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Quantum Sensing

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Quantum Sensor

- Quantum sensor works using quantum mechanical phenomena, such as quantum superposition, quantum entanglement, and quantum squeezing, to measure physical quantities.
- If a quantum system is measurable, and it interacts with its environment in a known way, then measurements can provide information about its environment.
- Quantum sensor precision is limited only by the uncertainty principle.
- Quantum sensing deals with the design and engineering of quantum mechanical systems and measurements with potential for better performance than any classical strategy in several technological applications connected mostly with photonic and solid-state systems.

Quantum Sensor vs Classical Sensor I

Classical sensor

material response → calibrated output

Quantum sensor

Prepare a quantum state

Let the signal shift its phase, frequency, spin or population

Read out the state statistically

Infer the physical quantity and uncertainty

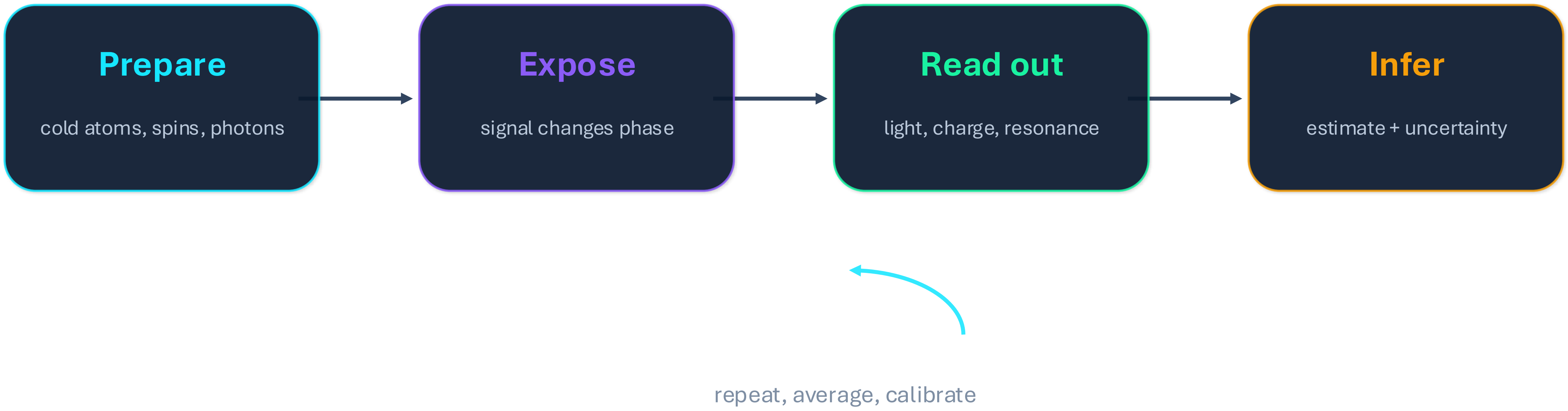
Quantum Sensor vs Classical Sensor II

Signal examples encoded in phase

Magnetic field
Gravity
Rotation

The practical challenge

Keep the quantum state coherent long enough to accumulate signal, while rejecting vibration, temperature drift, magnetic noise, laser noise and readout errors.



Quantum Sensors Landscape

Selection criteria

1. What is the signal?
2. Can the quantum state survive the environment?
3. Does the added complexity is better than the classical baseline?

Enabling technologies

- Lasers / photonics
- microfabrication
- cryogenics or thermal control
- shielding
- control electronics
- signal processing

Atoms & ions

time, gravity, acceleration

Atomic vapor

magnetic fields, RF

NV diamond

magnetic imaging, temperature

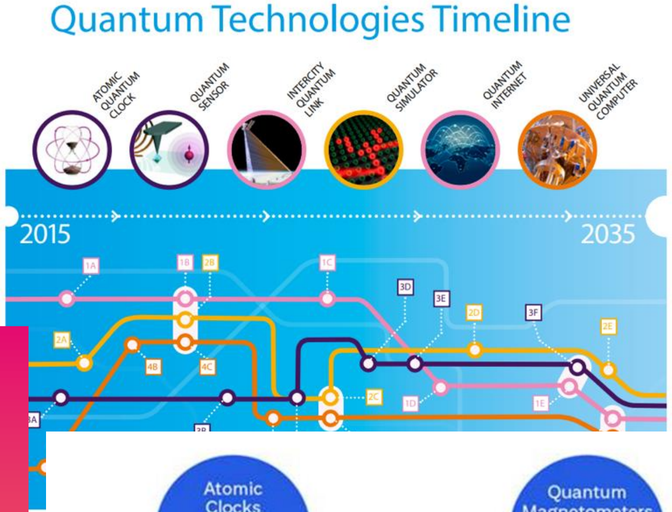
Superconducting

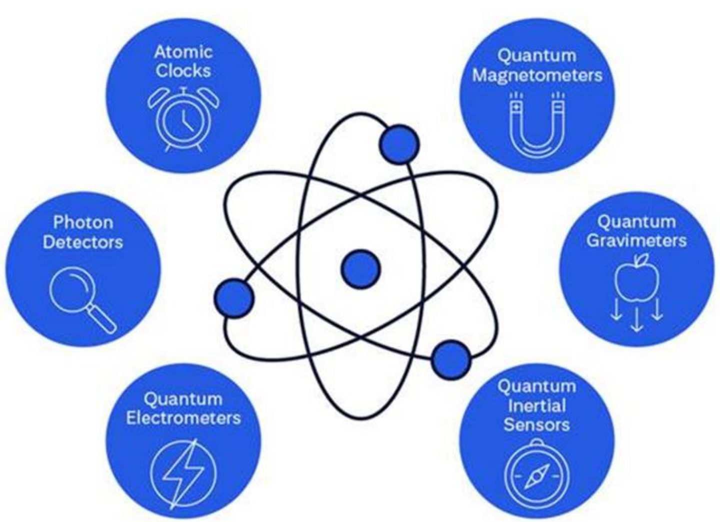
SQUIDs, microwave fields

Photonics

imaging, LiDAR, timing links

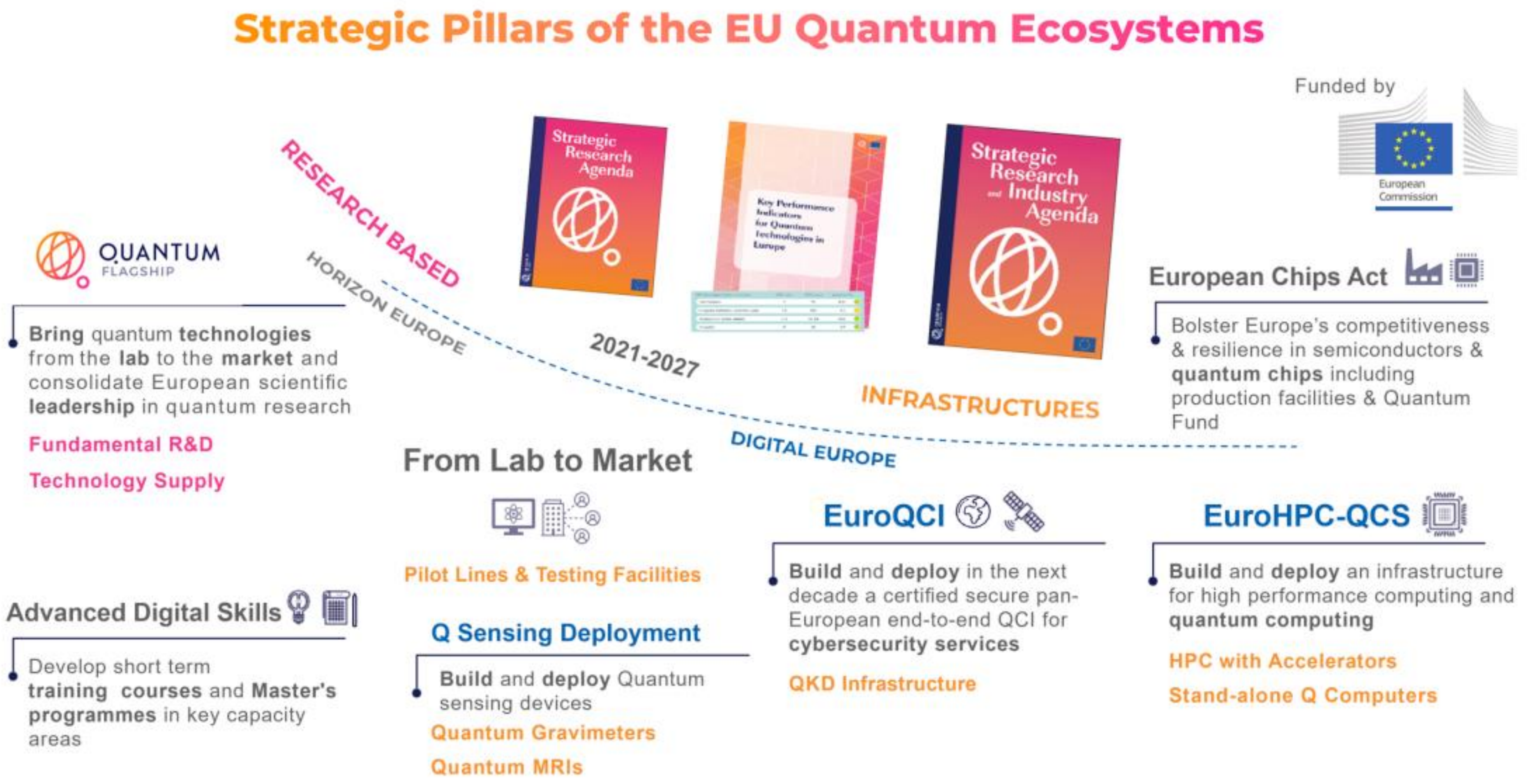
European Programs





	1. Communication	2. Simulators	3. Sensors	4. Computers
0 – 5 years	A Core technology of quantum repeaters B Secure point-to-point quantum links	A Simulator of motion of electrons in materials B New algorithms for quantum simulators and networks	A Quantum sensors for niche applications (incl. gravity and magnetic sensors for health care, geosurvey and security) B More precise atomic clocks for synchronisation of future smart networks, incl. energy grids	A Operation of a logical qubit protected by error correction or topologically B New algorithms for quantum computers C Small quantum processor executing technologically relevant algorithms
5 – 10 years	C Quantum networks between distant cities D Quantum credit cards	C Development and design of new complex materials D Versatile simulator of quantum magnetism and electricity	C Quantum sensors for larger volume applications including automotive, construction D Handheld quantum navigation devices	D Solving chemistry and materials science problems with special purpose quantum computer > 100 physical qubit
> 10 years	E Quantum repeaters with cryptography and eavesdropping detection F Secure Europe-wide internet merging quantum and classical communication	E Simulators of quantum dynamics and chemical reaction mechanisms to support drug design	E Gravity imaging devices based on gravity sensors F Integrate quantum sensors with consumer applications including mobile devices	E Integration of quantum circuit and cryogenic classical control hardware F General purpose quantum computers exceed computational power of classical computers

European Quantum Technologies Ecosystem



Atomic Clocks

Why: fundamental for GPS (every satellite has atomic clock onboard), finding oil and gas (geophone synchronization), high-frequency trading (avoid microsecond-scale clock drift) [2,] astronomical imaging (VLBI), altitude measurement with general relativity [1].

Technologies: We tune the microwave source (atomic clock) or laser (optical clock) to the energy transition in some element (cesium, usually). Energy is directly related to frequency (E=hf), which gives the clock signal. [2] We can differentiate: Beam clocks, Fountain clocks, Optical clocks and other types such as Rubidium, Hydrogen Maser, Chip scale and Nuclear Clocks.

Status: deployed

Use-cases: every GNSS (e.g. GPS, GALILEO), finance, telecom, relativistic geodesy and the famous first in history black-hole photography [2]

Quantum advantage: 9 orders of magnitude better accuracy [2]

[1] https://spie.org/news/atomic-clock-applications
[2] https://www.nist.gov/atomic-clocks

Magnetometers

Why: detection of magnetic objects (e.g. submarines), geophysical surveying and mapping, magnetic imaging of integrated circuit [1], biomedical imaging (brain acticity monitoring, subcellular resolution imaging [2])

Technologies: atomic vapor magnetometers, nitrogen-vacancy-center magnetometers, Rydberg atom RF sensors [1], SQUIDS

Status: commercially available, 300 pT fields in room temperature [6]

Use-cases: recent rescue of US pilot in Iran with quantum-magnetometer-based pulse sensor [4] off-satellite magnetic-field mapping [5] geophysics

Quantum advantage: sensitivity increased by 3-6 orders of magnitude [3]

[1] https://opg.optica.org/optica/fulltext.cfm?uri=optica-12-12-2008
[2] https://www.nature.com/articles/s42254-023-00558-3
[3] https://www.pnisensor.com/quantum-magnetometry-vs-classical-magnetometry/
[4] https://thequantuminsider.com/2026/04/08/did-a-quantum-sensor-help-rescuers-find-a-downed-american-pilot/
[5] https://space.skyrocket.de/doc_sdat/qmsat.htm
[6] https://qant.com/wp-content/uploads/2023/11/231114-Magnetometer-Brochure.pdf

Atomic Gravimeters

Why: no-GPS navigation (e.g. for submarines or spaceships), minerals and oil finding, predicting volcanic eruptions (underground lava monitoring), agriculture (soil humidity measurement), tunnels, voids, groundwater, space geodesy

Technologies: atomic interferometry, mixing of two laser-controlled atom beams free-falling in the void. Free-falling atoms provide an absolute reference test mass; interference converts small acceleration changes into a phase readout.

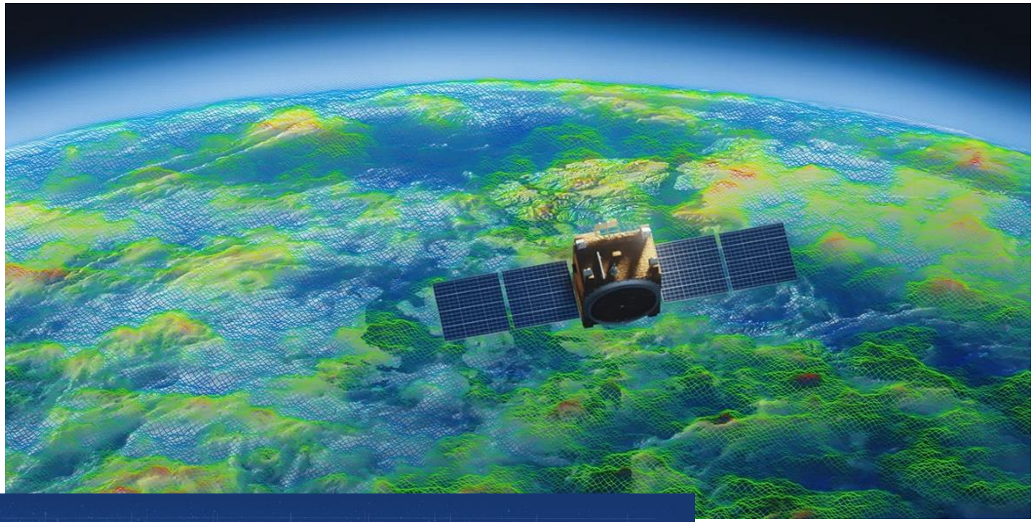
Status: first commercial products available (10 nm/s2) [1]; already 20+ units sold

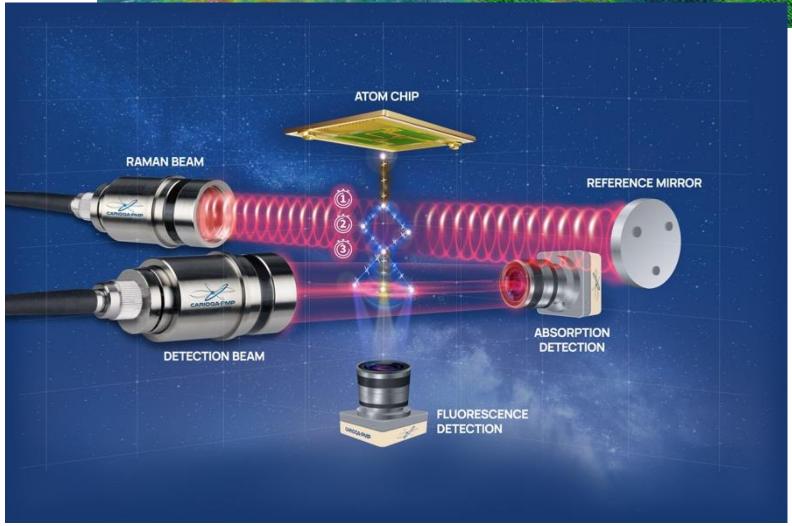
Use-cases: Quantum gravitometer scheduled to fly in space in 2030 [4,5] Successful Etna mount monitoring [6] Tenerife bought 3 gravitometers for volcanic activity monitoring [7]

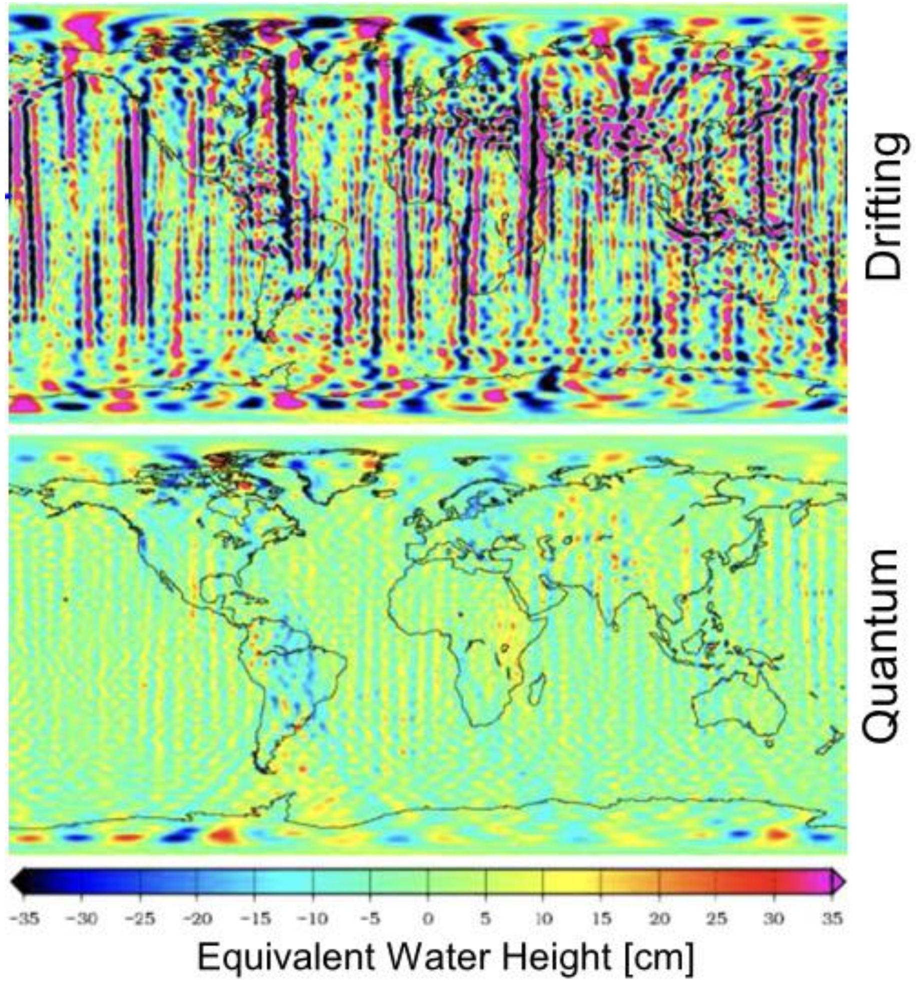
Quantum advantage: sensitivity increased by 3 orders of magnitude in commercial devices [1, 2] according to NASA sensitivity only 1 order of magnitude higher, but quantum device much smaller and lighter [4]

[1] https://www.exail.com/product/quantum-gravimeters
[2] https://www.mdpi.com/2072-4292/16/14/2634
[3] https://www.nist.gov/quantum-information-science/turning-atoms-waves-measure-gravity-and-acceleration
[4] https://www.jpl.nasa.gov/news/nasa-aims-to-fly-first-quantum-sensor-for-gravity-measurements/
[5] https://infleqtion.com/infleqtion-and-nasa-to-fly-the-worlds-first-quantum-gravity-sensor-to-space/
[6] https://www.exail.com/resources/customer-stories/a-year-long-field-campaign-on-mount-etna-to-prove-the-absolute-quantum-gravimeter-value-for-volcanology
[7] https://www.exail.com/news/three-exail-absolute-quantum-gravimeters-delivered-to-tenerife-for-advanced-volcano-monitoring

Atomic Gravimeters in Sapce - CARIOQA







Gyroscopes

Why: to navigate in the areas where no electronic or visible feedback is available (aircrafts, submarines, ships, missiles, drones) [1]

Technologies: atomic vapour is excited with laser to the superposition of two quantum states; these states have different inertia, and, when the gas chamber moves/rotates the atoms interact differently with its walls. This creates and interference pattern. [1]

Status: first prototypes ready; not available

Use-cases: prototypes delivered to US Army [2], Testing on satellites [3]

Quantum advantage: „potential to be significantly more sensitive" [1]

[1] www.nist.gov/noac/technology/time-and-frequency/atomic-gyroscopes
[2] https://payloadspace.com/vector-atomic-deliv
[3] https://www.quantum-australia.com/use-cases/quantum-gyroscopes-for-navigation

Quantum Imaging & Spectroscopy

Why: higher resolution in microscopy and metrology – for biomedical imaging, material science and fundamental research [1]. Quantum correlations and spin defects can reveal weak, hidden or nanoscale signals.

Technologies: imaging with squeezed light, imaging with single photons, imaging entangled photons, ghost imaging. NV centers map magnetic fields from currents, magnetization, strain and temperature. Atomic transitions can detect electric fields and radio-frequency signals.

Status: routinely used in research projects

Use-cases: as presented below

Quantum advantage: biomedical microscopy: 35% improvement in SNR, 14% improvement in spatial resolution (squeezed light) [1]
LIGO (gravitational wave detector) range increased by 65% [2]

[1] https://www.nature.com/articles/s41566-024-01516-w
[2] https://journals.aps.org/prx/abstract/10.1103/PhysRevX.13.041021

Quantum Antennas – Rydberg Sensors

Why: very broadband (DC - THZ), compact antennas capable of receiving very low and very high intensity RF waves [1]

Technologies: Vapor of Rydberg atoms stimulated by two probing lasers, which can turn on/off the transparency of the vapor. External electric fields alter the interaction between laser and atoms.

Status: First commercial products launched in last 3 years [2, 3]. Infleqtion offers 3 MHz – 6 GHz module,

Use-cases: research-grade so far. Prof. Parniak group from UW recently announced creation of some proposal of quantum antenna [4]

Quantum advantage: broadband while compact, works with very weak and strong fields, full-optical detection: doesn't disturb detected fields (robust against interference in complex RF environments)

[1] https://www.nist.gov/quantum-information-science/giant-atoms-measuring-radiation
[2] https://www.rydbergtechnologies.com/products
[3] https://infleqtion.com/quantum-rf-receiver/
[4] https://www.nature.com/articles/s41467-025-63951-9

Biomedical Applications for Quantum Sensors

- Quantum sensors can move closer to weak biological signals, often without cryogenics.

- Wearable OPM-MEG brain imaging for movement-tolerant studies. Magnetocardiography and fetal heart monitoring. NV-diamond nanoscale sensing of cells, proteins and local temperature. Hybrid diagnostics: quantum sensor + AI signal interpretation

- Biological magnetic fields are tiny and local. Smaller room-temperature sensors can sit closer to the source, improving signal quality and enabling new study designs.

Applications in Energy, Infrastructures & Climate

Power grids	magnetometers for fault detection; atomic clocks for synchronization
Carbon storage	gravimeters and single-photon LiDAR for leak detection
Subsurface assets	gravity and magnetic surveys for utilities and resource mapping
Critical infrastructure	resilient timing and RF sensing for telecom and transport

Implementation and Integration

Quantum core

atoms, spins, photons, defects

Photonics & control

lasers, modulators, microwaves, timing electronics

Packaging

vacuum, thermal control, shielding, rugged mechanics

Inference layer

calibration, drift modeling, uncertainty and sensor fusion

Operational workflow

testbeds, standards, maintenance and user training

Quantum sensing challenges

Challenge		*Mitigation path*
Decoherence & quantum noise	→	longer coherence, error-resistant protocols, better readout
Environmental vibration / fields	→	active isolation, shielding, reference sensors, sensor fusion
SWaP-C and cost	→	photonic integration, microfabrication, modular components
Validation & standards	→	benchmarking, traceable uncertainty, common testbeds
Workflow adoption	→	hybrid outputs, clear ROI, training and maintenance models

Opportunities for NRENs

Near-term

Fieldable clocks, magnetometers and gravimeters for PNT, healthcare, infrastructure and energy use cases testing

Long-term

Sensor networks, chip-scale quantum instruments, new time standards and measurement-driven autonomy in larger scale and integrated with existing infrastructures

PCSS

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