwan-Teq is a French startup integrating diamond-based magnetic sensors into optical fibers, allowing inspection in complex geometries and under a wide range of ambient conditions, with detection depths of up to 10 mm<sup>153</sup>. At present, the sensitivity of fiber-integrated NV devices remains limited, typically in the  $\mu\text{T}/\sqrt{\text{Hz}}$  range, restricting detection to sub-millimeter-scale defects, although further performance improvements are expected.

<sup>150</sup>« The growth of advanced semiconductor packaging | McKinsey », <https://www.mckinsey.com/industries/semiconductors/our-insights/advanced-chip-packaging-how-manufacturers-can-play-to-win>.

<sup>151</sup><https://investors.ontoinnovation.com/news/news-details/2025/Onto-Innovation-Announces-Agreement-to-Acquire-Semilab-Internationals-Materials-Analysis-Business/default.aspx>

<sup>152</sup><https://www.marketsandmarkets.com/Market-Reports/non-destructive-testing-ndt-equipment-services-market-882.html>

<sup>153</sup>« kwantek\_en\_NDT.pdf », s. d., [https://www.kwan-tek.com/wp-content/uploads/2024/01/kwantek\\_en\\_NDT.pdf](https://www.kwan-tek.com/wp-content/uploads/2024/01/kwantek_en_NDT.pdf).

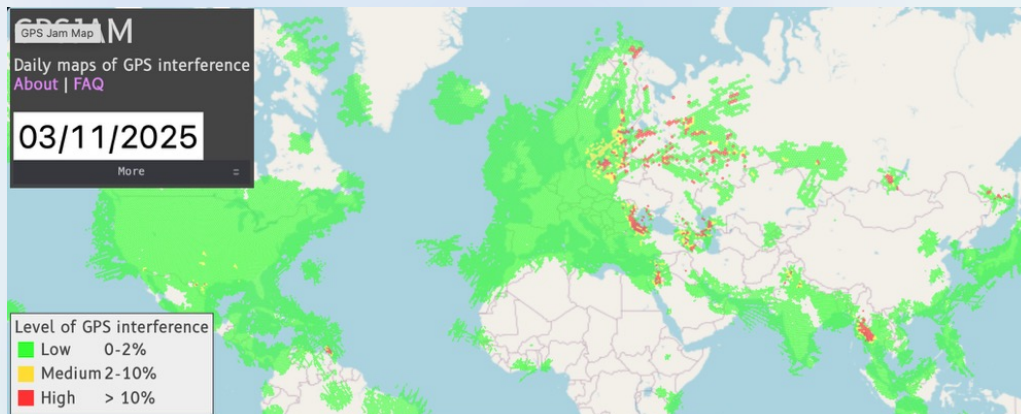
## 2.3. Position, Navigation and Timing (PNT)



Position, Navigation, and Timing (PNT) is the third major domain targeted by quantum sensing technologies. It encompasses three core capabilities: determining location and orientation (positioning), measuring and correcting course to reach desired locations (navigation), and maintaining accurate time synchronization (timing). For decades, the Global Positioning System (GPS), as part of the broader Global Navigation Satellite Systems (GNSS), has been the cornerstone of PNT, enabling precise positioning and time synchronization through satellite-based communication.

However, GNSS-based PNT critically depends on reliable communication with satellites. This reliance introduces vulnerabilities, including natural signal loss in man-made and natural environments such as tunnels, mines, urban canyons, and certain underwater locations, as well as disruptions caused by space weather events. In addition, GNSS signals can be intentionally disrupted through jamming or spoofing attacks, in which a third party interferes with or manipulates the signal, potentially denying service or providing false positioning information.

Classical complementary technologies can assist GPS/GNSS in these situations, including inertial navigation systems based on accelerometers and gyroscopes, auxiliary radio-based systems, and emerging approaches such as LiDAR- and vision-based navigation. These methods can be further enhanced by quantum sensors, which can offer improved performance or reduced SWaP, strengthening existing solutions and enabling new approaches to GPS-denied PNT using clocks, magnetometers, gravimeters, and inertial sensors. Importantly, these techniques are passive, as they do not require signal emission and are therefore inherently difficult to detect or interfere with.



### 2.3.1. Magnetic navigation (MagNav)

When walking, we rely on distinctive visual features of our surroundings to determine our location. Similarly, magnetic navigation exploits the invisible “hills and valleys” of Earth’s magnetic field, whose local variations form a spatial fingerprint. By mapping these geomagnetic anomalies, real-time magnetic field measurements can be matched to characteristic patterns to enable localization and navigation. While proof-of-concept demonstrations have existed for decades, recent progress in compact and portable magnetic field sensors is making magnetic navigation increasingly promising for future positioning systems.

The first demonstrations of magnetic-field-assisted navigation date back to the late 1980s in Sweden. In one early experiment, two magnetic sensors spaced 30 meters apart were deployed on a submarine and recorded the same geomagnetic pattern with a time delay, enabling speed estimation. The use of geomagnetic maps for submarine position determination<sup>154</sup>.

In 2010, the U.S. Air Force demonstrated indoor magnetic navigation with decimeter-level accuracy and maps that remained valid for more than 40 days, as well as a leader–follower navigation scenario, using a low-cost (~\$1k) classical three-axis AMR magnetometer<sup>155</sup>. Using the same sensor technology, they demonstrated in 2012 near meter-level positioning for

<sup>154</sup>« kwantek\_en\_NDT.pdf », s. d., consulté le 30 octobre 2025, [https://www.kwan-tek.com/wp-content/uploads/2024/01/kwantek\\_en\\_NDT.pdf](https://www.kwan-tek.com/wp-content/uploads/2024/01/kwantek_en_NDT.pdf).  
<sup>155</sup>Storms, William, Jeremiah Shockley, et John Raquet. « Magnetic field navigation in an indoor environment ». 2010 Ubiquitous Positioning Indoor Navigation and Location Based Service, octobre 2010, 1-10. <https://doi.org/10.1109/UPINLBS.2010.5653681>.

ground vehicles on an intermittent basis<sup>156</sup>. In 2016, they demonstrated aerial magnetic navigation with 13 meters accuracy at low altitudes and several kilometers accuracy at 3,000 meters altitude<sup>157</sup>, using a highly accurate optically pumped cesium magnetometer with noise levels well below temporal geomagnetic variations and aircraft-induced magnetic variations.

More recently, teams at Q-CTRL combined inertial navigation systems (INS)—the current strategic-grade technology for GPS-denied environments—with vector fluxgate magnetometers and rubidium optically pumped magnetometers (OPMs). This hybrid approach demonstrated superior performance compared to INS alone, achieving positioning accuracies of approximately 0.1 km at 1 km altitude<sup>158</sup>.

These demonstrations highlight the feasibility of navigation based on magnetic-field measurements and clarify the key requirements for broader deployment: reliable sensors—whose sensitivity need not be record-breaking and depends on the application—and accurate magnetic maps or models, accounting for the fact that geomagnetic fields evolve over time. They also underline the inherent limitations of magnetic navigation, including map variability, external magnetic noise, and the presence of magnetic “dead zones.”

Earth’s magnetic field has been mapped since the second half of the 20th century, well before the emergence of magnetic navigation (MagNav) concepts, primarily for geophysical exploration using airborne and satellite-based sensors<sup>159</sup>. Airborne magnetic surveys were also employed to improve heading determination (by providing more precise magnetic north references). However, this resulted in magnetic maps that often resemble a patchwork rather than a coherent global dataset and suffer from limited precision and confidence—particularly those generated prior to the advent of GPS—making them suboptimal for magnetic-enhanced positioning and navigation<sup>160</sup>.

As a result, the availability of accurate and reliable magnetic maps remains the primary limiting factor for magnetic navigation. With the growing importance of GPS-denied navigation, more extensive and systematic magnetic surveys will be required to fully exploit the potential of MagNav. This effort could be facilitated by reductions in the SWaP of magnetometers, enabling easier integration into drones and other mobile platforms for large-scale, high-resolution mapping<sup>161</sup>.

<sup>156</sup>Jeremiah A Schockley, Ground Vehicle Navigation Using Magnetic Field Variation. Dissertation, Air Force Institute of Technology, 2012.

<sup>157</sup>Aaron Canciani et John Raquet, « Absolute Positioning Using the Earth’s Magnetic Anomaly Field: Magnetic Anomaly Navigation », *Navigation* 63, no 2 (2016): 111-26, <https://doi.org/10.1002/navi.138>.

<sup>158</sup>Muradoglu, Murat, Mattias T. Johnsson, Nathaniel M. Wilson, et al. « Quantum-assured magnetic navigation achieves positioning accuracy better than a strategic-grade INS in airborne and ground-based field trials ». arXiv:2504.08167. Prépublication, arXiv, 10 avril 2025. <https://doi.org/10.48550/arXiv.2504.08167>.

<sup>159</sup>I. R. Shapiro et al., « The Vector Field Proton Magnetometer for IGY Satellite Ground Stations », *Journal of Geophysical Research (1896-1977)* 65, no 3 (1960): 913-20, <https://doi.org/10.1029/JZ065i003p00913>.

<sup>160</sup>Aaron Canciani et John Raquet, « Absolute Positioning Using the Earth’s Magnetic Anomaly Field: Magnetic Anomaly Navigation », *Navigation* 63, no 2 (2016): 111-26, <https://doi.org/10.1002/navi.138>.

<sup>161</sup>James S. Bennett et al., « Precision Magnetometers for Aerospace Applications: A Review », *Sensors* 21, no 16 (2021): 5568, <https://doi.org/10.3390/s21165568>.

However, the achievable precision of magnetic maps is fundamentally limited by temporal variations in the ionosphere and magnetosphere. While these variations can be partially mitigated using frequency-based models, residual uncertainties remain. Geomagnetic storms driven by solar activity are a particularly challenging example of such disturbances. To be effective, magnetic sensors must be sufficiently sensitive to resolve the signal of interest, with intrinsic noise levels below those of external magnetic fluctuations. Cesium OPMs are generally considered capable of meeting this requirement.

In addition to sensor performance, the strength of the magnetic signal itself is critical. Certain regions – such as highways<sup>162</sup> – exhibit intrinsically low magnetic field variability, resulting in so-called “dead zones” where magnetic navigation is ineffective. Furthermore, the amplitude of Earth’s magnetic anomalies decreases with altitude, implying that higher positioning accuracy is expected near the ground or at low altitudes.

Magnetometers must therefore be sufficiently sensitive to resolve magnetic footprint variations at vehicle speeds and at the targeted spatial resolution. However, this sensitivity requirement is not the most stringent constraint, as the limited precision of existing magnetic maps and the presence of external magnetic fluctuations remain dominant limiting factors. As a result, sensor priorities shift toward achieving sufficiently low SWaP for integration into vehicles, along with a wide dynamic range that allows operation without magnetic shielding in Earth’s ambient magnetic field (on the order of tens of microteslas).

Several magnetometer technologies have long been used in space applications to meet these requirements, including kilogram-scale proton-precession magnetometers, OPMs, and fluxgate sensors. Proton-precession magnetometers are bulky and heavy, while fluxgates and OPMs often require periodic recalibration. As a result, newer sensing technologies are attracting interest: NV-center-based sensors are well suited for harsh operating environments; MEMS- and optomechanics-based magnetometers have very low SWaP; chip-scale OPMs have very good sensitivities combined with low SWaP.

Recent economic trends testify to growing interest in these sensing platforms for magnetic navigation. In 2025, DARPA selected Q-CTRL for quantum navigation programs totaling \$24.4 million, including a collaboration with Lockheed Martin<sup>163</sup>, underscoring the importance the defense sector places on alternatives to GPS. Q-CTRL is a startup primarily developing Rb-OPMs combined with classical sensors and advanced navigation software, whereas Lockheed Martin is as a long-established defense contractor pursuing a multi-modal PNT strategy<sup>164</sup>.

<sup>162</sup>Jeremiah A Schockley. Ground Vehicle Navigation Using Magnetic Field Variation. Dissertation, Air Force Institute of Technology, 2012.

<sup>163</sup><https://quantumcomputingreport.com/q-ctrl-selected-for-darpa-roqs-program-to-develop-quantum-sensors-for-navigation>

<sup>164</sup>Lockheed Martin has invested in diamond-based magnetometry through a partnership with Element Six to develop its Dark Ice product : <https://www.lockheedmartin.com/en-us/news/features/2019-features/tech-thats-cool-as-dark-ice.html>

Additional startups are emerging in this space, including ArQSensors<sup>165</sup>, targeting diamond-based sensors for operation in extreme environments, and Deteqt<sup>166</sup>, focusing on diamond-on-chip development. Based on the technological requirements identified for MagNav, diamond sensors offer sufficient sensitivity for this application. Their strongest value proposition lies in operation under harsh or extreme conditions, where their robustness can be fully leveraged. In less demanding environments, diamond-on-chip implementations – once mature – could offer a significant SWaP advantage. In this context, the recent Bosch-Element Six diamond-on-chip initiative, targeting both medical and PNT applications, is also worth close attention<sup>167</sup>.

### 2.3.2. Gravimetry navigation (GravNav)

As with magnetic navigation, the Earth's uneven mass distribution creates a distinct gravitational footprint across its surface. In principle, a global gravity map could therefore serve as an absolute reference for position determination. Achieving this objective has long remained out of reach, despite more than a century of continuous improvements in gravimetry.

The first and only one available until the beginning of the 20th century, were based on classical pendulums. As absolute gravimeters, they measured the local value of gravitational acceleration at a given position. In the early 1930s, more precise spring gravimeters were developed and later miniaturized into portable instruments widely used for oil and mineral exploration. These devices are inherently relative: a variation in gravity induces a variation of a spring length. This means that they cannot be used for absolute gravity positioning or month-long measurements, as small drifts accumulate over time.

In the 1960s, even more precise relative gravimeters were introduced: the superconducting gravimeters. In these instruments, a superconducting sphere levitates in a magnetic field, and its motion records minute variations in gravity. While they remain the most sensitive gravimeters available, they are still relative sensors and require cryogenics.

In the same period, falling corner cubes absolute gravimeters were invented: a mass is dropped which acceleration is measured optically, giving absolute information about the local gravity. However, their reliance on moving mechanical parts, large size, and the need for a seismically quiet environment make them incompatible with mobile or embedded applications.

Atomic gravimeters are a more recent alternative for absolute gravimetry. They now reach accuracy comparable to falling corner-cube instruments, while offering the possibility of mobile deployment. As a result, they are progressively replacing spring-based relative gravimeters in shipborne and airborne geophysical surveys<sup>168</sup>. Several business models are

<sup>165</sup><https://arqsensors.io>

<sup>166</sup><https://deteqt.tech>

<sup>167</sup><https://www.bosch-quantumsensing.com/insights-and-updates/bosch-establishes-company-with-the-synthetic-diamond-solutions-provider-element-six/>

<sup>168</sup>Y. Bidel et al., « Airborne Absolute Gravimetry With a Quantum Sensor, Comparison With Classical Technologies », *Journal of Geophysical Research: Solid Earth* 128, no 4 (2023): e2022JB025921, <https://doi.org/10.1029/2022JB025921>.

expected to emerge around this technology, including instrument sales, leasing, and survey-as-a-service offerings. At present, direct instrument sales are favored, as a limited number of users require continuous access to the technology. Early customers include naval operators conducting ocean gravity mapping in preparation for GravNav, as well as geophysics institutes seeking improved measurements of geodynamic phenomena.

Developments are expected to address public works-type contracts making maps of the subsoil, tunnels and cavities. Another near-term objective is embedding of these sensors in autonomous surface drones. However, the platforms are currently about a m<sup>3</sup>-scale, and removing the need of gyrostabilization is a current R&D objective that would enable portability. Further technological developments are expected to send atomic gravimeters in space for geophysics exploration and Earth monitoring<sup>169</sup>.

The market for legacy gravimetry technologies is estimated to lie in the \$10–100 million range<sup>170</sup> – with use cases that have so far been limited by the capabilities of old technologies. It has yet remained relatively stable and highly concentrated, with a small number of established players. In relative spring gravimeters and free-fall corner-cube absolute gravimeters, major actors include LaCoste & Romberg – merged with Scintrex in the 2000s – while GWR Instruments dominates the market for superconducting gravimeters.

In atomic gravimetry, Muquans was a French pioneer, founded in 2011 and acquired by iXblue (now Exail) in 2021. More recent spin-outs include Nomad Atomics in Australia and the UK-based companies Delta g and Skylark Lasers.

### 2.3.3. Inertial sensors

Inertial sensors<sup>171</sup> are the most mature technology for GPS-denied navigation, spanning military- and aerospace-grade high-precision systems down to ultra-low-SWaP devices that are ubiquitous in consumer products such as smartphones. They measure acceleration and rotation, which can be used directly or integrated from a known initial position to reconstruct displacement along a trajectory, enabling position estimation in GPS-denied environments.

However, unavoidable measurement errors in acceleration and rotation accumulate over time, leading to a progressive drift in the estimated position until an absolute reference is available to correct it. Conversely, inertial sensors provide far superior accuracy over short timescales and distances compared with the absolute GPS-denied position references discussed above. For optimal positioning performance, inertial sensors must therefore be combined with complementary absolute reference technologies.

Gyroscopes were developed early, with mechanical versions dating back to the Foucault pendulum in 1852. Optical gyroscopes were introduced over the course of the 20th century,

<sup>169</sup>Sven Abend et al., « Technology roadmap for cold-atoms based quantum inertial sensor in space », *AVS Quantum Science* 5, no 1 (2023): 019201, <https://doi.org/10.1116/5.0098119>.

<sup>170</sup><https://www.credenceresearch.com/report/gravimeters-market> Aaron Canciani et John Raquet, « Absolute Positioning Using the Earth's Magnetic Anomaly Field: Magnetic Anomaly Navigation », *Navigation* 63, no 2 (2016): 111–26, <https://doi.org/10.1002/navi.138>.

<sup>171</sup>Vittorio M. N. Passaro et al., « Gyroscope Technology and Applications: A Review in the Industrial Perspective », *Sensors* 17, no 10 (2017): 2284, <https://doi.org/10.3390/s17102284>.

based on Sagnac interferometry: two counterpropagating optical beams circulating in a closed loop – one clockwise and the other counterclockwise – experience a relative phase shift when the loop rotates. This phase difference provides a direct measure of rotation. This principle is implemented in ring laser gyroscopes and fiber-optic gyroscopes, which offer excellent sensitivity and are widely used in strategic-grade applications. These classical technologies continue to improve.

MEMS gyroscopes rely on the mechanical resonance of microfabricated structures under rotation. While their performance is lower, their extremely small size, low cost, and low power consumption led to major market disruption at the end of the 20th century, with ubiquitous adoption in consumer electronics. MEMS gyroscopes are still improving and may become competitive with optical gyroscopes for some applications, as evidenced by the emergence of startups in that direction<sup>172</sup>. However, their ultimate performance is expected to remain below that of quantum gyroscopes.

Two main types of quantum gyroscopes are under development: atomic interferometer gyroscopes and NMR-based gyroscopes. Atomic interferometer gyroscopes rely on the same physical principles as atomic gravimeters. Atoms are manipulated as matter waves, exploiting wave-particle duality: they are coherently split into two paths that accumulate a differential phase shift before being recombined to interfere. A rotation induces such a phase shift between the two paths, in direct analogy with the optical Sagnac effect observed for counterpropagating light waves<sup>173</sup> – here realized with matter waves instead of photons. Measuring the resulting interference pattern provides a measurement of the rotation rate, with a precision that can surpass that of most optical gyroscopes.

While these devices have demonstrated outstanding precision in laboratory settings over the past decades, they remain bulky, typically on the order of a cubic meter. Significant efforts are therefore required to miniaturize and ruggedize atomic interferometer gyroscopes to enable field demonstrations and integration into practical platforms, following a development path similar to that of atomic gravimeters<sup>174</sup>.

Atomic interferometer gyroscopes are expected to find their primary applications in military platforms and satellite systems, where higher navigation accuracy can significantly enhance the performance of modern space-based technological infrastructures. However, substantial development is still required across all subsystems to reduce power consumption, size, and complexity, and to ensure sufficient reliability for space deployment, as these devices must compete with simpler and well-established optical gyroscopes.

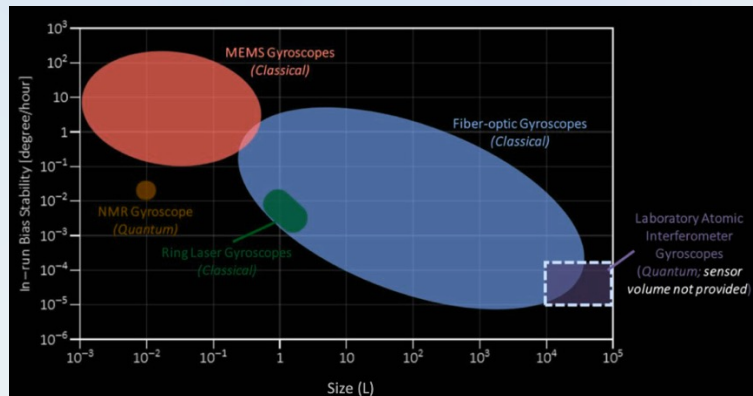
<sup>172</sup><https://www.ingage-mems.com/funding-to-industrialize-mems-navigation-sensors>

<sup>173</sup>« Accurate Measurement of the Sagnac Effect for Matter Waves », <https://doi.org/10.1126/sciadv.abn8009>.

<sup>174</sup>« Quantum Sensing of Acceleration and Rotation by Interfering Magnetically Launched Atoms », <https://doi.org/10.1126/sciadv.adg4498>.  
Sven Abend et al., « Technology roadmap for cold-atoms based quantum inertial sensor in space », *AVS Quantum Science* 5, no 1 (2023): 019201.

Atomic interferometer gyroscopes are a much more recent technology, suggesting room for significant future reductions in SWaP, particularly driven by spatial applications<sup>175</sup>. The commercialization of space-qualified, reliable systems still involves significant development effort, and atomic interferometer gyroscopes currently occupy a limited share of the gyroscope landscape compared with widely deployed low-SWaP-C technologies.

NMR gyroscopes are low-SWaP rotation sensors based on a different physical principle: precessing spins undergo a shift in their precession frequency when they are rotated. This concept has been known since the 1970s, but NMR gyroscopes became competitive with other technologies only in the 2000s with the advent of chip-scale atomic devices. Practical demonstrations have shown sensitivities an order of magnitude better than MEMS for a volume of  $\sim 10 \text{ cm}^3$ . While ongoing research continues to improve these technologies—e.g., glass-only cells developed by QSensato that may enhance sensitivity and simplify design—the rapid progress of MEMS must also be considered in comparison, and further size reduction is currently limited by the need for  $\text{cm}^3$ -scale magnetic shielding. More recent research has proposed NMR gyroscopes based on NV centers in diamond, offering lower performance today but with potential pathways for improvement<sup>176 177</sup>.



The global gyroscope market was estimated at \$2.7 billion in 2024 and is projected to reach around \$4 billion by 2034<sup>178</sup>, driven by increasing civilian and military demand as well as ongoing reductions in SWaP-C. The market remains largely dominated by long-established players. While several startups and research projects in atom interferometry have emerged, they have not yet disrupted the market structure. NMR quantum gyroscopes represent a potentially impactful alternative, combining high sensitivity with form factors compatible with intermediate-scale platforms.

<sup>175</sup>Sven Abend et al., « Technology roadmap for cold-atoms based quantum inertial sensor in space », *AVS Quantum Science* 5, no 1 (2023): 019201, <https://doi.org/10.1116/5.0098119>.

<sup>176</sup>« Demonstration of Diamond Nuclear Spin Gyroscope », <https://doi.org/10.1126/sciadv.abl3840>.

<sup>177</sup>Guoqing Wang et al., « Hyperfine-Enhanced Gyroscope Based on Solid-State Spins », *Physical Review Letters* 133, no 15 (2024): 150801,

<sup>178</sup><https://doi.org/10.1103/PhysRevLett.133.150801>.

<https://www.gminsights.com/industry-analysis/gyroscope-market>

Their volume and performance make them suitable candidates for integration in robots, vehicles, military systems, and certain space applications. In particular, they can achieve stability levels comparable to some classical fiber-optic gyroscopes used in space, while offering substantially reduced size (cm<sup>3</sup> rather than dm<sup>3</sup>), weight (tens of grams rather than kilograms), and power consumption<sup>179 180 181</sup>. Translating this performance into robust, long-lifetime devices remains a key engineering challenge. Initiatives such as the QYRO project (Q.ANT, Bosch, and partners) are explicitly addressing this objective.

Acceleration sensors are another class of inertial sensors, typically used in conjunction with gyroscopes. According to Einstein's equivalence principle, which links acceleration and gravitational fields, atomic interferometers based on the same technology as gravimeters can function as highly sensitive accelerometers. These devices offer excellent sensitivity, albeit at the cost of relatively large SWaP. Their technology readiness level is currently less advanced than that of atomic gravimeters, as practical field demonstrations with compact, out-of-the-laboratory systems remain limited. Consequently, startups developing atomic interferometer technologies often pursue accelerometers alongside gravimeters, gyroscopes, or clocks, leveraging a shared technological platform.

### 2.3.4. Clocks

Precise clocks<sup>182 183 184</sup> span a wide range of performance and SWaP. At one end of the spectrum, classical miniature crystal oscillators (XOs) and MEMS-based clocks provide timing errors on the order of 10<sup>-4</sup> – 10<sup>-5</sup> s per day at costs of a few hundred dollars, and are ubiquitous in consumer electronics, industrial systems, and telecommunications. At the other end, laboratory-scale hydrogen masers – weighing tens of kilograms – achieve timing errors of about 10<sup>-10</sup> s per day, but cost hundreds of thousands of dollars and are primarily used in ground-based scientific facilities.

Between these extremes, rubidium (Rb) and cesium (Cs) atomic clocks offer intermediate stability, and SWaP-C, and are widely deployed on satellites for communications, navigation, and network synchronization. Since the early 2000s, significant effort has been devoted to reducing their SWaP through the development of chip-scale atomic clocks (CSACs)<sup>185</sup>, driven in part by major U.S. research programs. These devices were envisioned as replacements for earlier satellite clocks and as candidates for broader deployment in vehicles, where they can reduce dependence on satellite-based navigation.

<sup>179</sup>[https://satcatalog.s3.amazonaws.com/components/320/SatCatalog\\_-\\_Airbus\\_-\\_Astrix\\_120\\_-\\_Datasheet.pdf](https://satcatalog.s3.amazonaws.com/components/320/SatCatalog_-_Airbus_-_Astrix_120_-_Datasheet.pdf)

<sup>180</sup><https://guidenav.com/fog-gyroscope/>

<sup>181</sup><https://cdn.northropgrumman.com/-/media/Project/Northrop-Grumman/ngc/what-we-do/mission-solutions/assured-navigation/g-2000-dtg-gyroscope-product-suite/G-2000-Gyroscope-Inertial-Product-Family-datasheet.pdf>

<sup>182</sup>Vittorio M. N. Passaro et al., « Gyroscope Technology and Applications: A Review in the Industrial Perspective », *Sensors* 17, no 10 (2017): 2284, <https://doi.org/10.3390/s17102284>.

<sup>183</sup>Bonnie L. Schmittberger Marlow et David R. Scherer, « A Review of Commercial and Emerging Atomic Frequency Standards », *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 68, no 6 (2021): 2007-22, <https://doi.org/10.1109/TUFFC.2021.3049713>.

<sup>184</sup>« Quantum vs Classical Complementary PNT », s. d., consulté le 19 septembre 2025,

<https://quantonation.sharepoint.com/sites/Quantonation/Documents%20partages/Main%20Drive/Background/Quantum%20Sensing/Quantum%20vs%20Classical%20Complementary%20PNT.pdf?CT=1758118987459&OR=ItemsView>.

<sup>185</sup>John Kitching, « Chip-Scale Atomic Devices », *Applied Physics Reviews* 5, no 3 (2018): 031302, <https://doi.org/10.1063/1.5026238>.

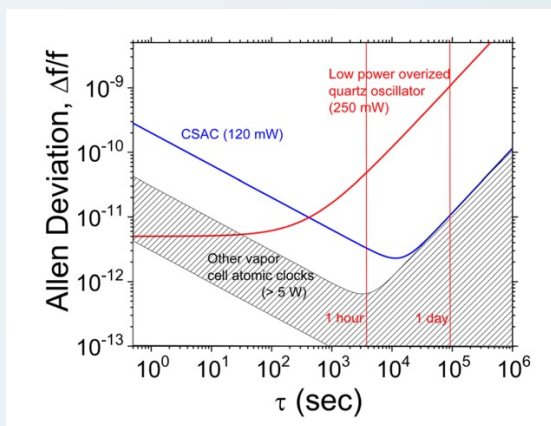
Accurate onboard timing can relax GNSS requirements: while four satellites are normally needed to solve for position and time (x,y,z,t), this number can be reduced when the receiver carries a sufficiently stable time reference, which is particularly valuable in partially GPS-denied environments. Military-grade GNSS-based communication systems also benefit from receiver clocks capable of maintaining sub-millisecond accuracy over several days at reasonable SWaP.

In practice, CSACs are often paired with crystal oscillators, which offer superior short-term stability. At the same time, continued improvements in MEMS-based crystal oscillators are narrowing the performance gap, reducing the relative competitiveness of CSACs in some applications. In parallel, chip-based cold-atom clocks are emerging as another interesting technology under development (at much lower TRL).

Since the 2010s, several established companies have developed CSACs, including Microchip (USA), Accubeat (Israel), Spectratime (Safran), Teledyne (USA), and Chengdu Spaceon (China). Recently, a number of startups have entered the field, targeting different technological approaches: CSAC development, cold-atom clocks, optical atomic clocks, and diamond-based chip-scale atomic clocks. This diversity of industrial actors reflects the maturation of multiple atomic clock technologies following decades of laboratory research worldwide.

The total atomic clock market was still recently estimated to be relatively small, at around \$325 M in 2024<sup>186</sup>. Despite the commercialization of CSACs beginning more than 15 years ago, they have not led to major market disruption. This can be partly explained by their cost, which remains too high for widespread integration into consumer or vehicle navigation systems, where satellite-based timing generally provides sufficient performance for most use cases. At the same time, the performance, reliability, and lifetime of CSACs have not yet been sufficient to justify major replacement of established satellite-grade clocks.

A promising near-term opportunity is military and critical applications, particularly where resilience to partial GNSS degradation is required. One of the main challenges may be in engineering for robustness and long-term reliability, particularly needed for operation in harsh environments.

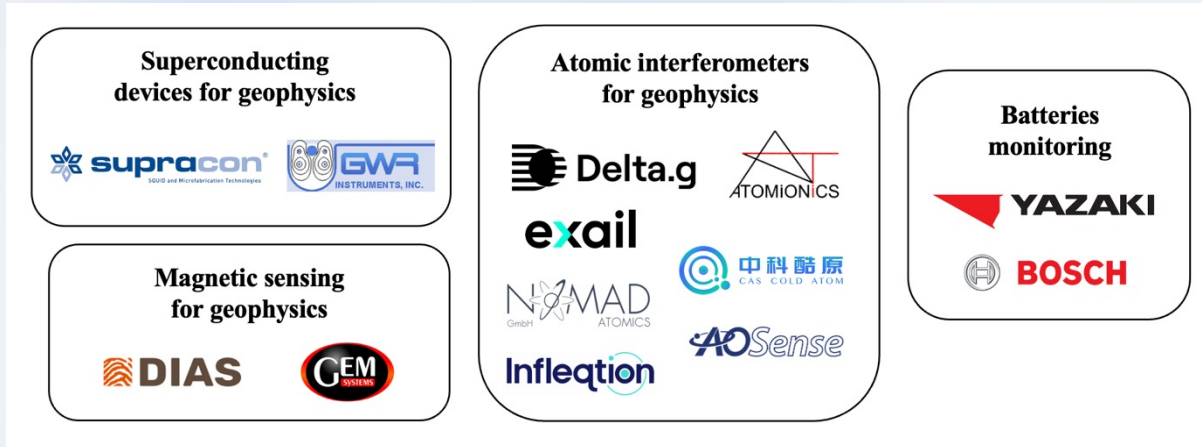


*Fractional frequency instability of different clocks<sup>187</sup>. CSAC are better than crystal oscillators at long times, but must be combined with them at short time. Lower power consumption and size make them competitive with some bigger commercial vapor cell clocks.*

<sup>186</sup><https://reports.valuates.com/market-reports/QYRE-Auto-23U456/global-atomic-clock>

<sup>187</sup>John Kitching, « Chip-Scale Atomic Devices », *Applied Physics Reviews* 5, no 3 (2018): 031302, <https://doi.org/10.1063/1.5026238>.

## 2.4. Geology and Energy



Several of the technologies and methods introduced earlier also have applications in geology and the energy sector.

### 2.4.1. Geophysics exploration

Gravity and magnetic field measurements, for instance, are used not only for navigation but also for geophysical applications. Since the last century, magnetic field measurements from ground-, airborne-, and space-based platforms have supported geophysical models enabling fundamental studies of Earth's core dynamics, its magnetic environment, and climate processes. Magnetic mapping is also widely used for resource exploration, with a market size estimated between \$1.8 B<sup>188</sup> and \$6.8 B<sup>189</sup> in 2024 and projected to reach the \$3–10 B range within the next decade. As in magnetic navigation, quantum sensors offer alternative magnetometer specifications, enabling more portable, more precise, or more robust sensing solutions depending on the application.

Geophysical gravimeters similarly benefit from the advantages seen in gravity-based navigation: cold-atom devices provide excellent absolute sensitivity while remaining portable, though typically with volumes on the order of cubic meters. They have already been demonstrated for volcano monitoring and underground structure detection<sup>190</sup>, and could find further applications in mining, carbon storage assessment, and water resource monitoring<sup>191</sup>.

<sup>188</sup><https://www.gminsights.com/fr/industry-analysis/magnetic-geophysical-services-market>

<sup>189</sup><https://www.marketresearchfuture.com/reports/magnetic-geophysical-service-market-30253>

<sup>190</sup>Ben Strau et al., « Quantum Sensing for Gravity Cartography », *Nature* 602, no 7898 (2022): 590–94, <https://doi.org/10.1038/s41586-021-04315-3>.

<sup>191</sup>Kai Bongs et al., « Quantum Sensors Will Start a Revolution — If We Deploy Them Right », *Nature* 617, no 7962 (2023): 672–75, <https://doi.org/10.1038/d41586-023-01663-0>.

Accurate onboard timing can relax GNSS requirements: while four satellites are normally needed to solve for position and time (x,y,z,t), this number can be reduced when the receiver carries a sufficiently stable time reference, which is particularly valuable in partially GPS-denied environments. Military-grade GNSS-based communication systems also benefit from receiver clocks capable of maintaining sub-millisecond accuracy over several days at reasonable SWaP.

Atomic gravimeters can address a wide range of applications. In practice, business models often focus on a first vertical market, with the understanding that once the technology is mature, the same platform can be extended to additional use cases. Bruno Desruelles, CEO Photonics at Exail, explains this strategy: “Today, we commercialize a static gravimeter for geophysics institutes. We are continuously improving this product and moving toward a more global, easy-to-use gravimeter, enabling us to address new applications. This includes the development of a differential gravimeter for public works, such as subsurface imaging of tunnels and cavities. We are also developing embedded sensors for oceanography and geophysics, to improve the understanding of geodynamic phenomena, as well as for defense applications, particularly navigation system calibration – a highly strategic and sensitive area with strong operational potential.”

#### 2.4.2. Energy infrastructure monitoring

The non-destructive testing methods discussed earlier are also valuable in the energy industry, for example in monitoring power plants, wind turbine blades, or pipelines. In many cases, in-situ detection is needed, making portable sensors essential – an area where chip-scale atomic vapor cells and diamond-based sensors are well suited.

Gas leak detection is another application where sensors are valuable, and quantum research can contribute added value. Gas is often detected optically, and integrated and quantum-enhanced photonics can improve both miniaturization and sensitivity. This domain also illustrates how classical technologies, developed as byproducts of quantum research, can find practical applications<sup>192</sup>.

#### 2.4.3. Batteries

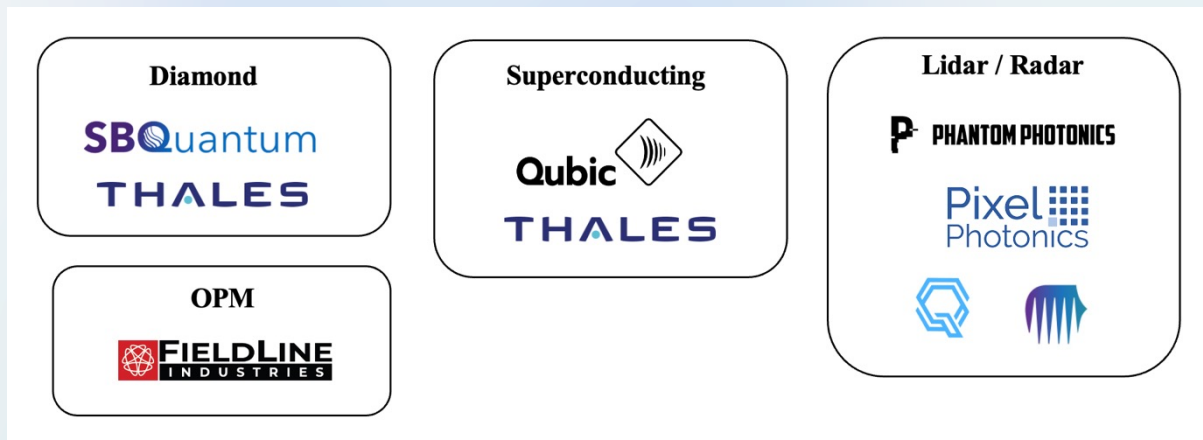
Batteries are another domain where quantum sensing could contribute. Quantum non-destructive testing technologies may be used in the development, manufacturing, and operation of batteries, offering higher imaging resolution than classical methods<sup>193</sup>.

<sup>192</sup>Mirega is a startup targeting CO<sub>2</sub> detection using integrated photonics, as a byproduct of atomic cavities from LKB laboratories at ENS: <https://www.lkb.fr/atomchips/about-the-team/mirega/>

<sup>193</sup>Mark G. Bason et al., « Non-Invasive Current Density Imaging of Lithium-Ion Batteries », *Journal of Power Sources* 533 (juin 2022): 231312, <https://doi.org/10.1016/j.jpowsour.2022.231312>.

Quantum sensors have also been demonstrated for battery optimization by the University of Tokyo and Yazaki Corporation<sup>194</sup>. The wide dynamic range of diamond sensors allows measurement of battery currents from hundreds of amperes down to 10 mA, providing high precision in the final percentages of discharge and thereby increasing the effective usable capacity. However, this application still requires enhanced robustness to operate reliably in the noisy environment of a vehicle, and classical alternatives continue to be improved.

## 2.5. Security and Defense



While we have already covered military applications of quantum-enhanced navigation in the PNT section, quantum sensors have broader uses across security and defense.

### 2.5.1. Security control

Advanced imaging plays a key role in security screening. The global market, valued at around \$11B in 2025<sup>195</sup>, is expected to double by 2035 due to rising demand. One notable unmet need is school safety, particularly in the United States, where conventional airport-style scanners are intrusive, anxiety-inducing, and difficult to deploy widely. Magnetic sensing offers a promising alternative for remote metal detection, and its performance can be significantly enhanced with quantum magnetic sensors. Diamond-based sensors, in particular, provide the necessary sensitivity in compact form factors, allowing discreet integration into entrances or hallways. SBQuantum is developing systems that combine these solid-state quantum sensors with signal-processing software to reliably detect weapons.

Security control market also encompasses stadiums, courthouses, airports and hospitals, with many opportunities for sensor innovation. Security in airports is an interesting opportunity as devices are changed every decade following technology and regulation evolution. It could benefit from remote magnetic detection developed by SBQuantum, or by new X-rays and millimetre wave detectors. For the latter detectors, superconducting devices have the best

<sup>194</sup>Yuji Hatano et al., « High-Precision Robust Monitoring of Charge/Discharge Current over a Wide Dynamic Range for Electric Vehicle Batteries Using Diamond Quantum Sensors », *Scientific Reports* 12, no 1 (2022): 13991, <https://doi.org/10.1038/s41598-022-18106-x>.

<sup>195</sup><https://www.futuremarketinsights.com/reports/security-screening-market>

sensitivities but with inappropriate operational constraints. Nanophotonics innovation are also likely to disrupt this field, enabling lower X-ray doses or faster and better detection.

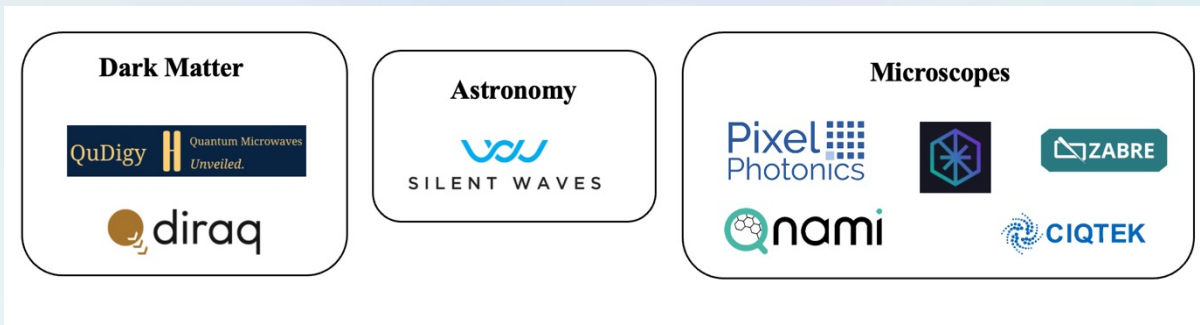
Optomechanics is another promising approach for security, particularly for drone intrusion detection. For example, distributed optical fiber acoustic sensors—already used in submarine monitoring—are being adapted for drones, and quantum-enhanced optomechanical techniques could further improve their sensitivity and range.

### 2.5.2. Military object detection

Remote object detection has significant military applications. For instance, magnetic detection of submarines has been demonstrated, including a 2025 proof of concept by China using a rubidium magnetic sensor mounted on a drone<sup>196</sup>.

Quantum lidar and radar technologies are also attracting interest for defense. They can increase the information extracted per photon, allowing systems to operate with lower light emission and therefore more discreetly. However, these technologies are still at an early stage, with some implementations requiring complex setups such as dilution refrigerators for microwave quantum control<sup>197</sup>.

## 2.6. Fundamental Science



Quantum sensing research has been strongly driven by fundamental science experiments, which benefit from long development timescales, exceptionally stringent precision requirements, and sustained interest from the physics community. Although this application domain does not correspond to the largest commercial markets, it plays a crucial role as a driver of sensor innovation. Being aware of the technological advances developed for fundamental research is therefore highly valuable, to identify sensing technologies with potential applications beyond fundamental physics and to anticipate which capabilities will be advanced by forthcoming experiments. Monitoring the roadmap of projected experiments provides insight into the sensor technologies that are likely to be further pushed and matured by this research.

<sup>196</sup>China unveils drone-mounted quantum device for submarine detection in South China Sea, Stephen Chen, South China Morning Post, April 2025.

<sup>197</sup>Quantum advantage in microwave quantum radar, R. Assouly, R. Dassonneville, T. Peronnin, A. Bienfait, and B. Huard, Nature Physics, June 2023.

sensitivities but with inappropriate operational constraints. Nanophotonics innovation are also likely to disrupt this field, enabling lower X-ray doses or faster and better detection.

requirements, and sustained interest from the physics community. Although this application domain does not correspond to the largest commercial markets, it plays a crucial role as a driver of sensor innovation. Being aware of the technological advances developed for fundamental research is therefore highly valuable, to identify sensing technologies with potential applications beyond fundamental physics and to anticipate which capabilities will be advanced by forthcoming experiments. Monitoring the roadmap of projected experiments provides insight into the sensor technologies that are likely to be further pushed and matured by this research.

### 2.6.1. Particle physics

Particle physics experiments make extensive use of quantum sensors, either to probe fields and interactions at the level of individual quantum systems or to enhance the sensitivity of large-scale experiments. A wide variety of ongoing and proposed experiments already rely on state-of-the-art quantum sensing platforms to study neutrinos, test fundamental symmetries, and search for dark matter, dark energy, and physics beyond the Standard Model<sup>198</sup>.

Use cases include:

Quantum sensor	Particle physics experiment	Reference
Cold Cs atoms	Detection of possible sterile neutrinos in the 5–100 keV mass range	HUNTER <sup>199</sup>
Electron spin manipulation in HfF <sup>+</sup> and ThO molecules	Search for electric dipole moments to probe charge-parity violation and matter–antimatter asymmetry	ACME, JILA EDM experiments, <sup>200</sup>
Cold neutron beams and trapped ultracold neutrons	Search for the neutron electric dipole moment	nEDM experiments <sup>201</sup> 202 203
Atom interferometry with Rb and Cs	Precision determination of the fine-structure constant	
Space-based atom interferometry	Tests of Galilean invariance	MICROSCOPE <sup>204</sup>

<sup>198</sup>Steven D. Bass et Michael Doser, « Quantum Sensing for Particle Physics », *Nature Reviews Physics* 6, no 5 (2024): 329–39, <https://doi.org/10.1038/s42254-024-00714-3>.

<sup>199</sup>Steven D. Bass et Michael Doser, « Quantum Sensing for Particle Physics », *Nature Reviews Physics* 6, no 5 (2024): 329–39, <https://doi.org/10.1038/s42254-024-00714-3>.

<sup>200</sup>Roussy, T. S. et al. An improved bound on the electron’s electric dipole moment. *Science* 381, 46 (2023).

<sup>201</sup>Alarcon, R. et al. Electric dipole moments and the search for new physics. Preprint at <https://arxiv.org/abs/2203.08103> (2022).

<sup>202</sup>Parker, R. H., Yu, C., Zhong, W., Estey, B. & Müller, H. Measurement of the fine-structure constant as a test of the Standard Model. *Science* 360, 191 (2018).

<sup>203</sup>Morel, L., Yao, Z., Cladé, P. & Guellati-Khélifa, S. Determination of the fine-structure constant with an accuracy of 81 parts per trillion. *Nature* 588, 61–65 (2020).

<sup>204</sup>Asenbaum, P., Overstreet, C., Kim, M., Curti, J. & Kasevich, M. A. Atom-interferometric test of the equivalence principle at the 10–12 level. *Phys. Rev. Lett.* 125, 191101 (2020).

<b>Quantum superposition of cold atoms in space</b>	Tests of Galilean invariance	STE-QUEST <sup>205</sup>
<b>Trapped antihydrogen</b>	Tests of Galilean invariance with antimatter	ALPHA-g <sup>206</sup> , AEGIS <sup>207</sup> , GBAR <sup>208</sup> <sup>209</sup>
<b>Cold, trappable highly charged ions (including antimatter-based techniques)</b>	Searches for physics beyond the Standard Model	
<b>Atomic and nuclear clocks</b>	Tests of Einstein's equivalence principle and searches for dark matter	<sup>210</sup> <sup>211</sup>
<b>Networked or space-based ionic, atomic, and nuclear clocks</b>	Tests of local Lorentz invariance and local position invariance	<sup>212</sup> <sup>213</sup> <sup>214</sup> <sup>215</sup> <sup>216</sup>
<b>Superconducting single-photon detectors</b>	Searches for axions (dark matter candidates)	Haloscope experiments, new photon detectors <sup>217</sup>
<b>Nuclear spin interferometers</b>	Searches for axions	CASPEr, <sup>218</sup>
<b>Network of optical clocks (Al, Sr, Yb ions and atoms)</b>	Searches for ultralight dark matter	BACON <sup>219</sup>

<sup>205</sup>Bassi, A. et al. STE-QUEST: Space Time Explorer and Quantum Equivalence Principle Space Test. Preprint at <https://arxiv.org/abs/2211.15412> (2022).

<sup>206</sup>Anderson, E. et al. Observation of the effect of gravity on the motion of antimatter. *Nature* 621, 716–722 (2023).

<sup>207</sup>Amsler, C. et al. Pulsed production of antihydrogen. *Commun. Phys.* 4, 19 (2021).

van der Werf, D. P. The GBAR experiment. *Int. J. Mod. Phys. Conf. Ser.* 30, 1460263 (2014).

<sup>208</sup>Kornakov, G. et al. Synthesis of cold and trappable fully stripped highly charged ions via antiproton-induced nuclear fragmentation in traps. *Phys. Rev. C* 107, 034314 (2023).

<sup>210</sup>Safronova, M. S. The search for variation of fundamental constants with clocks. *Ann. Phys.* 531, 1800364 (2019).

<sup>211</sup>Uzan, J.-P. Varying constants, gravitation and cosmology. *Living Rev. Rel.* 14, 2 (2011).

<sup>212</sup>Sanner, C. et al. Optical clock comparison for Lorentz symmetry testing. *Nature* 567, 204–208 (2019).

<sup>213</sup>Barontini, G. et al. Measuring the stability of fundamental constants with a network of clocks. *EPJ Quant. Technol.* 9, 12 (2022).

<sup>214</sup>Delva, P., Hees, A. & Wolf, P. Clocks in space for tests of fundamental physics. *Space Sci. Rev.* 212, 1385–1421 (2017).

<sup>215</sup>Schkolnik, V. et al. Optical atomic clock aboard an Earth-orbiting space station (OACESS): enhancing searches for physics beyond the standard model in space. *Quantum Sci. Technol.* 8, 014003 (2023).

<sup>216</sup>Beeks, K. et al. The thorium-229 low-energy isomer and the nuclear clock. *Nat. Rev. Phys.* 3, 238–248 (2021).

<sup>217</sup>C. Braggio et al., « Quantum-Enhanced Sensing of Axion Dark Matter with a Transmon-Based Single Microwave Photon Counter », *Physical Review X* 15, no 2 (2025): 021031, <https://doi.org/10.1103/PhysRevX.15.021031>.

<sup>218</sup>Graham, P. W. et al. Spin precession experiments for light axionic dark matter. *Phys. Rev. D* 97, 055006 (2018).

<sup>219</sup>Beloy, K. et al. Frequency ratio measurements with 18-digit accuracy using a network of optical clocks. *Nature* 591, 564 (2021).

<b>Atom interferometers</b>	Ultralight dark matter, low-frequency gravitational waves, tests of modified gravity	AION <sup>220</sup> , MAGIS <sup>221</sup> , MIGA <sup>222</sup>
<b>Solid-state spin defects</b>	Directional dark matter searches insensitive to solar neutrinos	223
<b>Macromolecule interferometry</b>	Searches for light dark matter	224
<b>Atom interferometers</b>	Searches for dark energy	225
<b>Quantum optomechanical systems</b>	Searches for dark energy	226
<b>Ultracold neutrons</b>	Searches for dark energy	227
<b>Quantum dots</b>	Enhanced performance of high-energy particle detectors	228
<b>2D materials</b>	Enhanced performance of high-energy particle detectors	229
<b>NV centers in diamond</b>	Enhanced performance of high-energy particle detectors	230

In Europe, the European Committee for Future Accelerators (ECFA) has developed a dedicated R&D roadmap to maximize the scientific impact of emerging quantum sensing platforms. Looking ahead, major directions include entanglement-enhanced sensing, already implemented in a limited number of experiments, and distributed quantum sensing, based on the remote entanglement of spatially separated quantum sensors.

<sup>220</sup>Badurina, L. et al. AION: an atom interferometer observatory and network. *J. Cosmol. Astropart. Phys.* 5, 011 (2020).

<sup>221</sup>Abel, M. et al. Matter-wave atomic gradiometer interferometric sensor (MAGIS-100). *Quantum Sci. Technol.* 6, 044003 (2021).

<sup>222</sup>Canuel, B. et al. Exploring gravity with the MIGA large scale atom interferometer. *Sci. Rep.* 8, 14064 (2018).

<sup>223</sup>Ebadi, R. et al. Directional detection of dark matter using solid-state quantum sensing. *AVS Quantum Sci.* 4, 044701 (2022).

<sup>224</sup>Kialka, F., Fein, Y. Y., Pedalino, S., Gerlich, S. & Arndt, M. A roadmap for universal high-mass matter-wave interferometry. *AVS Quantum Sci.* 4, 020502 (2022).

<sup>225</sup>Sabulsky, D. O. et al. Experiment to detect dark energy forces using atom interferometry. *Phys. Rev. Lett.* 123, 061102 (2019).

<sup>226</sup>Qvarfort, S., Rätzel, D. & Stopyra, S. Constraining modified gravity with quantum optomechanics. *New J. Phys.* 24, 033009 (2022).

<sup>227</sup>Sponar, S., Sedmik, R. I. P., Pitschmann, M., Abele, H. & Hasegawa, Y. Tests of fundamental quantum mechanics and dark interactions with low-energy neutrons. *Nat. Rev. Phys.* 3, 309–327 (2021).

<sup>228</sup>Decká, K. et al. Timing performance of lead halide perovskite nanoscintillators embedded in a polystyrene matrix. *J. Mater. Chem. C* 10, 12836 (2022).

<sup>229</sup>Orlandini, G. et al. Integration of CVD graphene in gaseous electron multipliers for high energy physics experiments. *JINST* 18, C06022 (2023).

<sup>230</sup>Doser, M. et al. Quantum systems for enhanced high energy particle physics detectors. *Front. Phys.* 10, 887738 (2022).

## 2.6.2. Astrophysics

One of the most prominent examples of the impact of quantum sensing on astrophysics is provided by the LIGO gravitational-wave detectors. Developed over more than six decades, these interferometers were designed to measure extraordinarily small displacements – on the order of thousands of times smaller than a nuclear diameter – induced by passing gravitational waves along interferometer arms several kilometers in length. Over the past decade, the implementation of squeezed states of light has led to substantial sensitivity improvements<sup>231</sup>, marking one of the first large-scale deployments of genuinely quantum-enhanced sensing in astrophysics. The extensive technological development driven by LIGO has significantly advanced the control and generation of non-classical states of light, benefits that continue to accrue today. These advances not only strengthen gravitational-wave astronomy but also open pathways for the application of quantum optical technologies to other areas of science and, potentially, to non-scientific domains.

Many theoretical predictions remain to be tested through gravitational-wave observations, including signatures of primordial black holes, phase transitions in the early Universe, and possible deviations from general relativity. These goals continue to drive advances in optical and quantum sensing technologies. On the ground, next-generation interferometers such as Cosmic Explorer and the Einstein Telescope aim to extend sensitivity well beyond current facilities (LIGO, Virgo, KAGRA). In space, missions including LISA, DECIGO, and TianQin will explore lower-frequency gravitational waves. In parallel, alternative quantum sensing approaches—most notably atom interferometry (e.g. AION, MAGIS, MIGA)—are being developed to access complementary frequency bands and probe new fundamental physics.

Superconducting photon detectors operating in the X-ray, infrared, and microwave regimes represent another major application of quantum sensing in astrophysics, currently enabling experiments to achieve single-photon sensitivity, ultra-low noise performance, and high energy resolution beyond the reach of classical detector technologies.

Looking ahead, quantum-assisted optical interferometry and quantum networking could play an important role in astronomical observations. Theoretical studies indicate that entanglement and quantum memories could enable long-baseline interferometry beyond classical limits by mitigating transmission losses, opening the prospect of super-resolution imaging at optical wavelengths<sup>232</sup>. More broadly, quantum sensor networks could provide a framework for coherently combining spatially separated quantum sensors, with potential applications in the detection of weak astrophysical or exotic signals with enhanced sensitivity<sup>233</sup>.

<sup>231</sup>W. Jia et al., “Squeezing the quantum noise of a gravitational-wave detector below the standard quantum limit”, *«All-Microwave Spectroscopy and Polarization of Individual Nuclear Spins in a Solid»*, <https://doi.org/10.1126/sciadv.adu0581>.

<sup>232</sup>E. T. Khabiboulline et al., Optical interferometry with quantum networks, *Phys. Rev. Lett.* 123, 070504 (2019).

<sup>233</sup>C. Dailey, C. Bradley & A. Derevianko, Quantum sensor networks as exotic field telescopes for multi-messenger astronomy, *Nature Astronomy* 5, 150–158 (2021).

### 2.6.3. Condensed matter

Quantum sensors play an important role in condensed matter research, where they enable the investigation of physical phenomena at the nanoscale with high sensitivity. Technologies such as single-electron transistors and muon spin spectroscopy have become established tools for probing electronic and magnetic properties in condensed matter systems. Condensed matter research has not only benefited from quantum sensing, but has also produced quantum sensors itself. Superconducting sensors or sensors based on tunnelling magnetoresistance are examples of important outputs from condensed matter research.

NV centers in diamond provide a representative example of a quantum sensor where research applications have sustained technology development. Widely used to probe the magnetic properties of condensed matter systems at the nanoscale, they offer a stable initial market that gives startups the time needed for technology maturation, organizational structuring, and sustained R&D, leading to high-performance sensors. Qnami illustrates this pathway: its early commercial success in research applications has allowed the company to continue developing its technology toward future markets such as semiconductor testing.

### 2.6.4. Quantum metrology

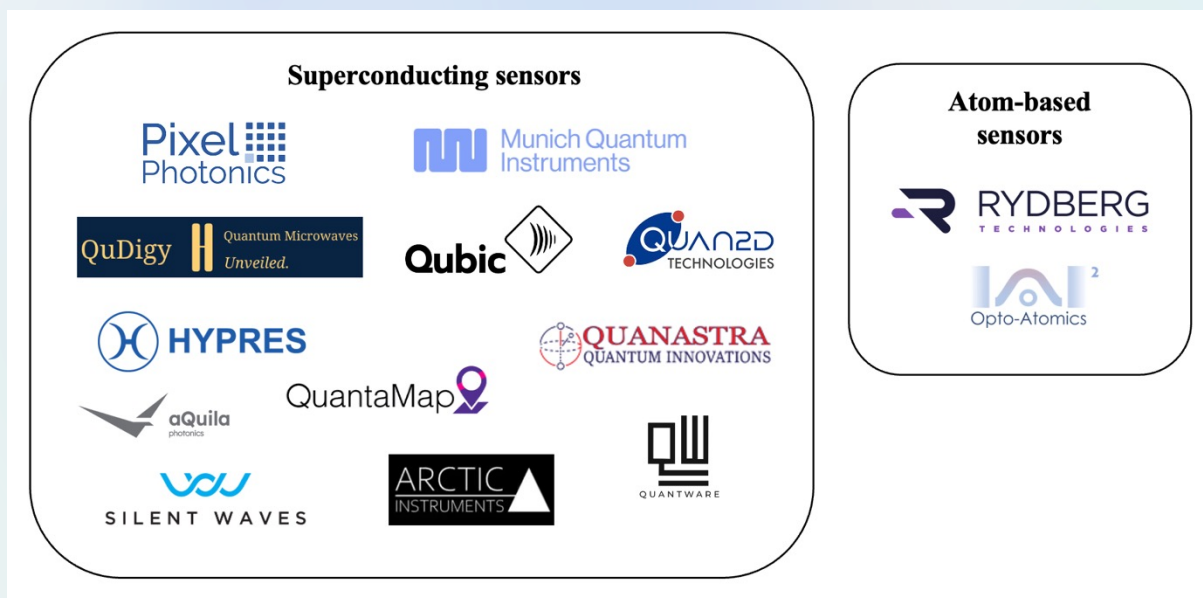
Quantum metrology is the academic field dedicated to measurements at the most fundamental scales. Theoretically, it defines the types of measurements allowed for a given physical system and establishes their fundamental sensitivity limits. Experimentally, it seeks to achieve the highest-precision measurements to test these predictions and extend the frontier of what is possible. This field is critical not only for understanding the ultimate capabilities of quantum sensors but also for guiding the development of increasingly sensitive measurement technologies.

For example, classical interferometers were long predicted to be limited in precision by quantum noise. To overcome this, quantum interferometry schemes using squeezed states of light were proposed<sup>234</sup>, and they have recently been implemented in gravitational-wave detectors, significantly enhancing their sensitivity.

<sup>234</sup>C. M. Caves, Quantum-mechanical noise in an interferometer, Phys. Rev. D 23, 1693–1708 (1981).

Like interferometry with squeezed light, quantum metrology predicts that entangled quantum states can enhance the fundamental sensitivity limits of measurements. For example, in a set of  $n$  independent Bernoulli trials, the resulting binomial distribution exhibits a signal-to-noise ratio scaling as the square root of  $n$ , which is known as the shot-noise limit. By correlating the  $n$  outcomes through entanglement, the signal-to-noise ratio can instead scale linearly with  $n$ , achieving the so-called Heisenberg limit. Quantum-correlated states – including squeezed states in optics and spin-squeezed states in atomic ensembles – are therefore explored to boost measurement precision. Spin squeezing, in particular, is currently applied in fundamental metrological experiments and could underpin the next generation of high-precision atomic clocks.

## 2.7. Quantum Technologies



The use of quantum sensors in quantum computing and communication highlights their strategic importance within the growing quantum technology industry. Many of the same core quantum platforms—superconducting devices, atoms, ions, spin defects in solids, and photonics—are employed across sensing, computing, and communication. Consequently, advances in the control and manipulation of these platforms are expected to benefit all three areas, supporting a unified approach to their development and commercialization. Some companies have integrated this versatility into their business models by developing quantum sensors alongside their primary platforms, creating higher-TRL products that generate early revenue.

This strategy is also highly relevant for investment approaches. Quantonation, for example, gathers multiple applications into a single portfolio, aligning the capabilities of quantum sensors with the needs of quantum computing platforms. As such, Pixel Photonics has developed record-performance single-photon detectors, supporting a wide range of quantum computing applications with companies including Pasqal, Quandela, and ORCA Computing.

### 2.7.1. Communication

Quantum sensing provides critical enabling technologies for quantum communication, notably through the development of ultra-sensitive single-photon detectors in both the optical and microwave domains, which are essential for low-loss quantum links, quantum key distribution, and quantum network architectures<sup>235</sup>.

Conversely, quantum networks used for quantum sensing require quantum communication tools such as entanglement distribution and storage in quantum memories. So advances in one domain directly accelerate the other, making quantum sensing and communication tightly coupled pillars of the same technological ecosystem.

### 2.7.2. Computing

Quantum computing benefits directly from advances in quantum sensing through more precise detection of qubit signals and improved characterization of qubit materials and noise sources. High-fidelity qubit readout relies on ultra-low-noise microwave amplification of the extremely weak signals generated by qubits, where quantum-limited amplifiers such as Josephson parametric amplifiers and traveling-wave parametric amplifiers (TWPA) have become central. These technologies have driven the emergence of a small number of highly specialized companies operating at the frontier between quantum sensing and quantum computing.

At the materials level, sensing techniques originally developed for metrology are used in quantum computing hardware to probe loss mechanisms, two-level systems, and magnetic or electric noise that limit coherence times, guiding fabrication improvements and device design<sup>236</sup>. More broadly, quantum sensors based on superconducting circuits, spins, or resonators increasingly act as diagnostic tools for quantum processors.

Conversely, quantum computers and quantum algorithms are expected to benefit quantum sensing. Techniques such as dynamical decoupling, quantum algorithmic cooling, quantum memories, quantum error correction, and quantum phase estimation find direct applications in enhancing sensitivity, coherence time, and readout efficiency in quantum sensors<sup>237</sup>.

<sup>235</sup>Robert H. Hadfield, « Single-Photon Detectors for Optical Quantum Information Applications », *Nature Photonics* 3, no 12 (2009): 696-705, <https://doi.org/10.1038/nphoton.2009.230>.

<sup>236</sup>Clemens Müller et al, Towards understanding two-level-systems in amorphous solids: insights from quantum circuits, *Rep. Prog. Phys.* 82 124501 (2019)

<sup>237</sup>C. L. Degen et al., « Quantum sensing », *Reviews of Modern Physics* 89, no 3 (2017): 035002, <https://doi.org/10.1103/RevModPhys.89.035002>.

---

Another compelling business model lies in sharing key components across different quantum technologies. High-performance sensing components developed for quantum sensors can be directly reused in other quantum applications. Bruno Desruelles, co-founder of Muquans (acquired by Exail), describes the strategy that enabled the company to generate revenue while sustaining R&D:

**“WE COMMERCIALIZED THE LASER TECHNOLOGIES ORIGINALLY DEVELOPED FOR OUR GRAVIMETER. THEY OFFERED EXCELLENT PERFORMANCE IN POWER AND FREQUENCY STABILITY, POLARIZATION QUALITY, LINEWIDTH, AND AGILITY, WHILE REMAINING COMPACT, ROBUST, FULLY FIBERED, AND EASY TO OPERATE—NO REALIGNMENT, AUTOMATED SOFTWARE CONTROL, AND TRANSPORTABLE. EARLY SALES ALLOWED US TO GENERATE REVENUE, AND WE REACHED FINANCIAL BREAK-EVEN VERY QUICKLY.”**

---

# CONCLUSION

## Takeaways

Our overview of the main quantum sensing technologies, their added value, and their many proposed applications – examined in light of actual implementations and market trends – leads to several key takeaways.

First, the experience with superconducting devices highlights a well-known but critical lesson for sensors: record performance alone is not sufficient. Even when proof-of-concept demonstrations exist, market adoption depends strongly on the overall value proposition, combining performance with SWaP-C constraints. This marks a key distinction from quantum computing, where a quantum advantage achieved in a centralized data center could already unlock major applications via remote access. In contrast, quantum sensors already demonstrate major advantages, but they must be deployed at scale, and operated directly in the field.

This leads to a second point: the transition from laboratory to field deployment often raises critical challenges for quantum sensors. The very sensitivity that underpins their performance can also make them more vulnerable to environmental disturbances, such as complex biological media, additional noise sources in healthcare settings, or motion and vibration in vehicles. Past startup experience suggests that achieving reliability typically requires an additional phase of engineering refinement, for which early partnerships enabling in-situ testing can be a significant asset. Assessing the future viability of a research result therefore requires careful investigation, as laboratory and commercial sensors can differ substantially. Laboratory systems are usually shielded from disturbances, larger in size, and built with high-quality or custom components. By contrast, market-ready sensors must accommodate miniaturization and cost constraints, often accepting some performance degradation as designs shift toward standardized components and industrial manufacturing processes.

These considerations add an additional layer of complexity to the task of matching the highly diverse specifications of technologies and requirements of markets. Throughout this report, we have examined applications where a broad dynamic range or DC sensitivity is critical; where combining two different clocks provides a performance advantage; where absolute measurements are more valuable than higher but relative sensitivity; where sensitivity is required either at the nanoscale or at the microscale. Quantum sensing is therefore a domain in which many technologies can be valuable for very different reasons, making case-by-case analysis essential to match the right specifications to the right applications. Jérôme Michon, CEO of InSpek, underscores this point: “Everyone needs sensors, but the devil is in the details, because no two applications require the same precision or parameters, and there is a huge range of solutions on the table. Identifying the application for which your sensor is truly the right fit requires a great deal of intellectual honesty and the ability to spot the opportunity where the match is strongest.” Examining technologies and market value on a case-by-case basis thus contributes to the broader effort to identify where quantum sensing technologies can generate real impact.

Beyond having the right product and application, broad market deployment of quantum sensors emerges from this retrospective as a major challenge, a point repeatedly highlighted in conversations with several CEOs. Sadeqh Raeisi, CEO of Focus, emphasizes this issue: “The main challenge is that our customers come from a different field. In many quantum sensing applications, you are typically dealing with electrical engineers or people with an engineering background. Engineers may not grasp all the details, but they understand the concepts at a high level. In healthcare, we do not share this common language, and practitioners do not necessarily know much about quantum.”

In healthcare, market access is first constrained by regulatory approval, but even beyond this hurdle, adoption can be slow. Ultralow-field MRI is a case in point: practitioners must adapt their diagnostic workflows to more frequent, more accessible scans that may come with lower image resolution. Semiconductor testing provides another example, where integration into an existing production line is a challenge, that can be circumvented by aligning one’s timeline with chip industry renewal. Prof. Walsworth, co-founder of EuQlid, echoes this broader adoption challenge: “When will industrial players decide to switch to your technology? There are subtleties – almost cultural in each industry – that determine when they choose to adopt a new technology. Quantum sensing has many modalities and addresses many sectors of the economy; it feels nearer term, so why have there not been more successes yet? Quantum sensing is doing the hard work that quantum computing will have to do in a few years if it grows and succeeds, or that AI also has to do: these technologies can work better for some tasks, but moving from a ‘playing-around’ tool to broad economic deployment requires an additional adoption effort.”

Another key takeaway from this report is that fundamental research in sensing remains highly active and deserves close attention across many domains. Quantum systems often display intrinsic sensitivity to a wide range of fields, meaning that new sensors frequently emerge as byproducts of advances in quantum control and manipulation. The field is further driven by research in quantum metrology, which seeks to push sensitivity to fundamental limits by exploring quantum-enhanced effects. In addition, sensing requirements originating from other areas of physics – such as astrophysics, particle physics, condensed matter, and more recently quantum computing – have consistently driven the development of record-sensitivity instruments. As a result, many new quantum sensors are expected to emerge in the future, stemming from fundamental research – especially from material science, qubit development and progress in quantum states manipulation.

Data emerged as another recurring theme across the applications explored in this report. MEG, in particular, illustrates the critical role of data collection in unlocking new use cases, as well as the importance of robust software to detect extremely weak signals amid significant noise and to analyze them in real time. More broadly, magnetic sensing often involves solving complex inverse problems, suggesting that shared expertise in quantum sensor data analysis could emerge as a transversal economic opportunity.

At the same time, data collection itself is often highly application-specific and can be a prerequisite for product deployment – for instance in brain-computer interfaces, widely deployed biosensors, chip defect detection, or magnetic and gravitational navigation. The business models associated with data generation and ownership must therefore be carefully considered. This raises important questions about the scope of a quantum sensing startup’s value proposition: sensing hardware can be sold as a standalone product, or embedded within a more complete solution, which typically requires additional development beyond the initial research device.

Jérôme Michon offers insight from having considered both approaches: “As in the gold rush, you can make pickaxes, but going to mine the gold yourself is more valuable. It can also be a very good business not to risk dying in a mine and to be satisfied with pickaxes. It’s a real question of strategy that needs to be studied case by case. With our elements, we thought it was worth going. Unlike a pickaxe, many people do not really realize what they can do with our sensors. If you sell a sensor and say, ‘if you use it well you can earn 20%,’ people do not necessarily know how to use it well. Whereas if you sell a 20% optimization, they buy it right away, without needing to know how you do it.”

---

## Priorities

From our analysis, at least two themes emerge as particularly important in quantum sensing.

The first is chip-scale atomic vapor cells. Developed since the early 2000s, this technology has matured significantly, with clearer performance roadmaps and the demonstration of several compelling use cases.

A major strength of chip-scale atomic devices is the breadth of applications in which they offer a differentiated advantage. This allows startups to focus on a specific initial vertical while continuing to invest R&D into the core vapor-cell platform, with the prospect of addressing broader markets over time.

A highly differentiative application is MEG, where OPMs have the potential to outperform legacy SQUID-based systems, compete with other brain imaging modalities, and enable new use cases. Key R&D challenges remain, including ambient magnetic field mitigation, scalable data acquisition and analysis, reliable large-scale production of OPMs, and further device engineering prior to regulatory approval. Market sizing also requires refinement, particularly with respect to practitioner adoption and hospital integration.

PNT is another area where vapor-cell technologies demonstrate strong potential. In particular for gyroscopes: for a given size, vapor-cell gyroscopes can offer an order-of-magnitude performance improvement over MEMS devices, or alternatively achieve similar performance at substantially reduced size compared to high-end Sagnac-based gyroscopes. Initial markets are likely to be driven by defense and space navigation needs, with potential spillover into robotics and autonomous vehicles. Competition with MEMS technologies, however, must be evaluated carefully on a case-by-case basis.

Vapor-cell atomic clocks offer attractive trade-offs between performance and SWaP, and may find applications in niche areas where size and power constraints are critical. In space systems, larger and more power-hungry clocks may continue to dominate, while terrestrial deployment may be limited to specific military or infrastructure use cases. Further miniaturization of optical and cold-atom clocks may also offer a promising pathway to combining high sensitivity with reduced SWaP.

Magnetic navigation using optically pumped magnetometers (OPMs) currently appears less mature. When operating in the Earth's magnetic field, OPMs do not reach their optimal sensitivity and face competition with other established technologies. In practice, the main limitations of magnetic navigation today are likely not the sensors themselves, but rather the availability and quality of magnetic cartography data, as well as the intrinsic reliability of magnetic navigation methods. A plausible near-term pathway therefore lies in the commercialization of magnetic cartography, for instance through drone-based surveys, where compact magnetometers could provide added value. In this context, OPMs can offer size advantages over fluxgates, and future chip-scale solid-state sensors, such as diamond-based devices, could also become relevant.

---

Finally, chip-scale atomic devices merit consideration for more forward-looking applications that may be unlocked by further research and engineering advances. Brain-computer interfaces are one such example, where out-of-hospital MEG-based systems could address large markets if ambient magnetic field challenges can be overcome.

A second topic of interest is spin-based sensing: while offering attractive opportunities in semiconductors and security, it is also emerging as a promising approach for addressing the high-value biosensing market. Research activity in this area has been particularly strong over the past two decades. Two main paths deserve attention in spin-based sensing technologies: improvements in diamond-based platforms and the development of emerging alternative technologies.

Diamond is a well-characterized material for which several sensitivity-improvement strategies are actively explored, following approaches similar to those pursued in quantum computing research. As with qubits, extending coherence times and improving readout fidelity are key objectives. A major challenge is to translate these laboratory-level performances into field-deployable devices, with improved reliability and reduced SWaP-C, without sacrificing too much sensitivity. In biological contexts, diamond sensing already offers sub-micron spatial resolution and intrinsically multimodal sensing abilities.

Emerging spin platforms represent another important area to monitor. They may complement diamond by offering advantages such as improved integrability or better sensitivity to single molecules, for instance using two-dimensional materials and other single spin manipulation platforms. Given the strong research interest in this field, significant advances could enable new regimes of biosample characterization.

As developments continue in this emerging field, pushing beyond classically attainable regimes, a clear understanding of the sensing market will be essential to align these capabilities with application requirements and opportunities.

# Thank you

We would like to warmly thank the following researchers and tech leaders for their time and expertise.

**Dr. David Roy-Guay** – CEO of **SBQuantum**, a company developing diamond-based magnetometers for security and defense applications.

**Prof. Vincent Jacques** – Researcher at **CNRS** (Laboratory Charles Coulomb, Montpellier), where he leads experimental research on spin defects in diamond.

**Dr. Mathieu Munsch** – CEO of **Qnami**, a company developing diamond-based scanning probe instruments for nanoscale magnetic imaging.

**Prof. Simone De Liberato** – CTO of **Sensorium**, bringing expertise in photonics systems for semiconductor defect inspection.

**Dr. Jérôme Michon** – CEO of **InSpek**, a company specializing in industrial optical spectroscopy solutions for process analysis.

**Dr. Sadegh Raeisi** – CEO of **Foqus**, a company working at the interface of advanced physics and engineering to translate laboratory technologies into deployable systems.

**Dr. Bruno Desruelle** – CEO Photonics at **Exail**, overseeing the development of cold atom systems for navigation and geology applications.

**Prof. Ronald Walsworth** – Professor at the **University of Maryland** and Co-founder of **EuQlid** and of **QCat**, where he supports the transfer of academic research into scalable commercial products.

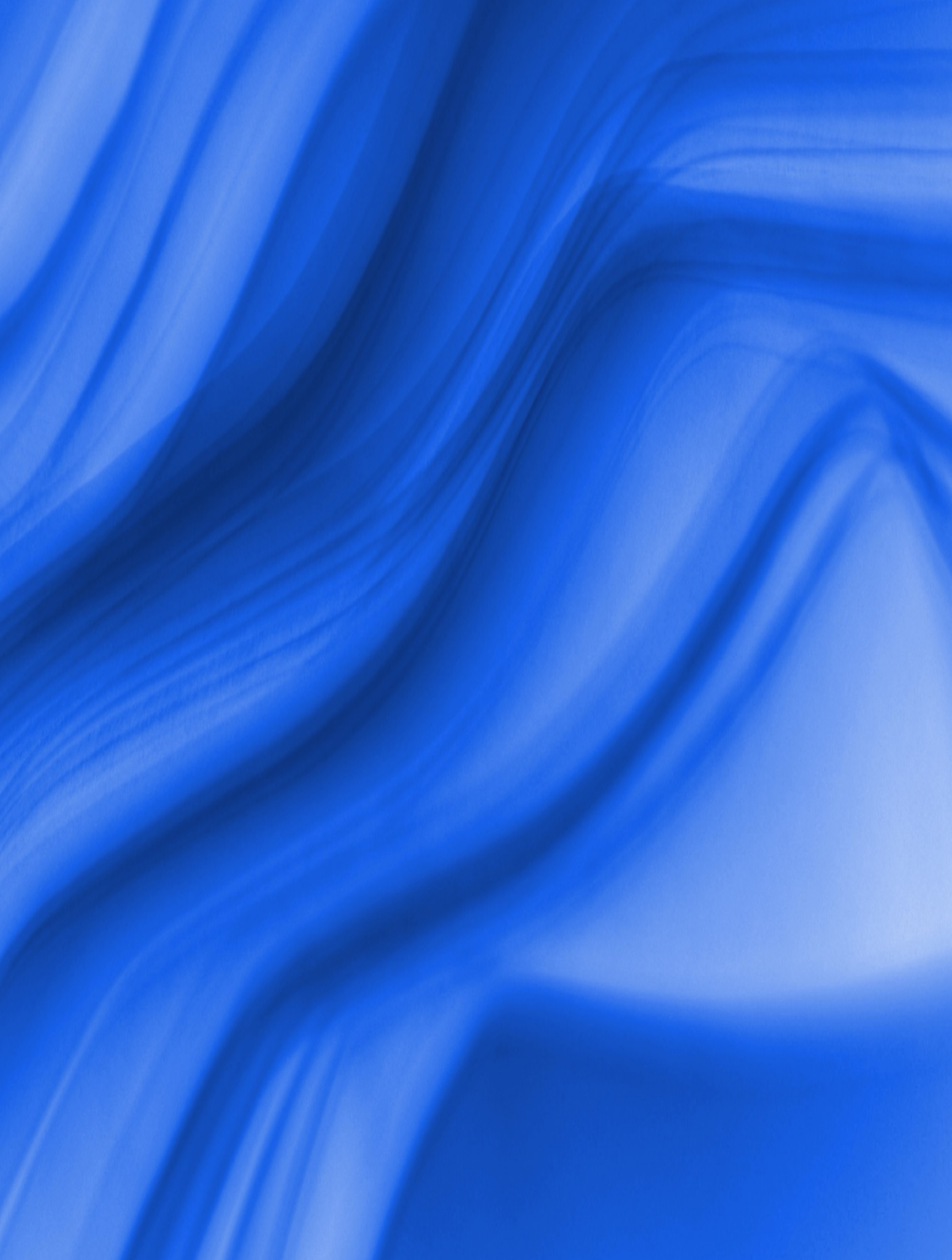
**Prof. Giovanni Lucivero** – CEO of **QSENSATO**, a company focused on atomic vapor cells for precision sensing instruments.

**Prof. Chong Zu** – Researcher at **Washington University in St. Louis**, conducting experimental work on spin defects and solid-state quantum systems.

**Dr. Giovanni Scuri** – Researcher at **Stanford University**, studying spin defects and quantum materials with applications in sensing and information science.

**Dr. Dimitri Labat** – CSO of **Chipiron**, where he leads scientific strategy for the development of compact MRI systems based on novel hardware architectures.

We are grateful for their insights and support, which help bridge academic research and industrial innovation.



**QUANTONATION —  
INVESTING IN THE  
PHYSICS  
FRONTIER  
SHAPING THE 21ST  
CENTURY**

QUANTONATION VENTURES  
SOCIÉTÉ PAR ACTIONS SIMPLIFIÉES – 135 704€ SHARE CAPITAL  
REGISTERED UNDER NUMBER 849 813 522 RCS PARIS  
58, RUE D'HAUTEVILLE -75010 PARIS  
APPROVED BY THE AMF UNDER NUMBER GP-202211

**QUANTONATION**