Vector Magnetometry Using Nitrogen-vacancy Centers in Diamond

Christopher Lew

A. Chew, F. Meneses, A. Sivamalai, L. Anderson, A. Sayers, L. T. Hall, A. Silvester, A. D. Greentree, B. C. Gibson, L. C. L. Hollenberg, and D. A. Simpson

Project Summary

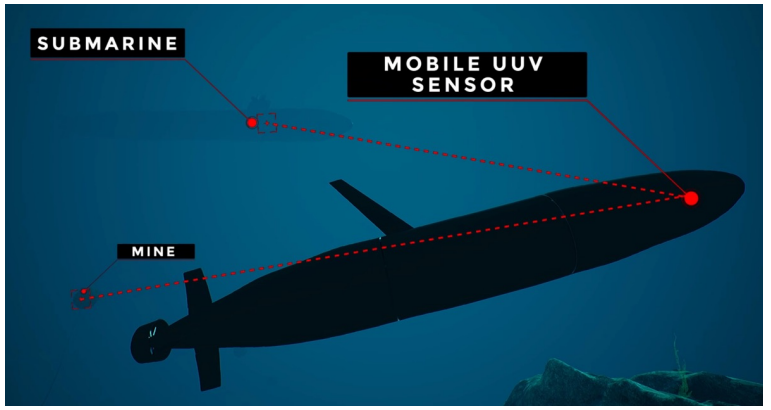
Part of the Army Quantum Technology Challenge 2021 and Next Generation Technology Fund

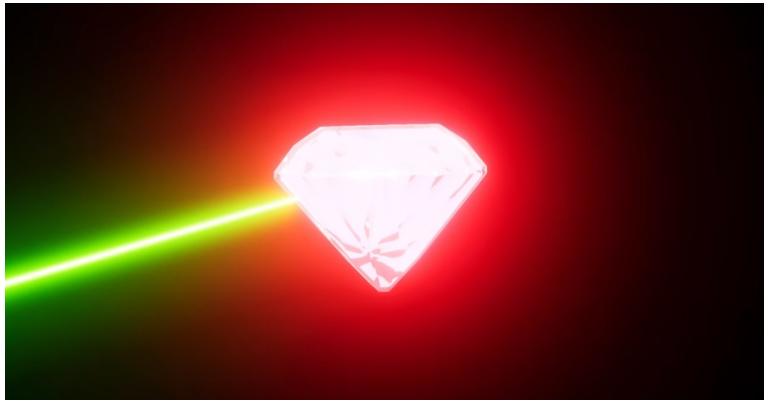
Aim to understand the advantages of vector over scalar sensing for defence applications

1. GPS-denied magnetic navigation
2. Underwater and underground magnetic anomaly detection
3. Subterranean imaging

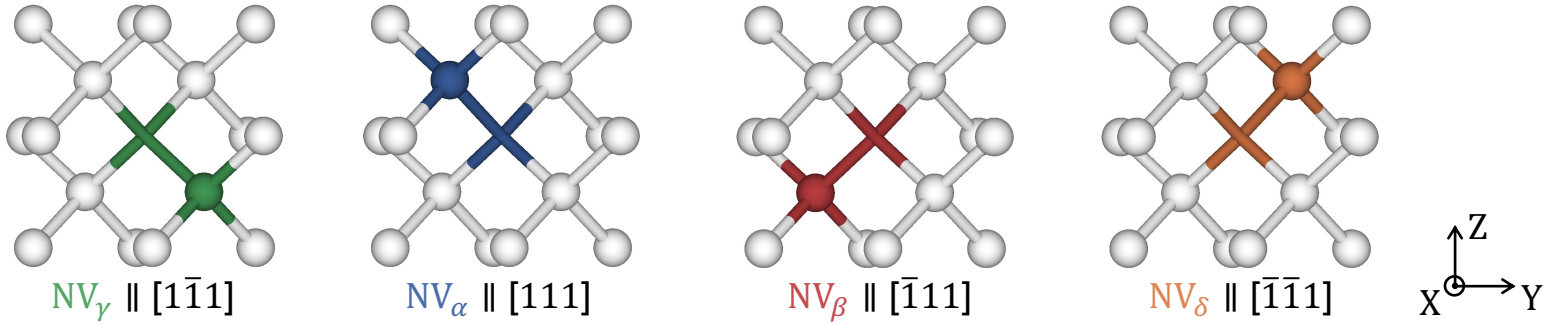
Quantum diamond magnetometer platform offers:

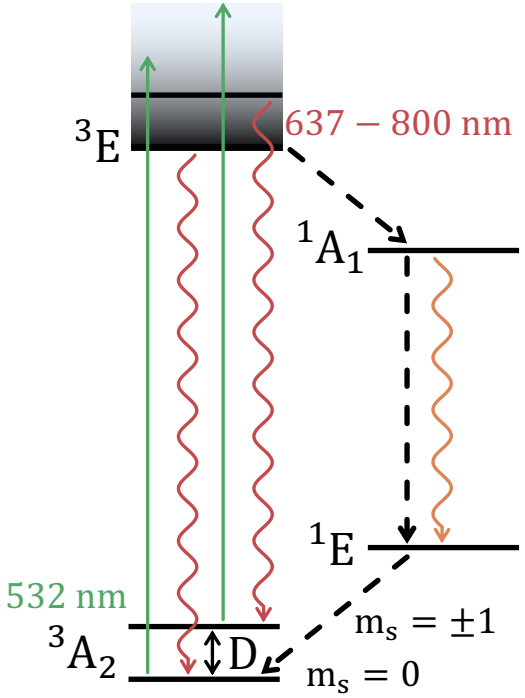
- Vector (+ scalar)
- High dynamic range
- Low drift
- High sensitivity
- Large bandwidth



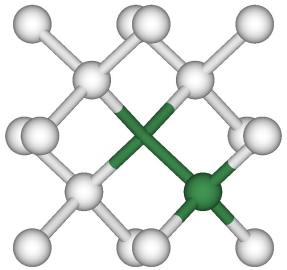


Nitrogen Vacancy Centre

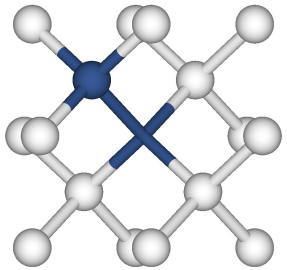




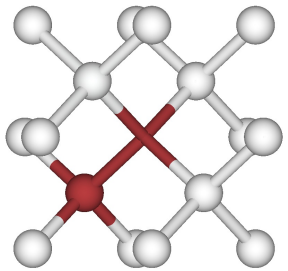
Nitrogen Vacancy Centre



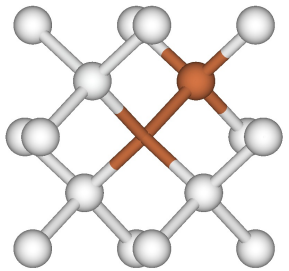
$NV_\gamma \parallel [1\bar{1}1]$



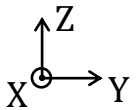
$NV_\alpha \parallel [111]$



$NV_\beta \parallel [\bar{1}11]$



$NV_\delta \parallel [\bar{1}\bar{1}1]$

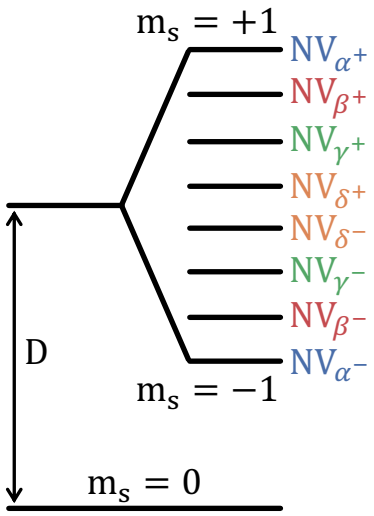


$$\hat{\mathcal{H}}^i = \left(D + \mathcal{M}_z^i\right)\left(S_z^i\right)^z + \gamma(\vec{B}\cdot\vec{S}^i)$$

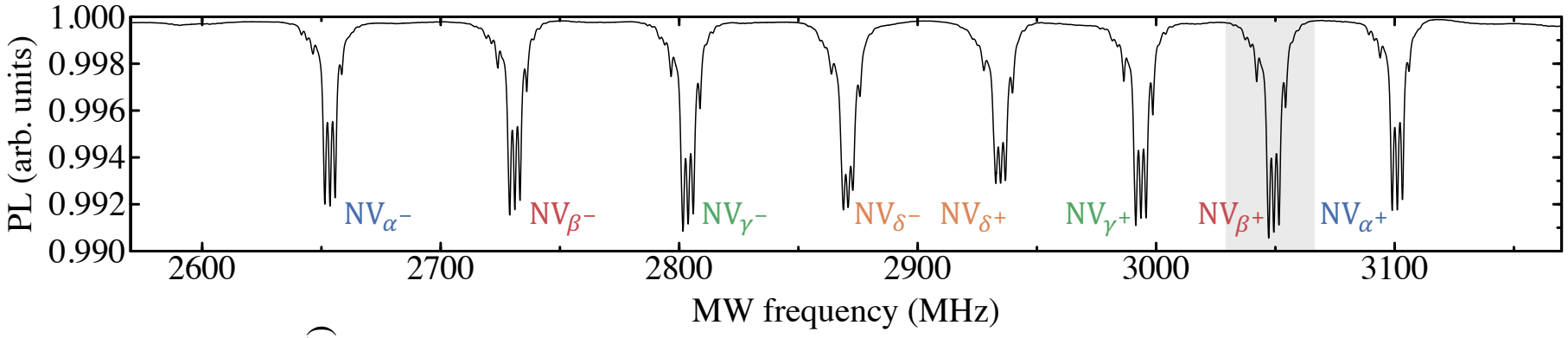
$$D = 2869.73\ \text{MHz}\ (\sim 23.6°\text{C})$$

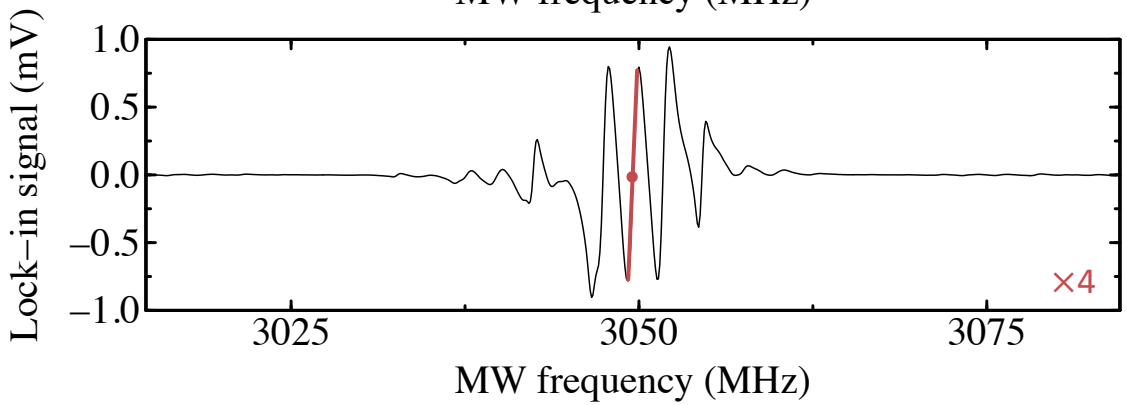
$$\vec{B}_0 = (4.23, 1.41, 7.85)\ \text{mT}$$

$$\vec{M}_0 = (9.22, 8.16, 4.27)\ \text{kHz}$$



D~2870 MHz
κ~ − 74 kHz/K

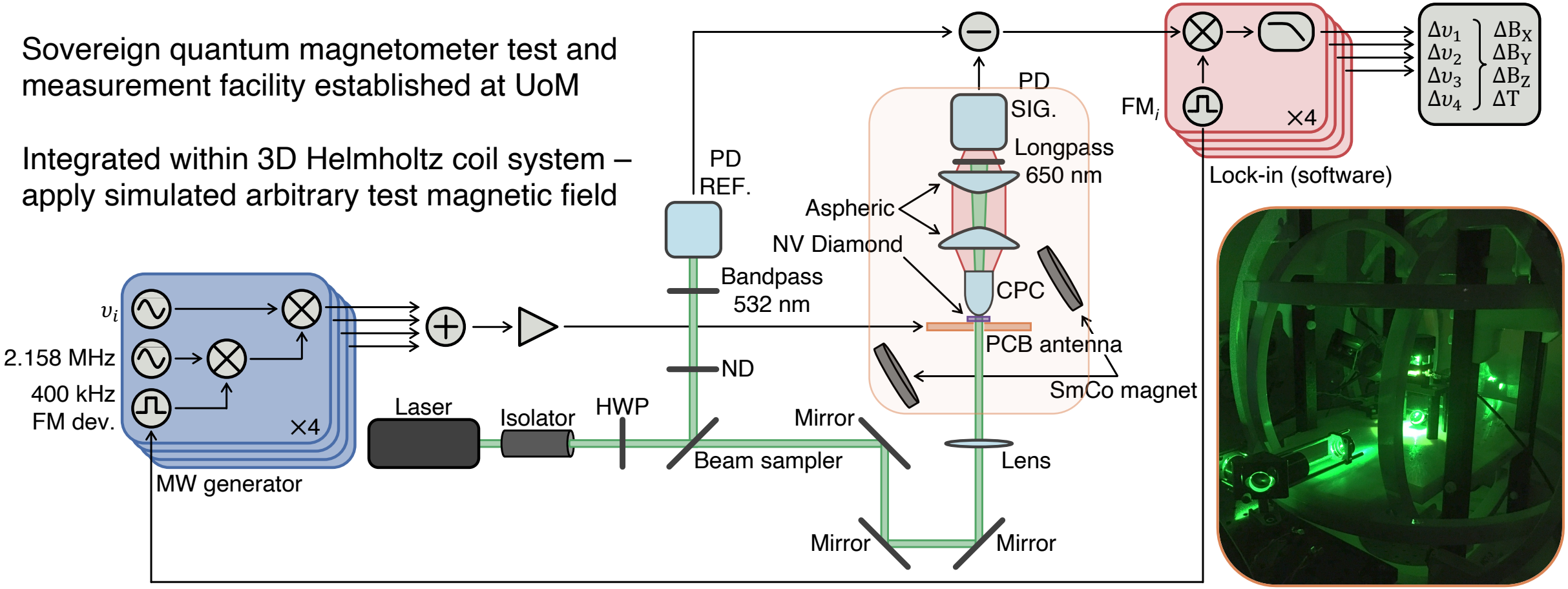




Test and Measurement Facility

Sovereign quantum magnetometer test and measurement facility established at UoM

Integrated within 3D Helmholtz coil system – apply simulated arbitrary test magnetic field



Unshielded Sensitivity

Calculate noise spectral density – FFT 10 s time trace

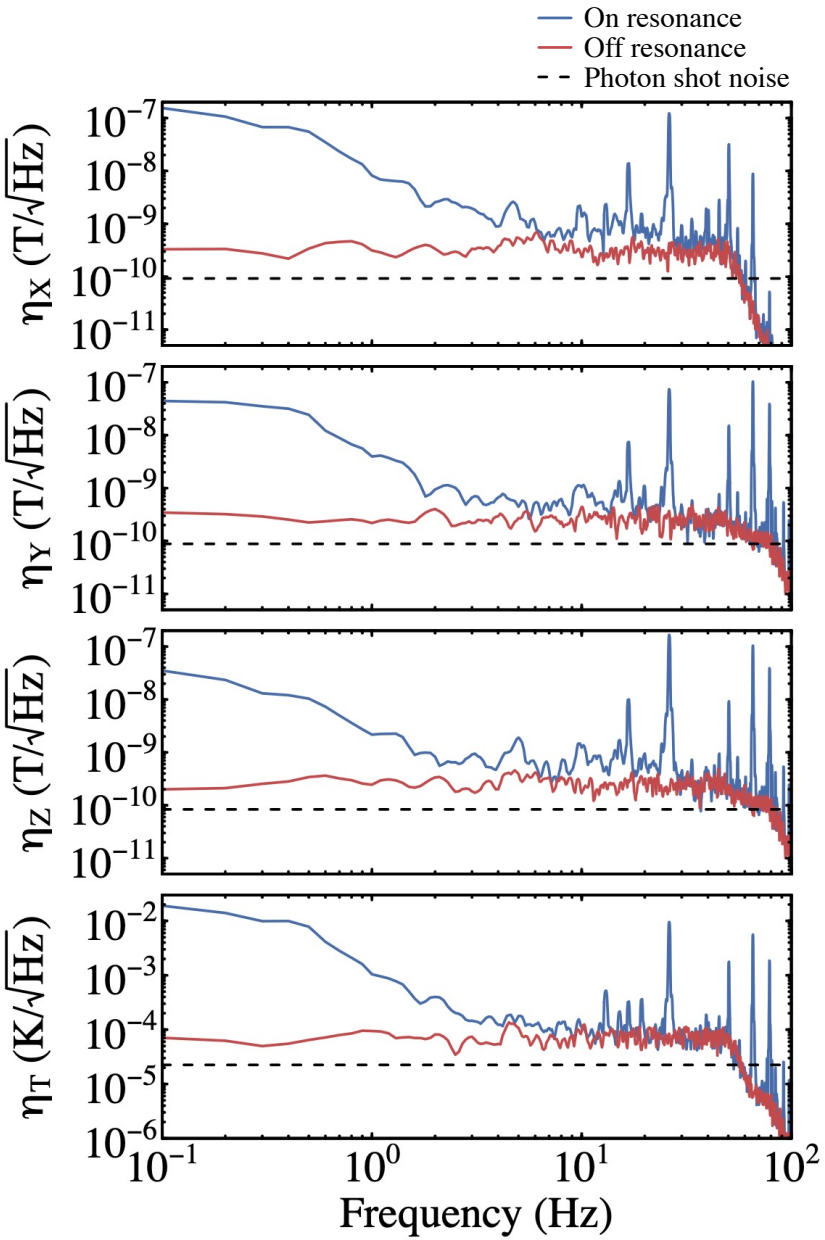
532 nm green pump beam ~ 320 mW

NV photoluminescence ~ 10.6 mW

Current sensitivity: $\eta_X \sim 346\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$, $\eta_Y \sim 264\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$
$\eta_Z \sim 267\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$, $\eta_T \sim 73\ \mu\mathrm{K}/\sqrt{\mathrm{Hz}}$

Photon shot noise limited sensitivity: $\eta_X \sim 93\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$, $\eta_Y \sim 88\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$
$\eta_Z \sim 84\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$, $\eta_T \sim 22\ \mu\mathrm{K}/\sqrt{\mathrm{Hz}}$

Identified key strategies to further enhance the sensitivity



Unshielded Sensitivity

Calculate noise spectral density – FFT 10 s time trace

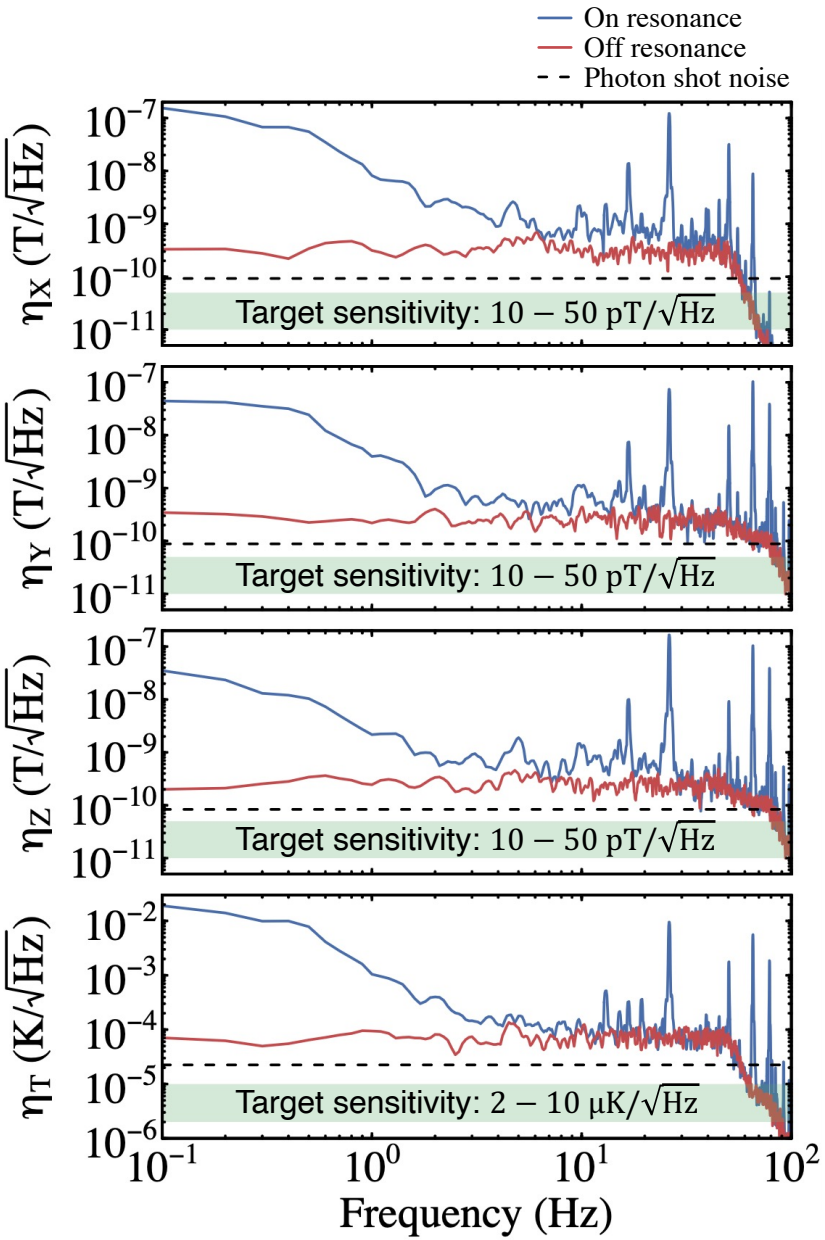
532 nm green pump beam ~ 320 mW

NV photoluminescence ~ 10.6 mW

Current sensitivity: $\eta_X \sim 346\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$, $\eta_Y \sim 264\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$
$\eta_Z \sim 267\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$, $\eta_T \sim 73\ \mu\mathrm{K}/\sqrt{\mathrm{Hz}}$

Photon shot noise limited sensitivity: $\eta_X \sim 93\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$, $\eta_Y \sim 88\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$
$\eta_Z \sim 84\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$, $\eta_T \sim 22\ \mu\mathrm{K}/\sqrt{\mathrm{Hz}}$

Identified key strategies to further enhance the sensitivity

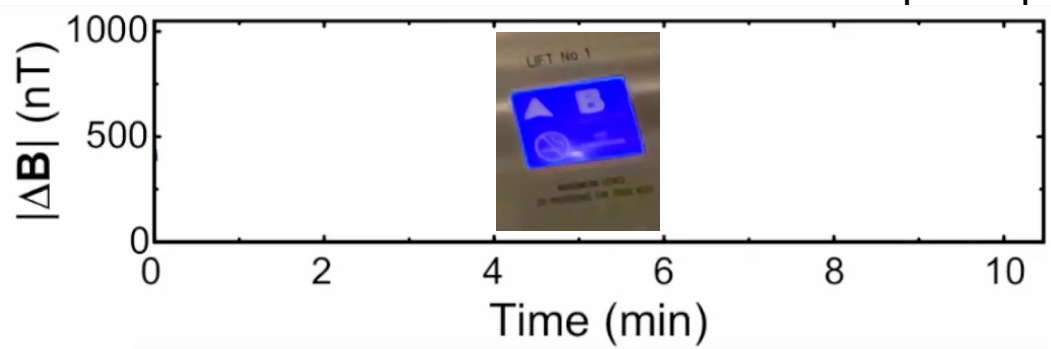


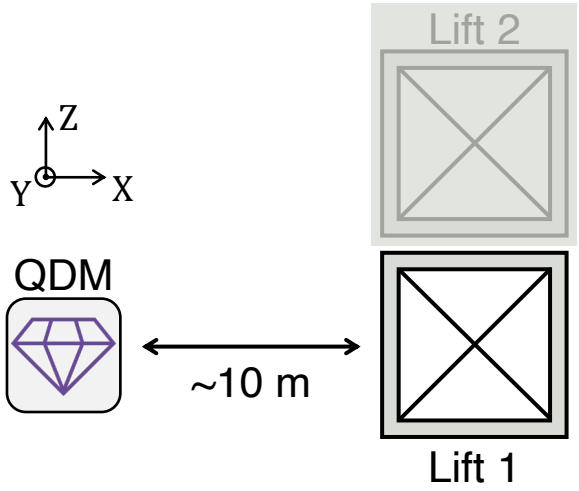
Target Tracking and Classification

Complex urban environment – sum of multiple magnetic noise sources

Controlled measurement – park lift 2 and travel on lift 1

×20 speedup





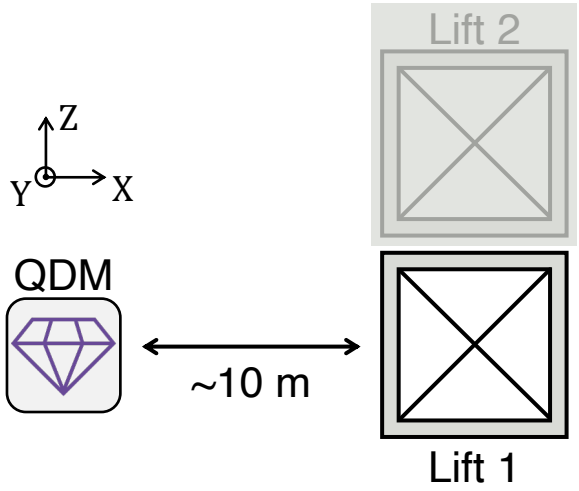
Target Tracking and Classification

Complex urban environment – sum of multiple magnetic noise sources

Controlled measurement – park lift 2 and travel on lift 1

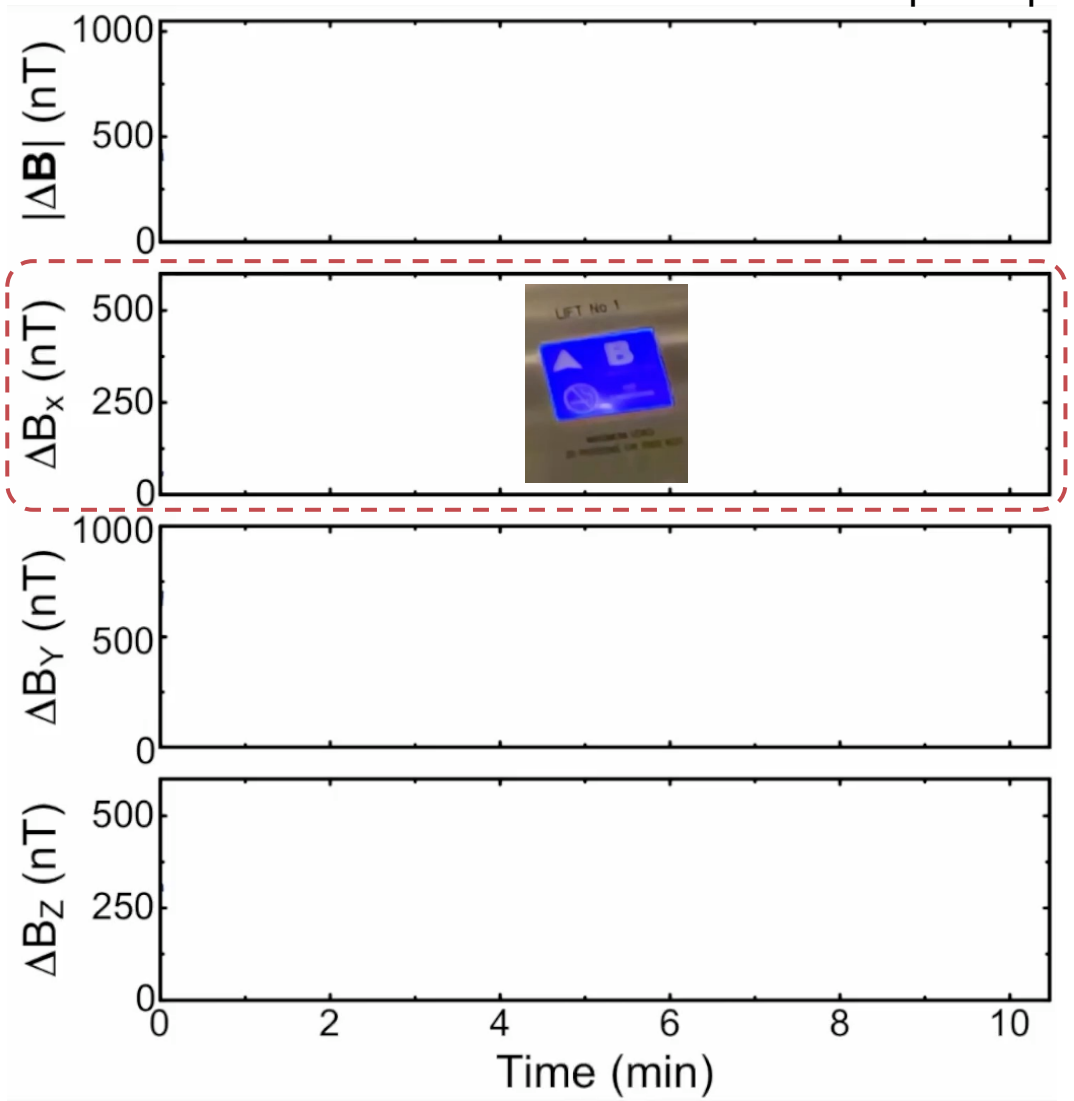
Directional magnetic noise in B_Y and B_Z due to tram situated ~105 m away overlap with lift signal

Training machine learning algorithm for real-time tracking



Wikimedia Commons

×20 speedup



Summary and Acknowledgements

Designed and developed a fully functional laboratory vector QDM

Current sensitivity: $\eta \sim 264 - 346\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$

Sensor miniaturization for field trial deployment and magnetic navigation applications

A. Chew
F. Meneses
A. Sivamalai
L. Anderson
A. Sayers
L. Hall
A. Silvester
A. Greentree
B. Gibson
L. Hollenberg
D. Simpson