Some Initial Experiences of Quantum Sensors

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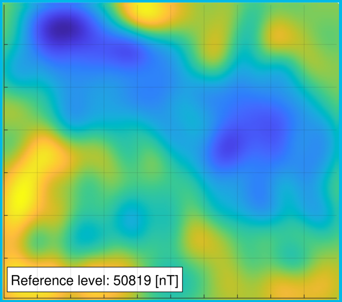

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SEDIT
Sensor Informatics and Decision-making for the Digital Transformation

Talk Outline

- Quantum Sensors
- Quantum Magnetometers
- Experimental Experiences
- Concluding Remarks

Acknowledgment

Thank you to Isaac Skog (KTH), and the Vinnova and Swedish Armed Forces project 2024-03194 (*Electromagnetic navigation for smaller unmanned underwater vehicles*), for fruitful collaborations when collecting data and preparing this presentation.

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Disclaimer:

This presentation reflects a **signal processing perspective** of quantum sensors, and quantum magnetometers in particular. For details on the sensor construction, and underlying physical principles, please, ask a physicist. :)

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Quantum Sensors

Definition

A quantum sensor is a sensor that uses **quantum mechanical phenomena** to **measure physical quantities** with **precision** beyond classical sensors.

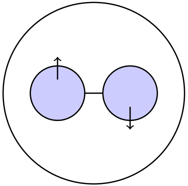
Quantum sensors leverage fundamental physics to achieve sensitivities unattainable by classical devices.

Quantum Sensors: phenomena

Quantum Mechanical Phenomena

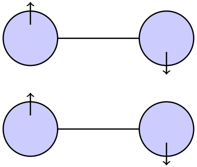
- *Superposition:* Particles exist in multiple states simultaneously
  $\Longrightarrow$ higher sensitivity.
- *Entanglement:* Linked particles improve measurement accuracy.
- *Coherence:* Maintains quantum states long enough for reliable data.

Superposition



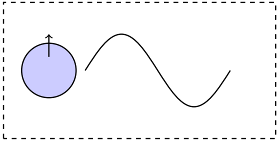
Particles exist in multiple states simultaneously

Entanglement



Linked particles share quantum states

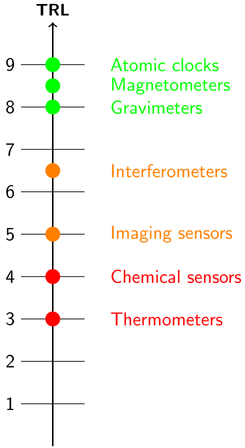
Coherence



Quantum state maintained over time

Quantum Sensors: examples

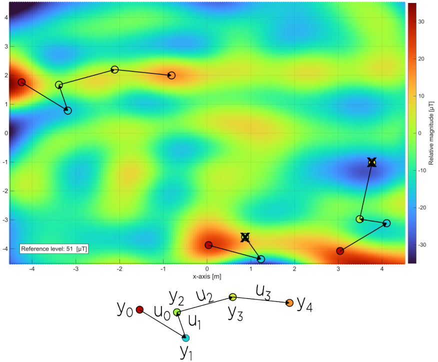
- Atomic clocks:
  Ultra-precise timekeeping (GPS, telecom).
- Magnetometers:
  Detect weak magnetic fields (medical imaging, geology, navigation).
- Gravimeters:
  Measure gravity variations (resource exploration).
- Interferometers:
  Used in navigation and gravitational wave detection.
- Imaging sensors:
  Quantum-enhanced cameras for low-light imaging.
- Chemical sensors:
  Detect trace molecules with high sensitivity.
- Thermometers:
  Measure temperature at the quantum limits.



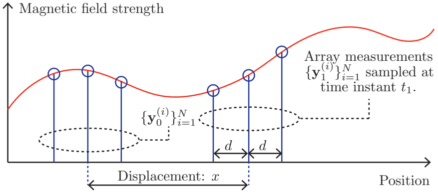
Magnetometers: motivation

Magnetic field measurements can be used for, *e.g.*, localization and odometry.

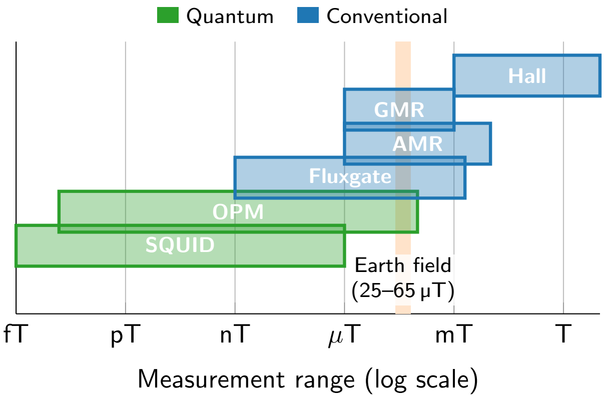
Localization



Odometry (from a sensor array)



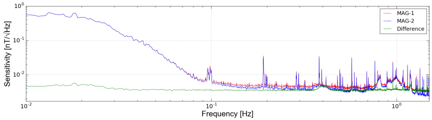
Magnetometers: sensor technologies (miniature sensors)



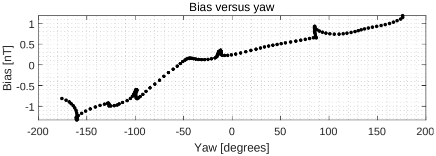
Experiment Equipment

QuSpin QTFM

Type:	Optically pumped (OPM)
Field Sensitivity:	$< 1\,\mathrm{pT}/\sqrt{\mathrm{Hz}}$ in 0.1–100 Hz band
Dynamic Range:	1 000–100 000 nT
Power:	5 V to 19 V, 2 W total
Dimensions:	$19 \times 19 \times 47$ mm (sensor)
Weight:	18 g (sensor)
Max data rate:	400 Hz
Axis of sensitivity	Magnitude only
Cost:	\$10 000



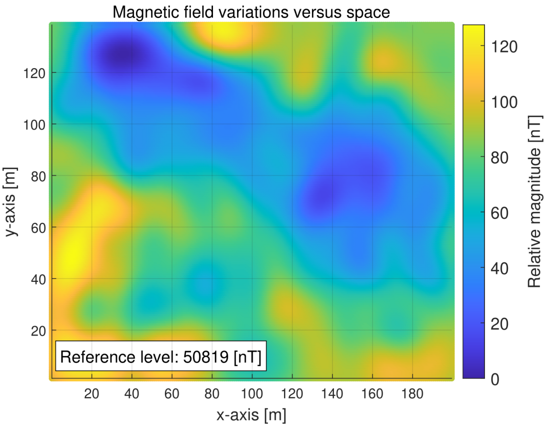
Noise spectrum



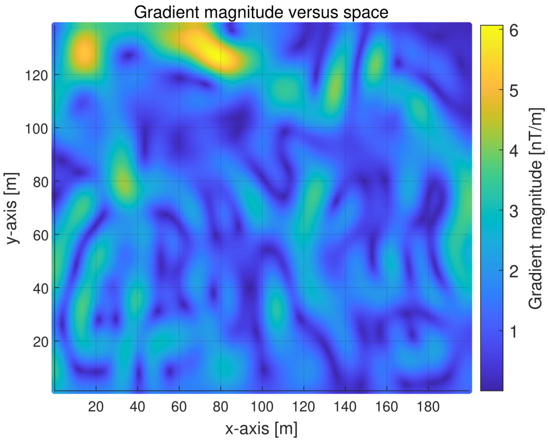
Bias vs Yaw

Gränsö Field Trial

Gränsö Field Trial: results

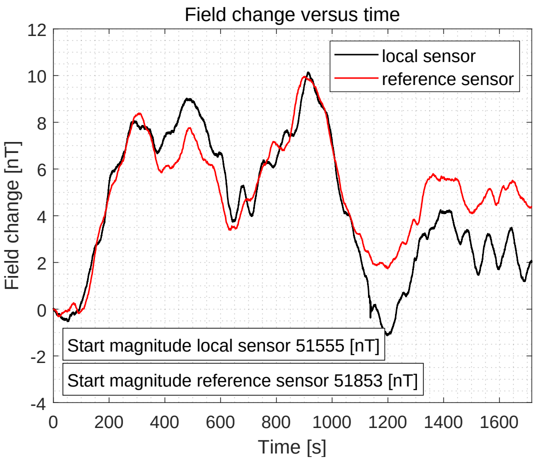


Magnetic field norm



Gradient of magnetic field norm

Gränsö Field Trial: background level



- Background magnetic field measured with dedicated sensor.
- Temporal variations of almost the same order of magnitude as the spatial.
- Reference measurements available from Uppsala.
- Clear correlations to reference sensor.

Gränsö Field Trial: reflections

- Sensor characteristics obtained.
- Gränsö data indicates significant field variations, not measurable with classic sensors.
- Changes in background level are significant, cannot be ignored.
- Sensor properties must be handled, *e.g.*, direction dependent measurements.
- Usefulness without knowing the background level is limited.

Concluding Remarks

- "Just" any sensor, from a signal processing perspective. . .
- **but** new challenges, *e.g.*:
  - sensor noise often not dominating error source,
  - modeling errors (new phenomena significant),
  - numerics becomes noticeable,
  - platform interference is significant.
- Potential for impressive accuracy and resolution.
- Interesting prospects, but not a "golden" solution.

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