Mapping Earth Field Anomalies with a Quantum Vector Magnetometer for Underwater UXO Detection

MR24-4533

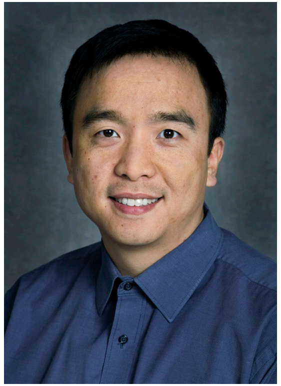
Zhao Hao

Lawrence Berkeley National Laboratory

In-Progress Review Meeting

1/15/2025

Project Team and Collaborators



Zhao Hao
LBNL

Quantum Engineering Student Team

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University of California, Berkeley (UCB)

Ashok Ajoy, Emanuel Druga

White River Technology (WRT) - *Gregory Schultz*

Molecular Foundry (MF) and Advanced Light Source (ALS)

Bottom Line Up Front
- Progress and Challenges in Quantum Vector Magnetometer Development for UXO Detection

- What technology or methodology is being evaluated?
  - Quantum vector magnetometer for UXO detection.
- Core Features:
  - High-sensitivity magnetic field detection using nitrogen vacancy centers in diamond.
  - Compact and low-power design for UAV integration.
  - Advances in high-bandwidth (MHz) dc/ac field sensing and noise isolation.

Bottom Line Up Front
- Progress and Challenges in Quantum Vector Magnetometer Development for UXO Detection

- What's been going well?
  - Completed optical design and acquired essential hardware (NV-diamonds, shielding chamber).
  - Demonstrated picotesla sensitivity on a benchtop optical system.
  - Achieved nanometer-scale gradient field and chemical magnetic resonance (MR) sensing in parallel experiments.
  - Progress in flux concentrator simulation for 10x field amplification.
  - Strong collaboration with the team and alignment on objectives.
  - Effective communication: regular updates and valuable feedback from SERDP management.

Bottom Line Up Front

- Progress and Challenges in Quantum Vector Magnetometer Development for UXO Detection

- What's not working?
  - Procurement Delays:
    - Long lead time (3-6 months) in hardware procurement (NV-diamonds, shielding chamber, customized optics).
    - 1-month delay in funding arrival.
  - Logistical Challenges:
    - Limited student availability during the fall semester, slowing progress.
    - However, final construction of the magnetometer in a low-field environment in progress (expected to finish in 2 months).

Bottom Line Up Front
- Progress and Challenges in Quantum Vector Magnetometer Development for UXO Detection

- What support do you need?
  - Additional funding and resources to support field-testing and integration with UAV platforms.
  - Continued guidance and feedback from the project manager to overcome current challenges.
  - We appreciate a possible project extension through the end of this year to complete milestones and maximize outcomes (ESTCP?).

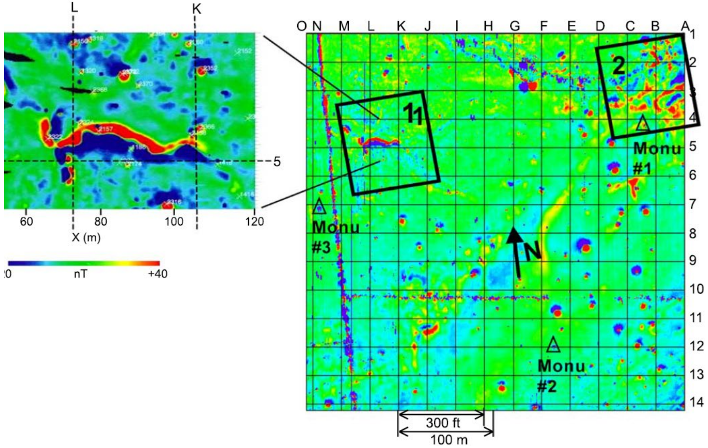
Technical Objective

- **Proven Records of Magnetometry**: Magnetometry is a successful method for UXO detection and geological surveys (without surface interference).
- **Quantum Sensor Transformation**: Leveraging a quantum sensor array as a vector magnetometer improves sensitivity for airborne and underwater UXO detection.
- **Noise Isolation Innovation**: Pulsed coherent control and sensing schemes (MHz) isolate the quantum magnetometer from operational noise (kHz), enabling versatile platform integration like UAVs.
- **Technical Advancement Goal**: Elevate the quantum vector magnetometer from TRL 4 to TRL 6 for prototype demonstrations in relevant environments.
- **Enhanced UXO Detection**: Anticipates high dynamic range, compact quantum devices enabling efficient and sensitive UXO detection for high-throughput surveys.
- **Mission Impact**: Broader DOD utility through multimodal sensing capabilities (e.g. chemical sensing), reducing survey costs and flight times while improving underwater UXO characterization.

We seek to revolutionize the current sensing protocols and platform.

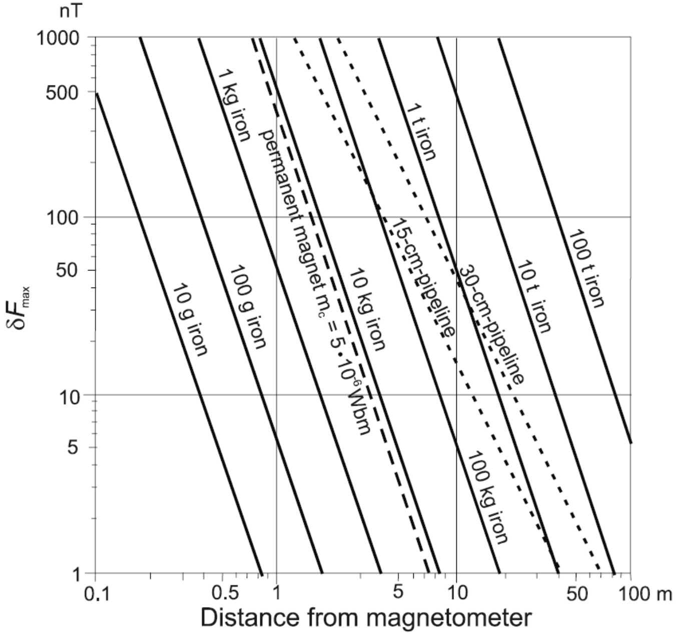
UXO Detection with Magnetometer - a Mature Technology

a. Typical ordnance items



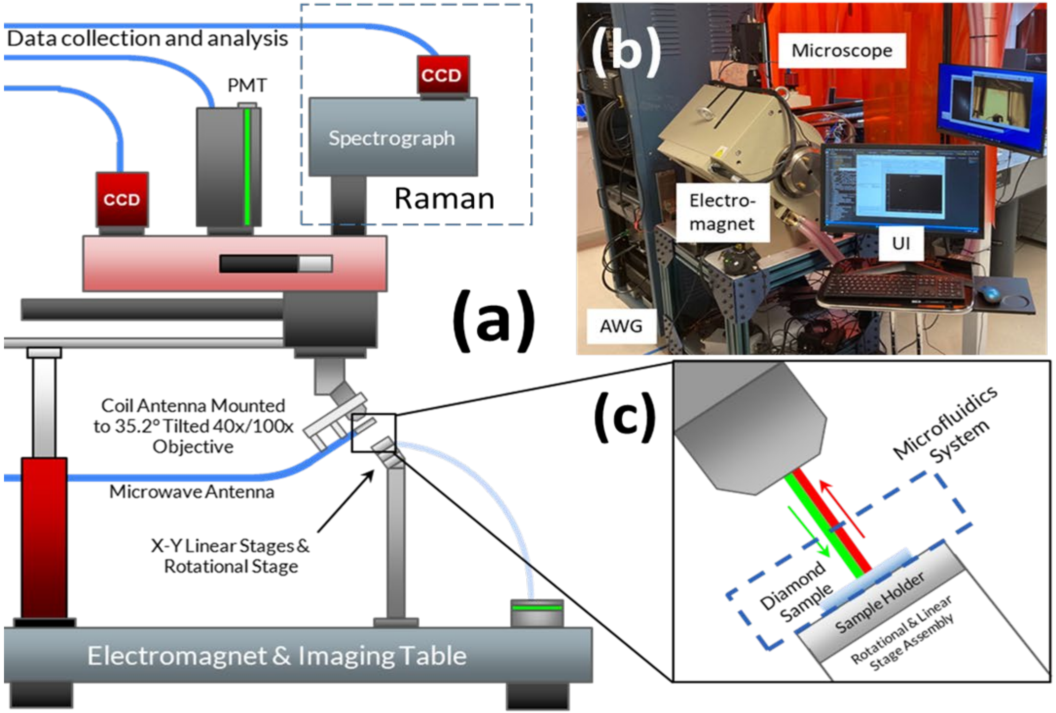
c. Site with prominent geologic magnetic anomalies, Jefferson Proving Ground, Indiana

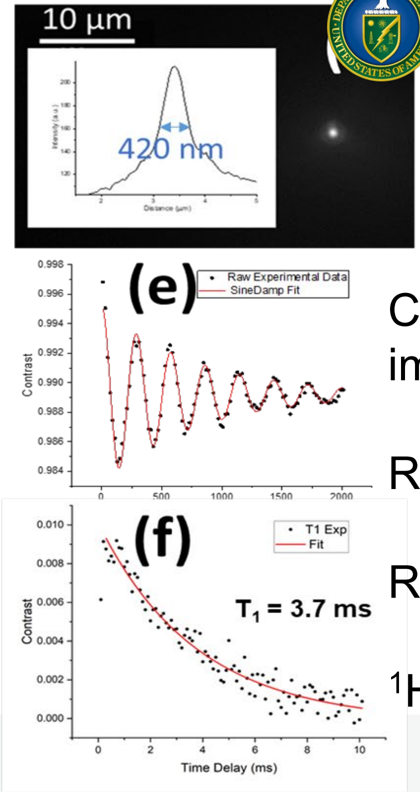
Butler, 2003



Environmental Geology, 2007

Quantum Sensing Laboratory for Geosciences





Confocal chemical imaging

Rabi Oscillation

Relaxometry

^{1}H-NMR @ nm

U.S. DEPARTMENT OF ENERGY

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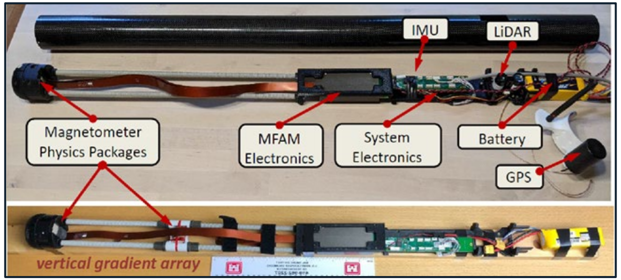
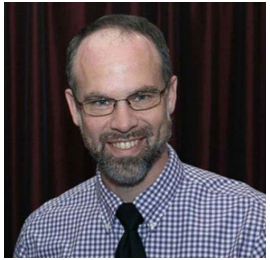
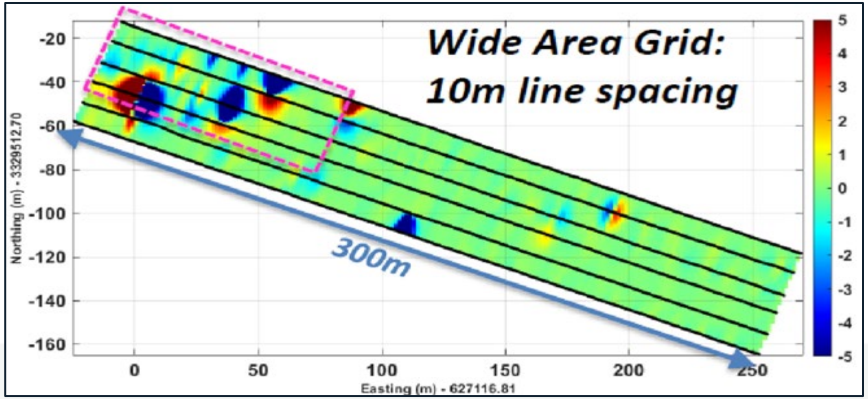
Partnership with WRT – Technology Transition

UAV Magnetic Field Sensing Platform

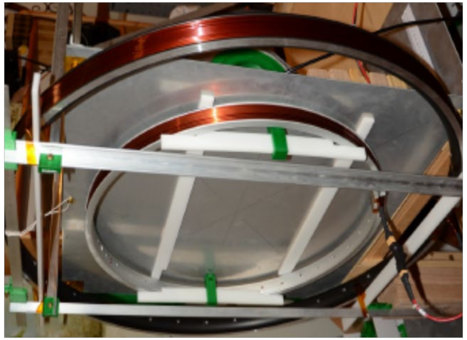


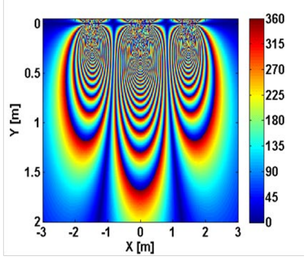


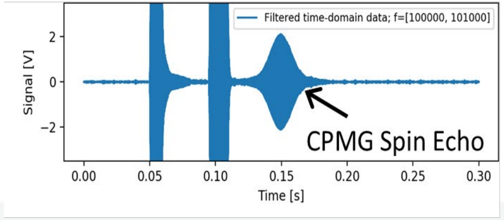
Dr. Greg Schultz

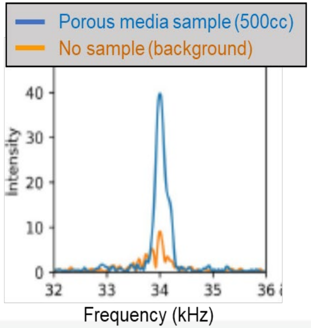


Subsurface EMI and MR Sensing Platform









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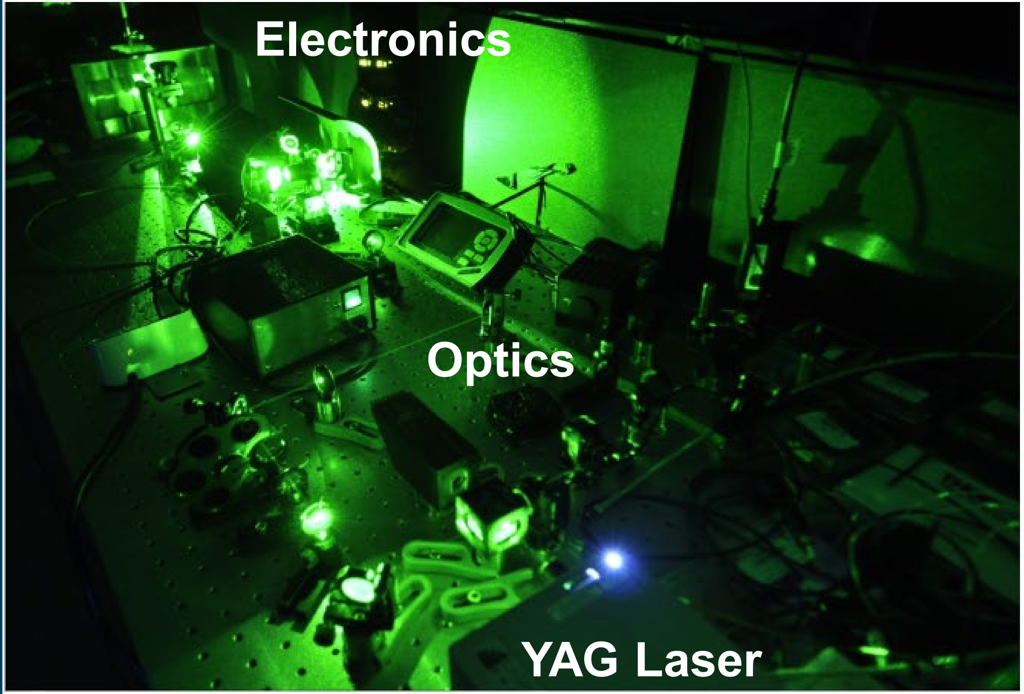
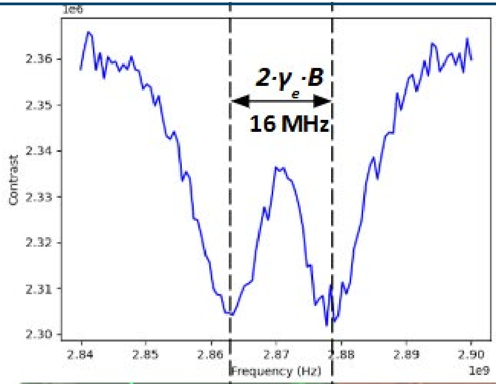
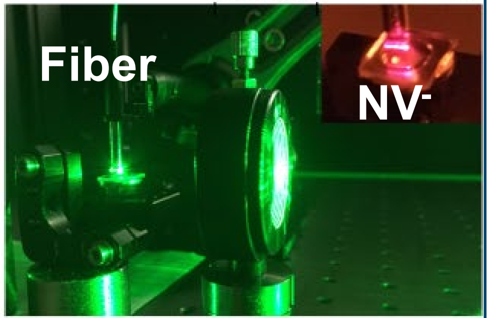
Our Answer to the Challenge: Quantum Sensing of Magnetic Field using NV- Centers in Diamond

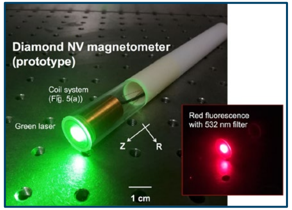






Sub-Picotesla

At what cost?



~10s nT, Kuwahata, 2020

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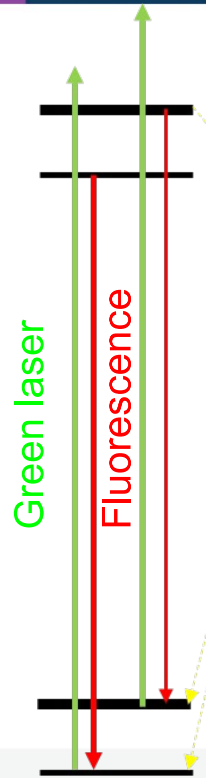
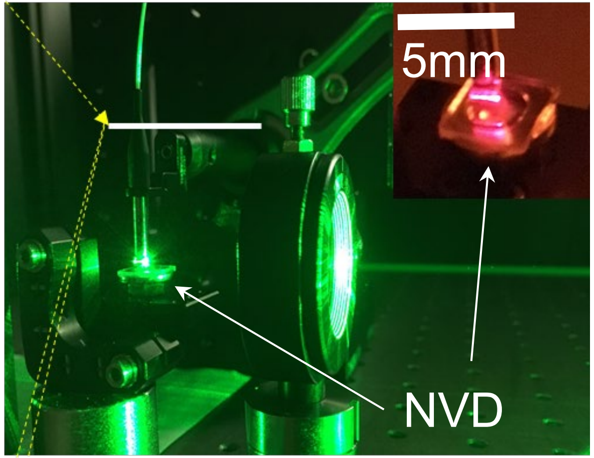
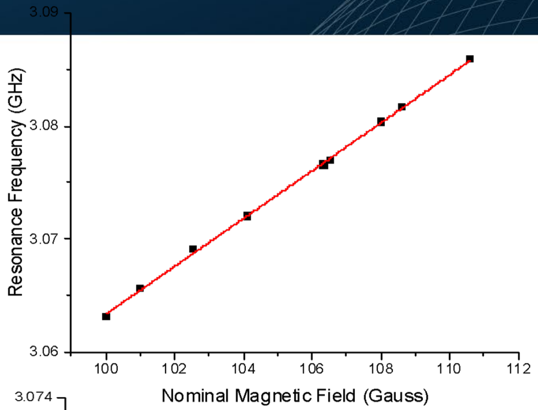
Task 1 – Improve the current NV magnetometer

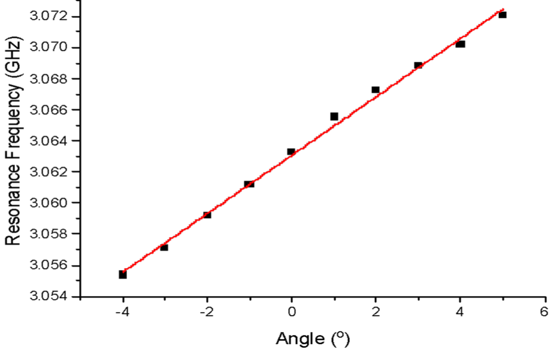


Fiber-based NVD-Magnetometer



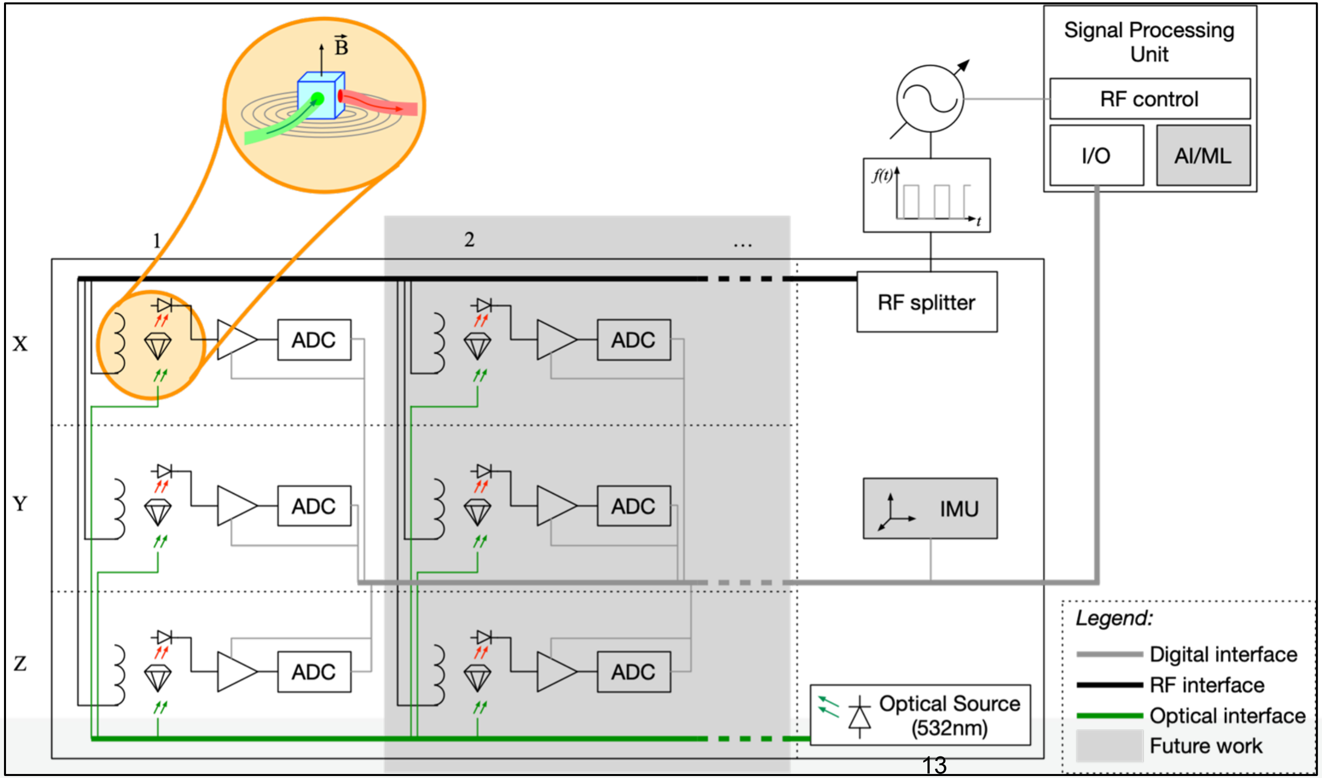


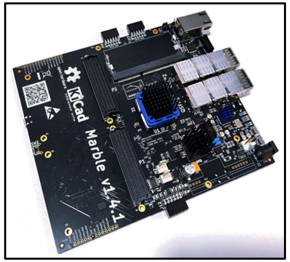
Field Strength Dependence



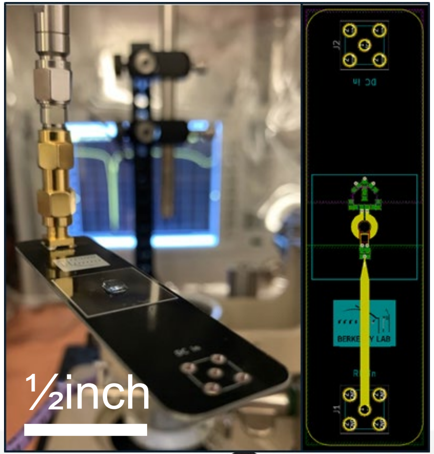
Field Directional Dependence

Task 2. RF Signal Chain





Dr. Stijn Wielandt



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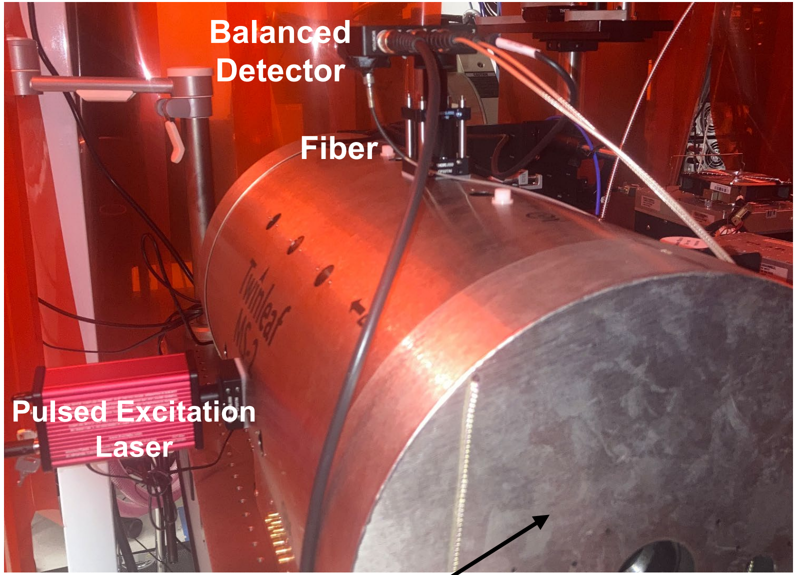
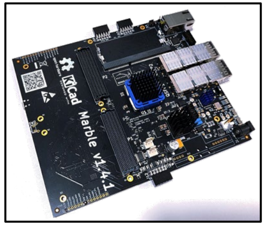
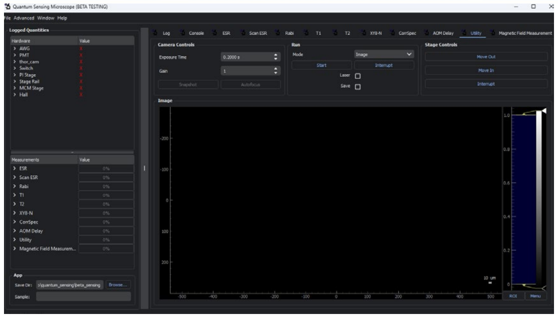
Task 3 – Integration (In Progress)



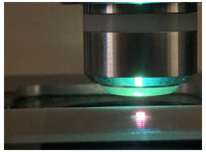
Zero-field chamber for low field characterization

Function Generator
& Desktop Computer

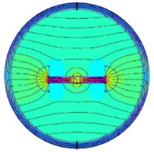


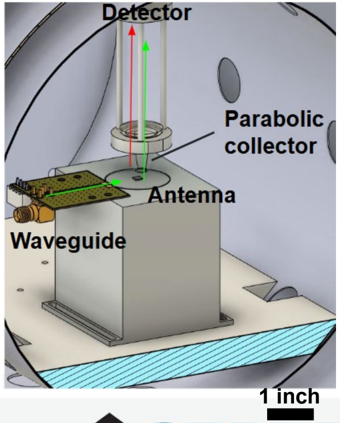


NV-diamond



Flux Concentrator





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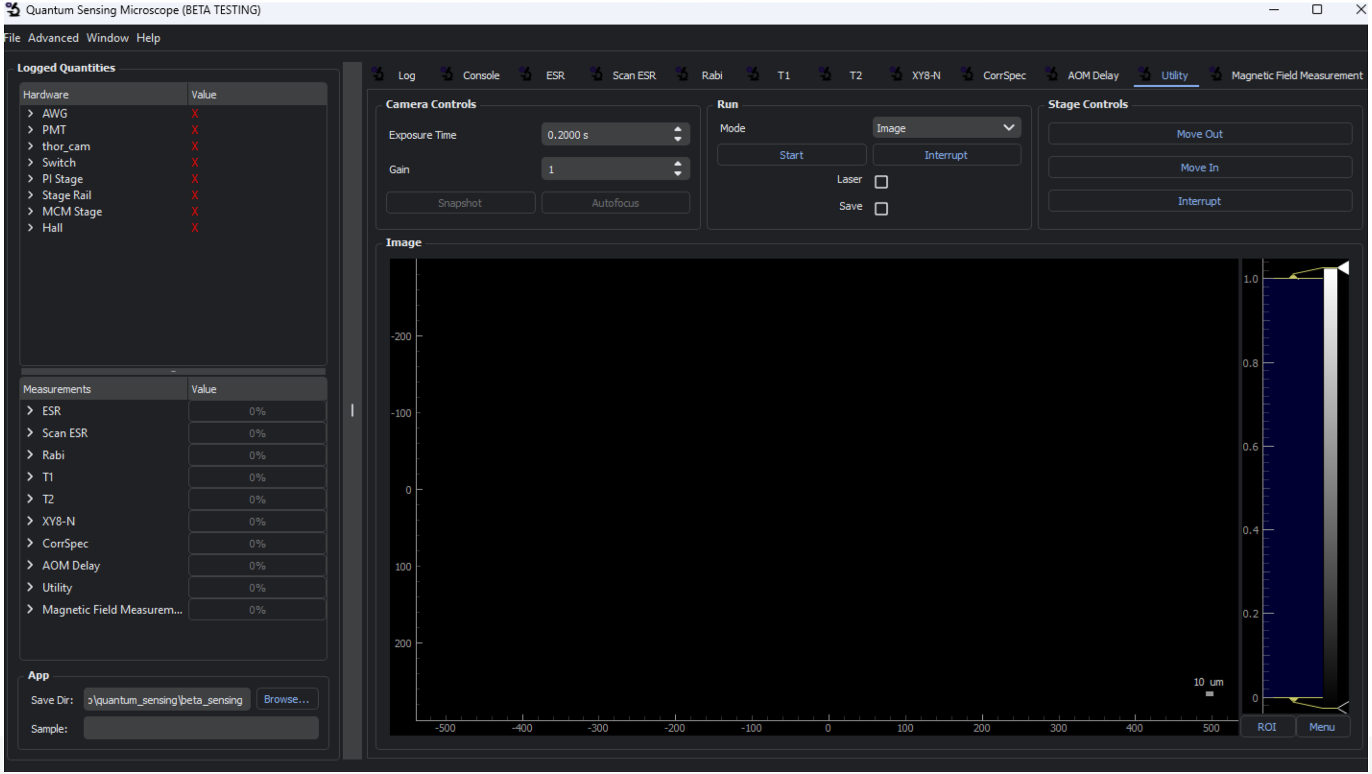
Highlight: Completed Magnetometry GUI



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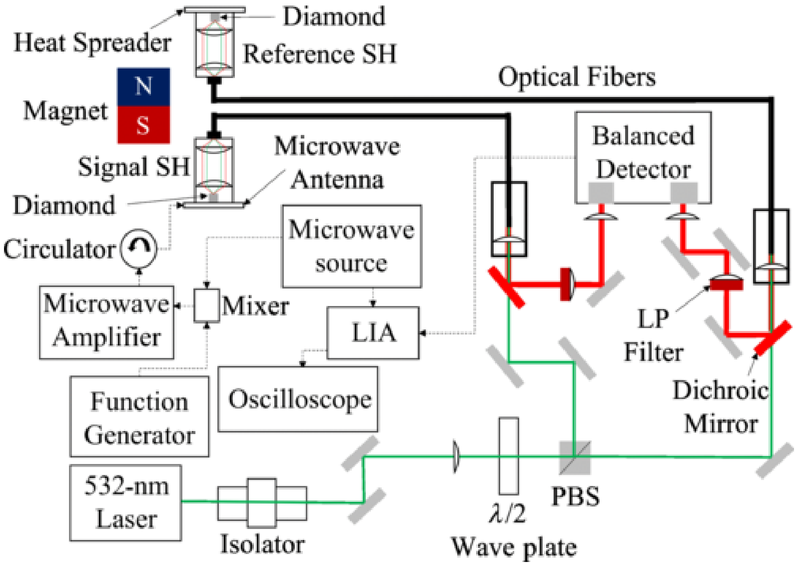
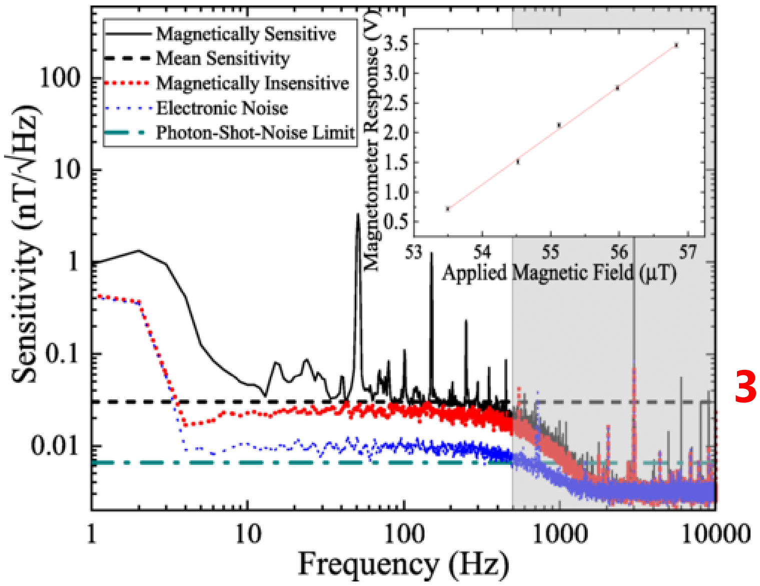
Inspiration from Recent Literature





30 pT

Graham, 2023

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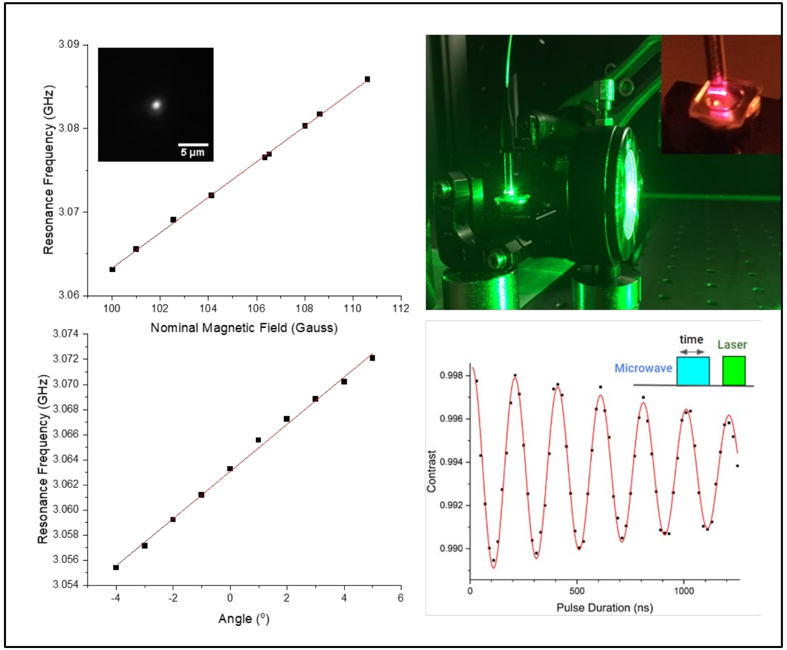
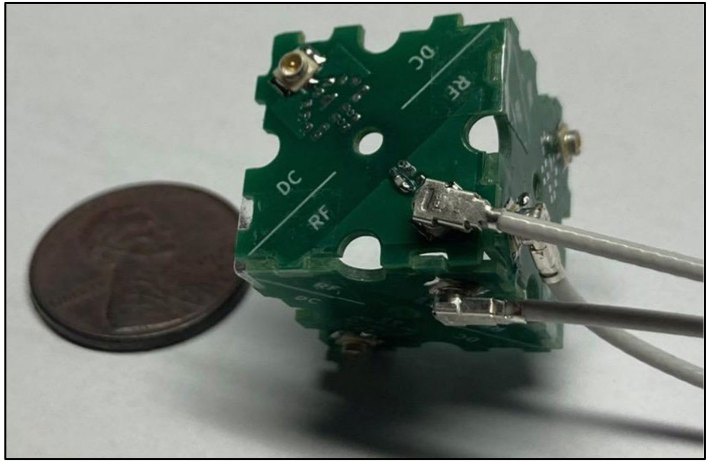
Future Research Plan A: Futher Reduction in Size



sub-picoTesla sensitivity



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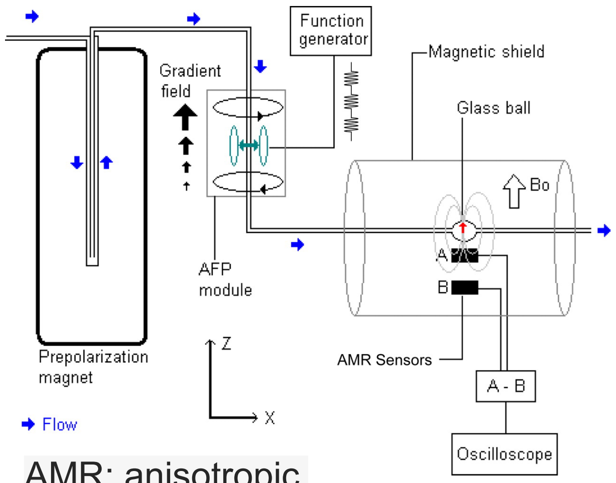
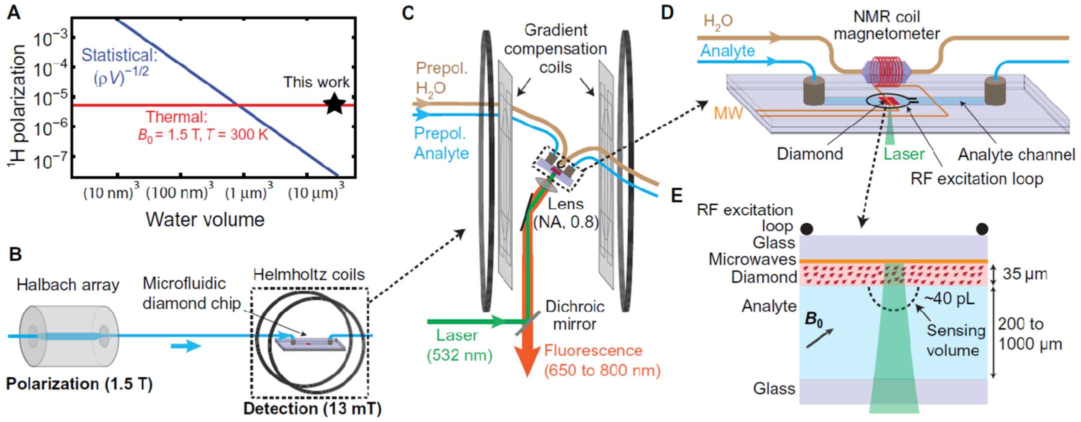
Future Plan B: Deployable and Remote MR Sensing



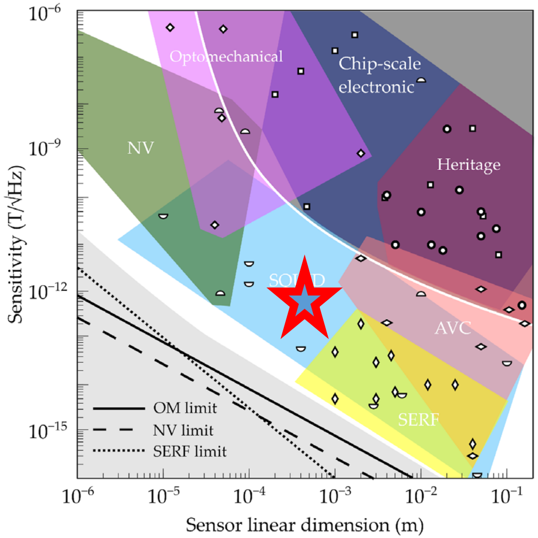
AMR: anisotropic magnetoresistive

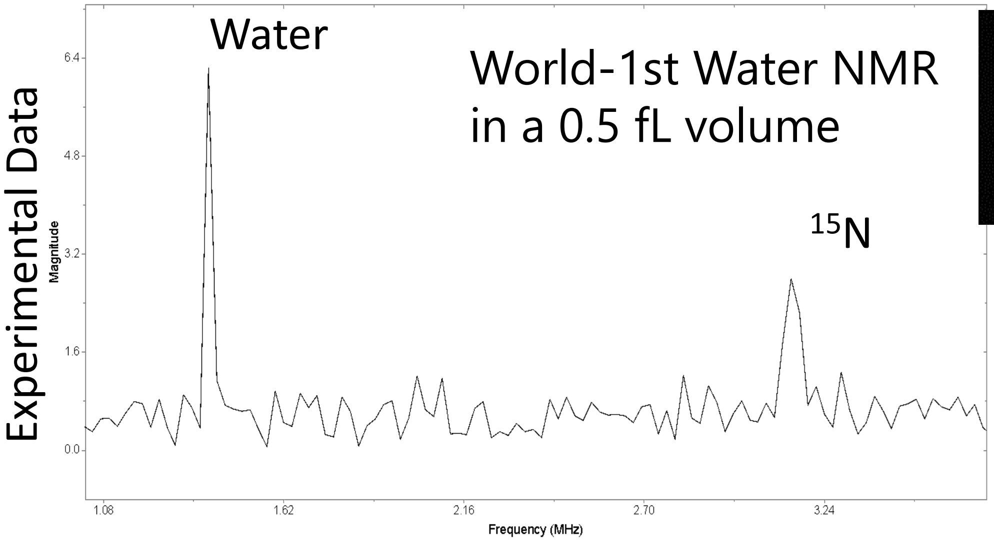
Verpillat, 2008

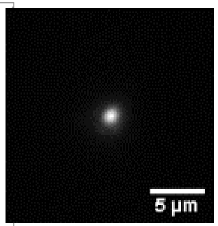


Smits, 2019

Lab Demonstration: Chemical MR Sensing Capabilities







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Conclusion

- **Expertise:** LBNL and WRT have extensive expertise in geophysical surveys, quantum sensing, and advanced electrical engineering.
- **Key Achievements:**
  - Achieved sub-pT sensitivity in laboratory settings.
  - Demonstrated nanometer-level sensitivity of confined water in nanotubes.
  - Developed a state-of-the-art magnetometer housed within a zero-field chamber (construction nearing completion).
- **Next Steps:**
  - Demonstrate dc/ac magnetic field sensitivity using a low-power diode laser.
  - Evaluate at low-field conditions equivalent to Earth's magnetic field.
  - Toward integration with UAV platforms.
- **Future Plan:** Explore remote MR applications for chemical detection

A preproposal submitted for FY26 SERDP Core Solicitation.

BACKUP MATERIAL

MR24-4533: Mapping Earth Field Anomalies with a Quantum Vector Magnetometer for Underwater UXO Detection

Performer: Zhao Hao, Lawrence Berkeley National Lab

Technology Focus

- *A state-of-the-art quantum vector magnetometer using NV-diamond for UXO detection.*

Research Objectives

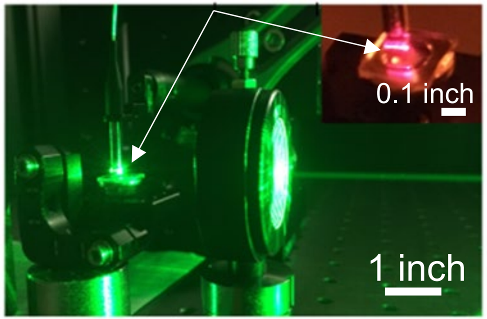
- *Develop a vector magnetometer with unprecedented sensitivity.*
- *Ensure low power consumption and compact design for UAV integration.*
- *Advance TRL from 4 to 6.*

Project Progress and Results

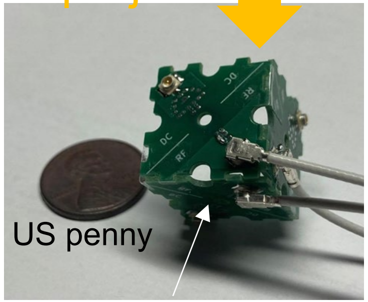
- *Procured high-performance NV-diamonds and shielding chamber.*
- *Demonstrated sub-picotesla sensitivity in the laboratory setting.*
- *Completed circuit-board package and optical fiber-based setup.*
- *Will collect performance data and finalize reports.*

Technology Transition

- *Further reduce cost and overall size for practical deployment.*
- *Additional funding required for field trials and technology transition.*



This project



Circuit boards for 3-axis vector magnetometer

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Plain Language Summary

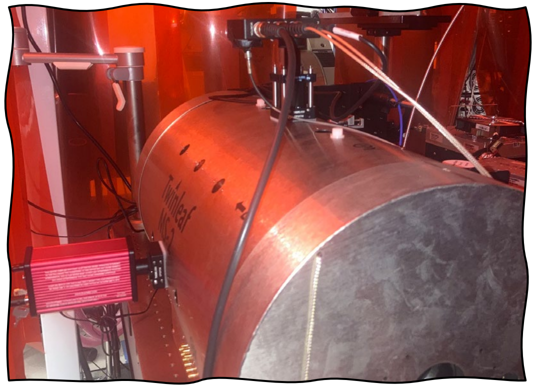
- Problems we are addressing
  - The difficulty of detecting underwater unexploded ordnance (UXO) safely and accurately.
  - Limitations of current magnetic sensing technologies in sensitivity, compactness, and/or power consumption for UAV deployment.
  - The need for more precise and scalable tools for UXO detection.
- What are you trying to achieve and how are you doing it?
  - Quantum sensing!!
  - Build a highly sensitive, portable, and energy-efficient magnetometer for UXO detection.

Plain Language Summary

- Expected Outcomes:
  - A magnetometer that can detect very weak magnetic signals (sub-picotesla sensitivity).
  - A portable and energy-efficient device that can easily be deployed with UAVs.
  - Real-world tests showing its ability to identify UXO with high accuracy.
- Advancing Knowledge:
  - This project uses cutting-edge quantum sensing to solve real-world problems.
  - It introduces new ways to amplify weak magnetic signals and reduce noise.
  - The work will help bridge the gap between lab research and practical field applications for UXO detection.

Impact to DoD Mission

- Current Progress
  - Successfully demonstrated nanometer-scale and sub-picotesla sensing capabilities.
  - Designed a flux concentrator to facilitate high sensitivity in a compact size.
  - Procured high-performance NV-diamonds and shielding chamber.
  - Completed circuit-board package and optical fiber-based setup.
  - Will collect performance data and finalize reports.



- Potential Impact in the Field
  - Breakthrough in state-of-the-art sensitivity.
  - Improved reliability by reducing and isolating noises.
  - Enables rapid deployment if integrating with UAV platforms.
- Broad impact to DOD mission
  - Versatile sensing capabilities including electromagnetic fields [1-4], chemical [5-7], and audio signals [8].
  - Portable low-power designs enable remote and autonomous UXO detection.

Publications

- Presentations
  - Young, et al., Coherent Control of Nitrogen Vacancy Centers in Diamond using Broadband Micro-coil Antennas, APS March meeting, 2025.
  - De Leon, et al., Coherent Control of Quantum Spin Sensors for Biogeochemical Imaging, APS CU*iP Conference, 2025
- One peer-reviewed publication in preparation.

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4. *Graham, S. M., Rahman, A. T. M. A., Munn, L., Patel, R. L., Newman, A. J., Stephen, C. J., ... & Morley, G. W. (2023). Fiber-coupled diamond magnetometry with an unshielded sensitivity of 30 pT/Hz. Physical Review Applied, 19(4), 044042.*
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6. *Smits, J., et al., Two-dimensional nuclear magnetic resonance spectroscopy with a microfluidic diamond quantum sensor. Science Advances, 2019.* ***5****(7).*
7. *Hao, Z., et al. Understanding Water Chemistry in a Submicron Scale Environment with Quantum Sensing. in Goldschmidt 2023 Conference. 2023. GOLDSCHMIDT.*
8. *Zhang, C., Dasari, D., Widmann, M., Meinel, J., Vorobyov, V., Kapitanova, P., Nenasheva, E., Nakamura, K., Sumiya, H., Onoda, S., Isoya, J., & Wrachtrup, J. (2022). Quantum-assisted distortion-free audio signal sensing. Nature Communications, 13(1).*