QUANTUM SENSING

Technologies at a Glance

July 2026

“TECHNOLOGIES AT A GLANCE” REPORT

ANALYSING KEY TRENDS FOR INFORMED DECISION-MAKING

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Agenda

01 Quantum Sensing

In a nutshell

What is quantum sensing?

Quantum sensing is the practice of exploiting **quantum-mechanical phenomena** (superposition, entanglement and quantum coherence) to measure **physical quantities** (time, magnetic and electric fields, gravity, acceleration, rotation and temperature) with a **precision that fundamentally surpasses classical instruments**.

Unlike quantum computing, which seeks computational advantage, or quantum communication, which secures the transmission of information, **quantum sensing converts** the **fragility** of quantum states into a **measurement asset**: the same sensitivity to environmental disturbance that makes qubits hard to control in a quantum computer is precisely what allows a quantum sensor to detect vanishingly small changes in its surroundings.

Why now?

Quantum sensing is, in several respects, the **most commercially mature branch of the second quantum revolution**. Atomic clocks, the original quantum sensors, have underpinned GPS and global telecommunications for decades, and the field has progressed rapidly as photonic engineering, laser cooling and nanofabrication have matured.

Three forces are accelerating adoption today. First, the proliferation of **GNSS** (Global Navigation Satellite System) **jamming** (blocking the signal) and **spoofing** (sending fake location data) in conflict zones and contested maritime corridors is exposing the fragility of satellite-dependent positioning, navigation and timing (PNT), creating urgent demand for resilient, quantum-grade backups. Second, breakthroughs in **solid-state and biological qubit platforms** (diamond colour centres, fluorescent proteins) are extending quantum sensing from defence and metrology laboratories into life sciences and healthcare. Third, defence and government procurement programmes are now funding **field trials** rather than laboratory demonstrations, marking a genuine transition from research to operations.

For what?

Quantum sensing represents a strategic imperative for:

- resilient navigation in GNSS-denied and GNSS-degraded environments,
- next-generation medical imaging and early disease diagnostics,
- the detection of underground resources and structural defects,
- the sub-shot-noise measurement of fields and forces that underlies frontier physics, dark matter searches and gravitational-wave astronomy.

02 Quantum Sensing

Introduction

This report sits alongside Luxinnovation's "Quantum Communication - Technology at a Glance" and "Quantum Computing - Technology at a Glance" studies, as the third pillar of the Knowledge Hub's quantum series. Together, the three reports map the full value chain of the second quantum revolution: quantum computing for computation, quantum communication for the secure transmission of information, and quantum sensing for the precise measurement of the physical world.

Quantum sensing exploits the same counter-intuitive properties of quantum mechanics that underpin quantum computing and quantum communication but turns them towards a different end: **extracting information about the external world with a precision unattainable by classical instruments**. Where a classical sensor measures an analogue signal subject to thermal and electronic noise, a quantum sensor uses a well-controlled quantum system as the measurement probe itself, so that the laws of quantum mechanics set the ultimate limit on achievable precision.

Key takeaways

- **Quantum sensing** is the most commercially mature pillar of the quantum technology stack: atomic clocks and inertial sensors are already deployed at scale, while magnetometry, gravimetry and biological quantum sensing are moving rapidly from trial to early adoption.
- **2025** marked an **inflection point** for field-proven performance: Q-CTRL's Ironstone Opal demonstrated up to 50 to 111 times better positioning accuracy than inertial navigation systems in real flight and maritime trials, and the UK's Dstl validated jamming-immune cold-atom timing (AQlock) aboard Royal Navy vessels.
- **Scientific breakthroughs** in **2025/2026** are widening the application space**:** USC's coherence-stabilised sensing protocol nearly doubled measurement sensitivity over standard Ramsey interferometry, and the University of Chicago's biological qubit opened the door to quantum sensing inside living cells.
- **Market risk** remains **concentrated** in miniaturisation, cost, and the talent pipeline; however, the convergence of defence urgency (GNSS denial) and life-science opportunity (biological qubits) gives quantum sensing a broader and more diversified commercialisation pathway than quantum computing or quantum communication at the same stage of maturity.

Next, this report maps the maturity of the ten core modalities of quantum sensing and provides deep dives on the two most strategically relevant technologies: **Atomic clocks** and **NV-diamond / spin-defect magnetometry**.

03 10 key technologies

Quantum sensing - Tech radar

ADOPT

1 Atomic clocks: Ultra-precise timekeeping based on atomic transition frequencies; the most mature and widely deployed quantum sensing technology, underpinning GNSS, telecoms and financial infrastructure.

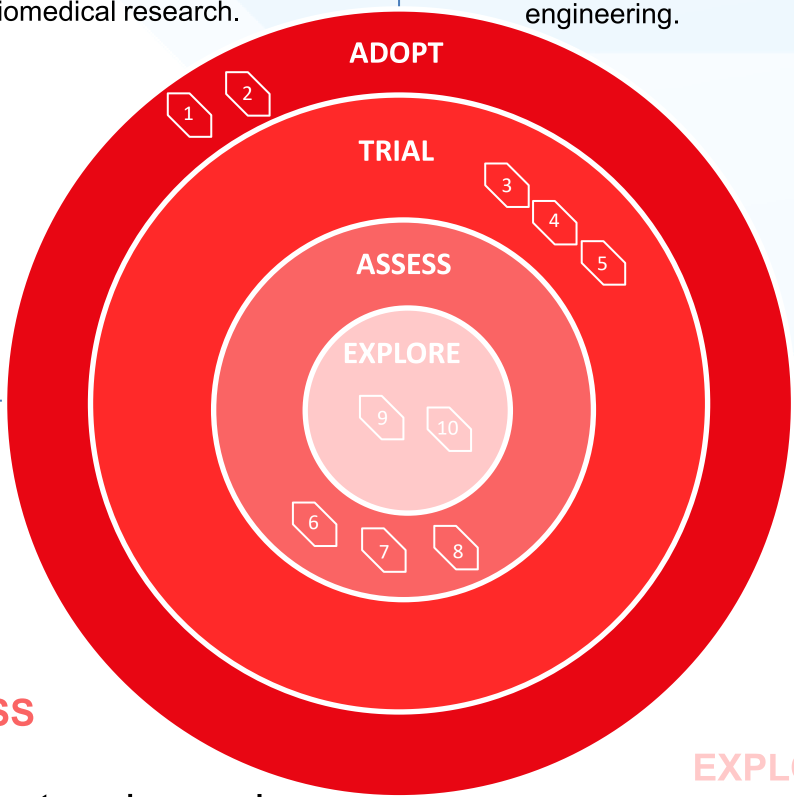
2 NV-diamond / spin-defect magnetometry: Nitrogen-vacancy and related colour centres in diamond enable room-temperature, high-resolution magnetic field sensing, already commercialised for materials characterisation and biomedical research.

TRIAL

3 Cold-atom interferometry: Laser-cooled atomic ensembles used as inertial sensors for GNSS-denied navigation and gravity mapping.

4 Quantum magnetometers: Chip-scale, cryogen-free magnetic field sensors increasingly used in biomagnetic imaging as an alternative to SQUID-based systems.

5 Quantum gravimeters / gravity gradiometers: Atom-interferometric instruments capable of detecting subsurface density variations for resource exploration, infrastructure inspection and civil engineering.



Non-exhaustive list of quantum sensing technologies

The primary target market for quantum sensing applications today spans defence and aerospace primes, national metrology institutes, the oil, gas and mining sectors, and an emerging cohort of medical technology and life-sciences companies exploring biological quantum sensing.

ASSESS

6 NV / spin-defect thermometry and nanoscale NMR: Solid-state spin defects used to measure temperature and local nuclear magnetic resonance signals at the nanoscale, with emerging applications in cellular biology.

7 Quantum-enhanced LIDAR and imaging: Sensing protocols using squeezed or entangled light to improve ranging precision and image contrast beyond the classical shot-noise limit.

8 Biological / protein-based qubits: Genetically encodable spin qubits hosted in fluorescent proteins, enabling quantum sensing natively inside living cells, demonstrated for the first time in 2025/2026.

EXPLORE

9 Quantum radar and RF sensing: Entanglement- or squeezing-enhanced radar concepts seeking improved target detection in low signal-to-noise environments; largely confined to laboratory and early prototype stages.

10 Quantum sensor networks: Networks of spatially separated, entangled quantum sensors aimed at correlated, sub-shot-noise measurement across distributed locations; a long-term convergence point with quantum communication.

04 Key technologies

Deep dive: Atomic clocks

What are atomic clocks?

Atomic clocks are the most established quantum sensing technology available today. Rather than relying on a mechanical or electronic component to keep time (which can drift as it ages or reacts to changes in temperature) atomic clocks measure something far more stable: the natural oscillations of electrons inside atoms. Because these oscillations happen at an extraordinarily high and perfectly consistent frequency, they give atomic clocks a level of precision that no conventional clock can match.

This precision has of course real-world impactful consequences. Atomic clocks form the timing backbone of GPS and satellite navigation systems, telecommunications networks, and global financial infrastructure, where even a tiny timing error can cause transactions to fail or signals to fall out of sync. In short, much of the digital world we rely on every day runs on time kept by atomic clocks.

How does it work?

By continuously tuning a laser or microwave source to the exact frequency of an atomic transition, and correcting for any drift via feedback, an extremely stable time standard is achieved; optical clocks, which utilise visible light frequencies far higher than those of caesium, achieve even greater accuracy, paving the way for a new definition of the second.

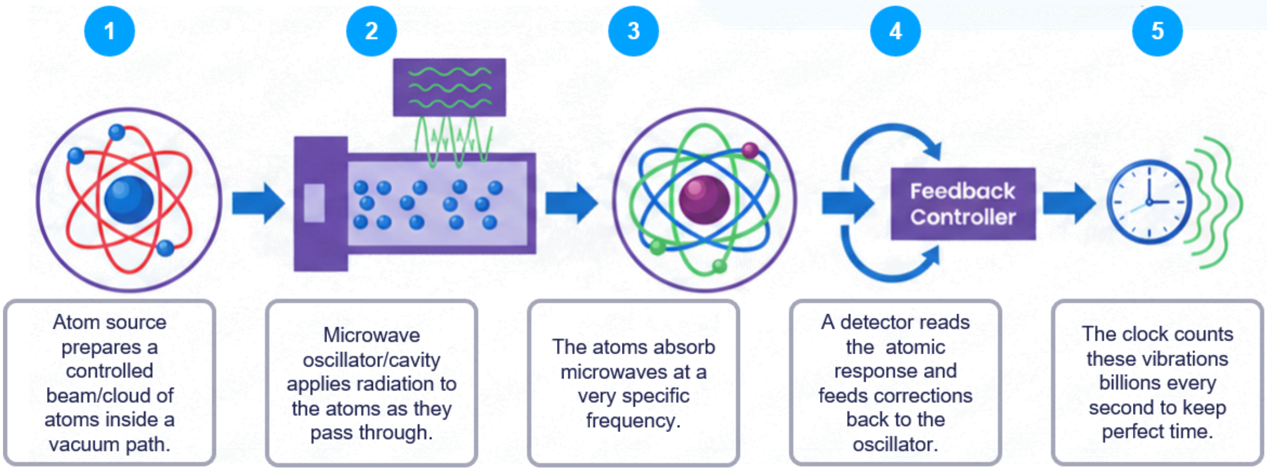


Fig. 1: What is an atomic clock? (source)

Strategic importance

Today, almost all navigation and timing systems used in business and military operations rely on GPS (or similar satellite networks). However, since GPS signals travel from satellites, they are inherently weak by the time they reach Earth's surface. This makes them easy to block either naturally by buildings and bad weather, or deliberately through "jamming" and "spoofing".

A local atomic clock acts as a powerful shield against these threats. Because it is kept directly on-site (such as on a ship, an aircraft, or inside a data centre), it does not need to receive external satellite signals to work. If the GPS signal is blocked or faked, this local clock can accurately "hold" the correct time for long periods. This allows systems to keep tracking their position and stay perfectly synchronised, even when GPS is completely unavailable.

04 Key technologies

Deep dive: Atomic clocks

What are the concrete applications?

Atomic clocks are already moving beyond metrology laboratories into defence, maritime and critical-infrastructure deployments:

Defence and resilient navigation: Q-CTRL's Ironstone Opal system combined cold-atom timing with AI-driven stabilisation to provide GPS-free positioning up to 111 times more accurate than inertial navigation alone during 2025 flight tests and Royal Australian Navy sea trials, which led DARPA to award the company a contract to adapt the system for US defence platforms.

Military and naval timing: In 2025, the British company Aquark Technologies successfully tested its new portable atomic clock, the AQlock, on a Royal Navy ship. Over a three-day trial in open waters, the clock ran continuously and kept perfect time without relying on GPS. The device proved it could withstand the constant shaking, tilting, and vibrations of a moving military ship, showing that this highly sensitive technology is finally ready to leave the laboratory and work in harsh, real-world environments.

Critical infrastructure timing: Beyond defence, atomic-clock-grade holdover increasingly underpins telecommunications network synchronisation and high-frequency financial transaction timestamping, where even microsecond-level drift can trigger settlement and regulatory-compliance failures.

Luxembourg's key player

Atomic clocks are already operational in Luxembourg, not confined to trials: national telecommunications operator **POST Luxembourg** (Deep) has run ADVA's coreSync OSA 3350 ePRC+, an optical caesium atomic clock, inside its core network since 2022, defending against GNSS jamming and spoofing. It shows the Grand Duchy's most mature quantum sensing technology reaching commercial deployment through vendors and operators acting independently of the public research pipeline, a useful contrast with the earlier-stage, research-led NV-diamond trajectory discussed next.

European projects

AQuRA **(Advanced Quantum Clock for Real-world Applications)**: Horizon Europe project (2022–2026, €8.9 million, University of Amsterdam-coordinated, nine partners across six countries) building the first industry-ready, transportable optical atomic clock, targeting 20x better accuracy and 3x smaller volume at Technology Readiness Level 7, for GPS-free navigation, network synchronisation and geodesy.

04 Key technologies

Deep dive: NV-diamond and spin-defect magnetometry

Diamond-Based Quantum Sensors (NV Centres)

A nitrogen-vacancy (NV) centre is a tiny, atomic-scale defect inside a diamond's crystal structure. It is created when a single nitrogen atom replaces a carbon atom next to an empty space (a "vacancy") in the diamond.

Even though it is a defect, this tiny structure behaves like an incredibly stable, microscopic sensor. Its internal quantum state is highly sensitive to the world around it. When there are changes in nearby magnetic fields, electric fields, temperature, or physical pressure, the defect's quantum properties shift in a way that can be precisely measured.

Unlike other quantum technologies that require extreme, sub-zero cooling to work, these diamond sensors operate perfectly at room temperature. Because they are made of diamond, they are also chemically safe, non-toxic, and incredibly small.

How does it work? Formation of the NV Center

We all know that crystals can contain tiny imperfections called **defects**. These defects appear when an atom is missing, an extra atom gets stuck inside the crystal, or one atom is replaced by a different type of atom. An **NV centre** is one of these defects in diamond. It forms when a carbon atom is replaced by a nitrogen atom, and the space next to it is left empty. The nitrogen atom is called **N**, and the empty space is called a **vacancy**, or **V**. Together, they form a **nitrogen-vacancy centre**.

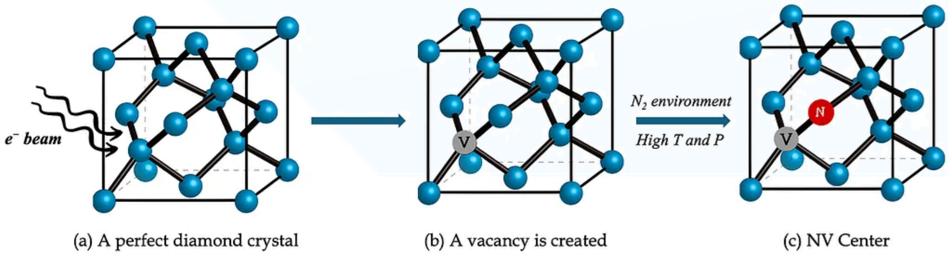


Fig. 2: Formation of the NV Center (source)

The Physical Properties of the NV Center

Apart from being a point defect, the NV centre is also an optically active colour centre. As *Fig. 3* shows, when green laser light is shone on our diamond containing NV centres, photoluminescence is emitted in the red region of the visible spectrum. Remarkably, the brightness of this red fluorescence depends on the 'spin state' of the NV centre. This spin-dependent photoluminescence is one of the NV centre's defining features and plays a key role in making it a **magnetometer**.

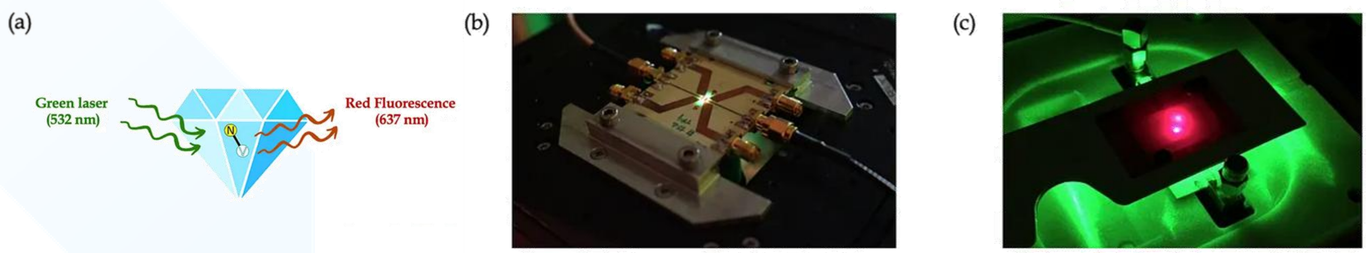


Fig. 3: (a) Schematic of the red fluorescence generated when the NV center is irradiated with green light (b) Image of a real diamond showing fluorescence emission (Picture Courtesy: IMO-IMEC) (c) Explicitly visible red fluorescence emission out of the NV center (Courtesy: Dr. Adam Wojciechowski) – (Source)

04 Key technologies

Deep dive: NV-diamond and spin-defect magnetometry

What are the concrete applications?

Diamond-based quantum sensors are moving beyond traditional industrial, and military uses into new areas, including:

Medicine and Life Sciences: Researchers at the University of Chicago have recently created the first "biological" quantum sensor. They managed to turn a glowing yellow protein (similar to the proteins that make jellyfish glow) into a microscopic sensor that can operate inside living cells. This opens the door to incredibly detailed, nanoscale MRI scans that could detect diseases at the level of individual molecules.

Manufacturing and Electronics: Diamond-based sensors are already used commercially to test microchips and electronic components. Because they work at room temperature and can inspect objects and environments at a microscopic scale, they can find tiny defects that traditional testing tools structurally miss.

Space and Defence: The same sensors are also being prepared for extreme environments. They have already been tested on the International Space Station, and a new satellite mission is scheduled to launch them into orbit in 2026. The goal is to use the Earth's magnetic fields to create a highly accurate navigation system that works completely independently of GPS.

Strategic European Projects

- ASTERIQS (2018–2022, Thales-coordinated, 23 partners across eight countries): established core diamond growth, implantation and readout techniques, raising NV-diamond sensing to Technology Readiness Level 4–5.
- AMADEUS (2022– March 2026, Thales-coordinated, €7.1 million, now closed): pushed four applications to Technology Readiness Level 6–7, including 5G/6G radio-frequency cartography, semiconductor defect analysis, and medical and space-grade magnetic monitoring.
- MUQUABIS (2022–2027, €6.7 million, still active): developing a diamond-based quantum magneto-microscope for cardiac tissue imaging, directly relevant to the biological extension of NV-diamond sensing described above.

05 Conclusion

Projections, opportunities and risks

Quantum sensing is advancing along a more diversified and, in several respects, more commercially de-risked path than quantum computing or quantum communication, because many of its core platforms (atomic clocks, NV-diamond magnetometers, cold-atom inertial sensors) are already deployed or close to deployment rather than confined to laboratory demonstrations.

The events of 2025 and early 2026 illustrate this momentum concretely: Q-CTRL's field-validated quantum navigation system progressed from airborne trials to sustained maritime operation and a DARPA-funded defence programme within a single year; the UK's Dstl validated jamming-immune cold-atom timing at sea aboard Royal Navy vessels; USC demonstrated a near-universal technique to counteract the decoherence that has long limited quantum sensor sensitivity; and the University of Chicago opened an entirely new application domain by creating the first functional biological qubit, extending quantum sensing into living cells for the first time.

The global quantum sensing market is forecast to grow substantially over the remainder of this decade, with defence, aerospace and critical infrastructure positioning, navigation and timing applications expected to be the earliest and largest commercial drivers, followed by biomedical imaging and diagnostics as biological quantum sensing matures, and longer-term opportunities in resource exploration, structural health monitoring and fundamental physics instrumentation.

Significant risks and uncertainties remain. Miniaturisation, ruggedisation and cost reduction are still required before many quantum sensing modalities can move from defence and scientific procurement into mass-market commercial and consumer applications. The talent pipeline for atomic, solid-state and quantum biology expertise remains narrow relative to demand, and geopolitical competition over dual-use sensing technologies (particularly those with direct defence and positioning applications) raises the prospect of export controls that could slow international collaboration and technology transfer.

As for Luxembourg, the country has the opportunity to position itself as a credible, emerging contributor to the European quantum sensing landscape, complementing its existing strengths in quantum computing and quantum communication. This objective forms Phase 1 of the country's Quantum Strategy 2030 roadmap. To achieve this, the Grand Duchy can build on the foundations already laid by LIST's quantum materials and photonics capability, as well as SnT's ISAC research. The 2026 Joint Call Data–AI–Quantum offers an opportunity to channel research-led projects towards near-term commercialisation.

For Luxembourg-based companies and research organisations, the immediate priority is to identify where the most mature quantum sensing modalities intersect with existing national strengths. Specifically, they should look at how atomic timing, magnetometry, and inertial navigation can support established sectors such as finance, satellite communications, logistics, and space technologies. Once these opportunities are identified, organisations should engage early with available national funding instruments. This proactive engagement will support the critical transition of these technologies from academic research to commercial pilots.

Explore our Market Applications report on our Knowledge Hub to discover concrete market applications and use cases where early commercial traction in quantum sensing is already emerging, and where future growth may be most impactful.

06 Sources

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