VIRGINIA TECH

Hyperfine Resolved Optical Pumping for Precision Magnetometry in Earth-scale Fields

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Virginia Tech NSI + ECE Dept.

DAMOP 2026

Providence, RI

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PHYSICAL REVIEW A **113**, 033102 (2026)

Probe-assisted depopulation pumping in low-pressure alkali-metal vapor cells for magnetometry

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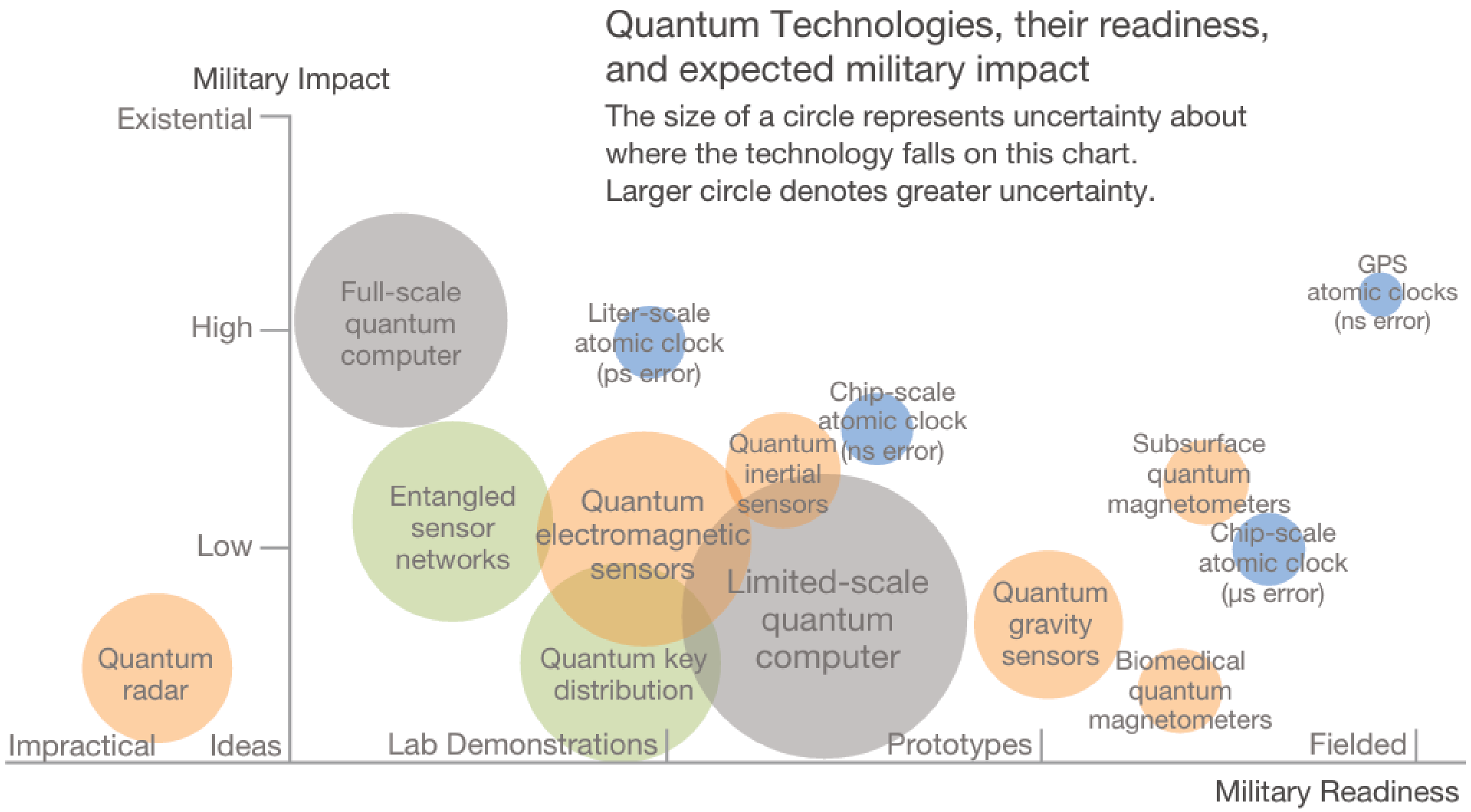
Quantum and the military

- “An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology”, Parker, et al., RAND 2022
- Nominally, this graph seems to be roughly the same in 2026, in the opinion of the OUSW(R&E)

FIGURE 1.1

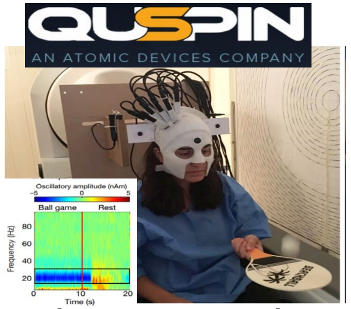
Summary of Military Readiness and Impact of Various Quantum Technologies

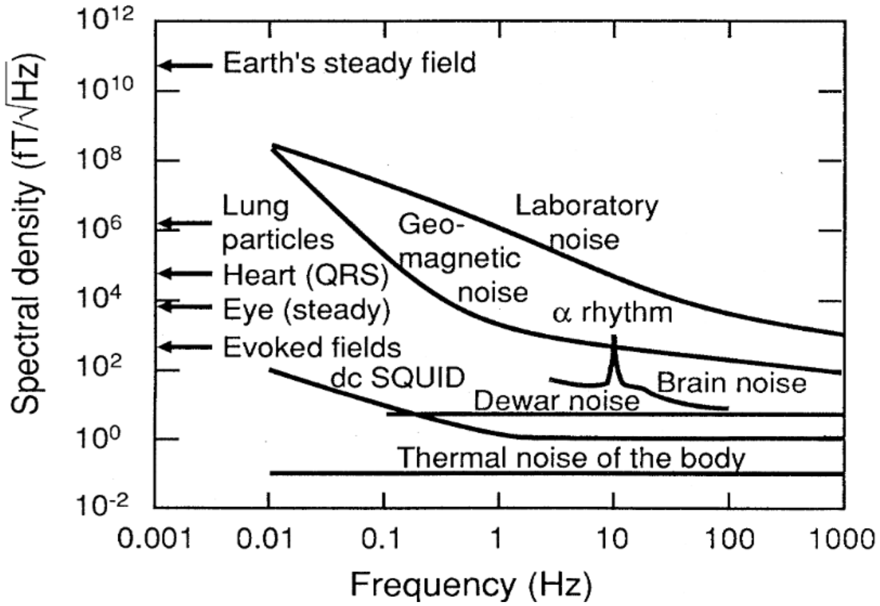


SOURCE: Provided to RAND by the Office of the Undersecretary of Defense for Research and Engineering.
NOTE: This chart updates a previous version published in the Fiscal Year 2020 Industrial Capabilities Report to Congress, 2021.

Atomic/Optical Magnetometry

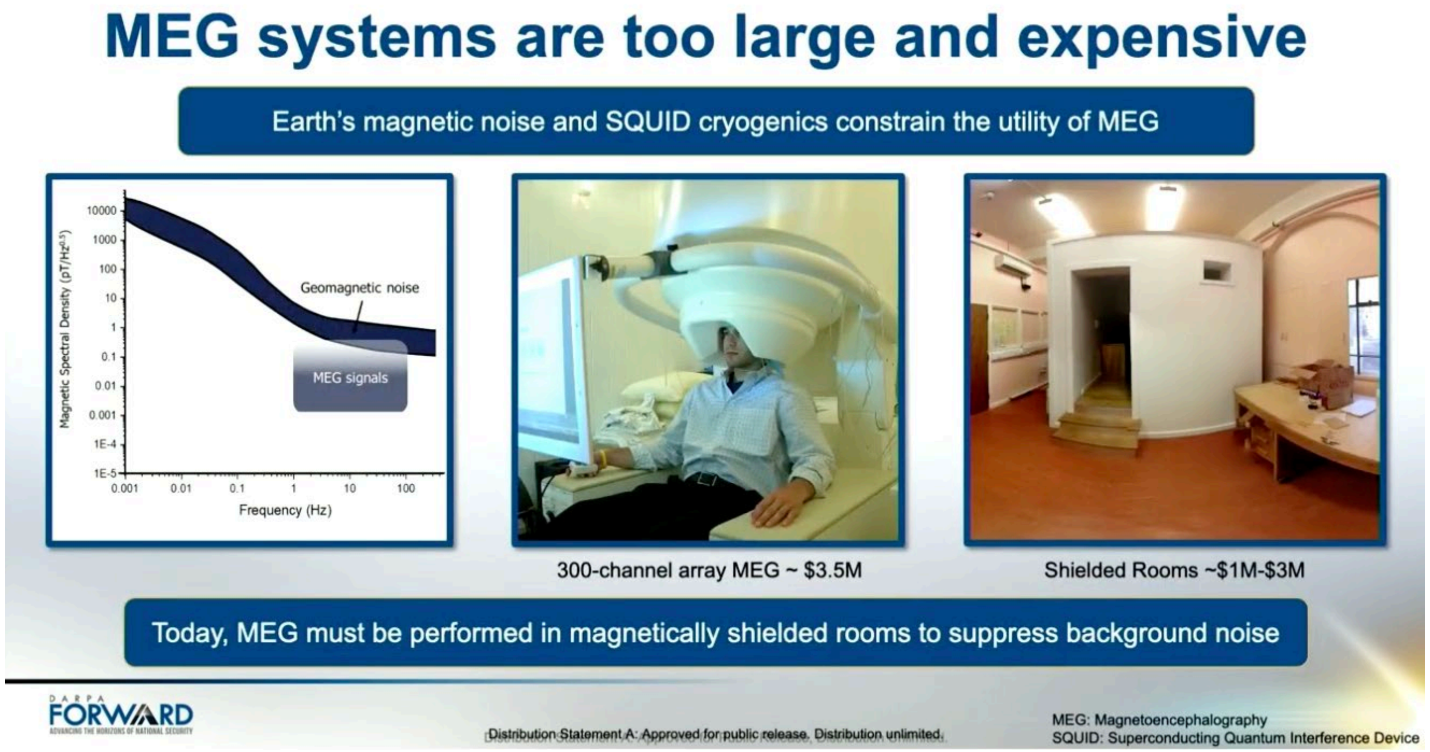
Near-zero field commercial sensors

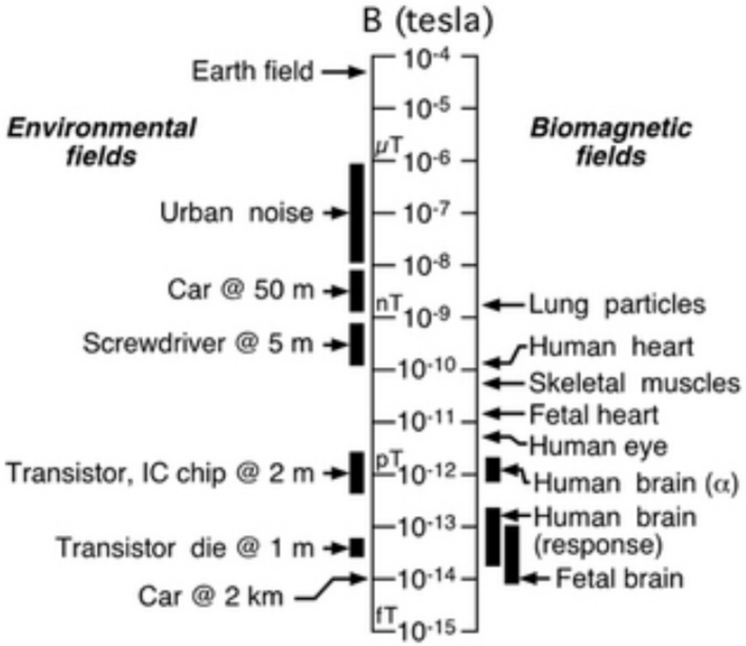




DARPA AMBIIENT : Can we push all-optical tech to obviate need for magnetic shielding and lower price point significantly

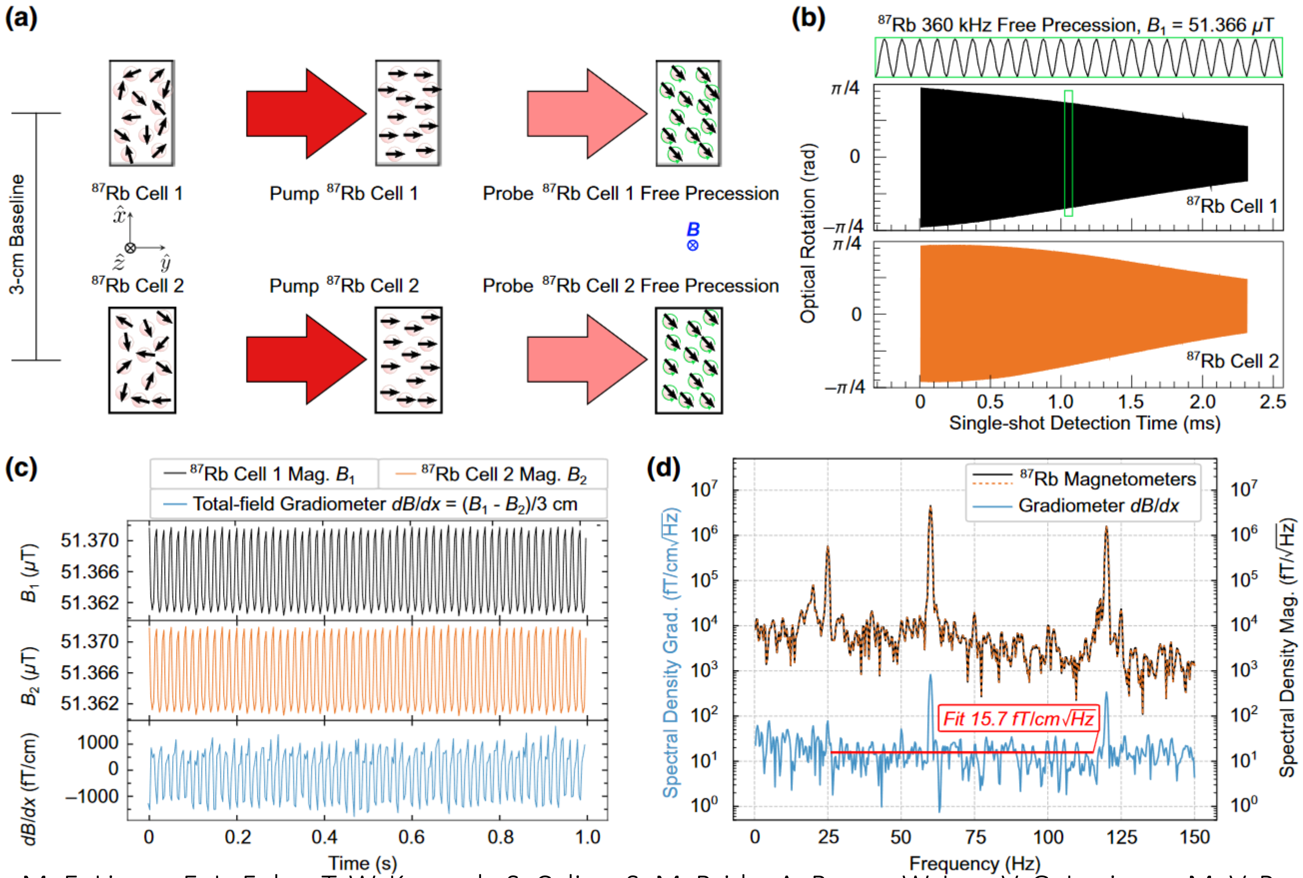
Magnetic brain noise at ~ 10-100 fT/rtHz

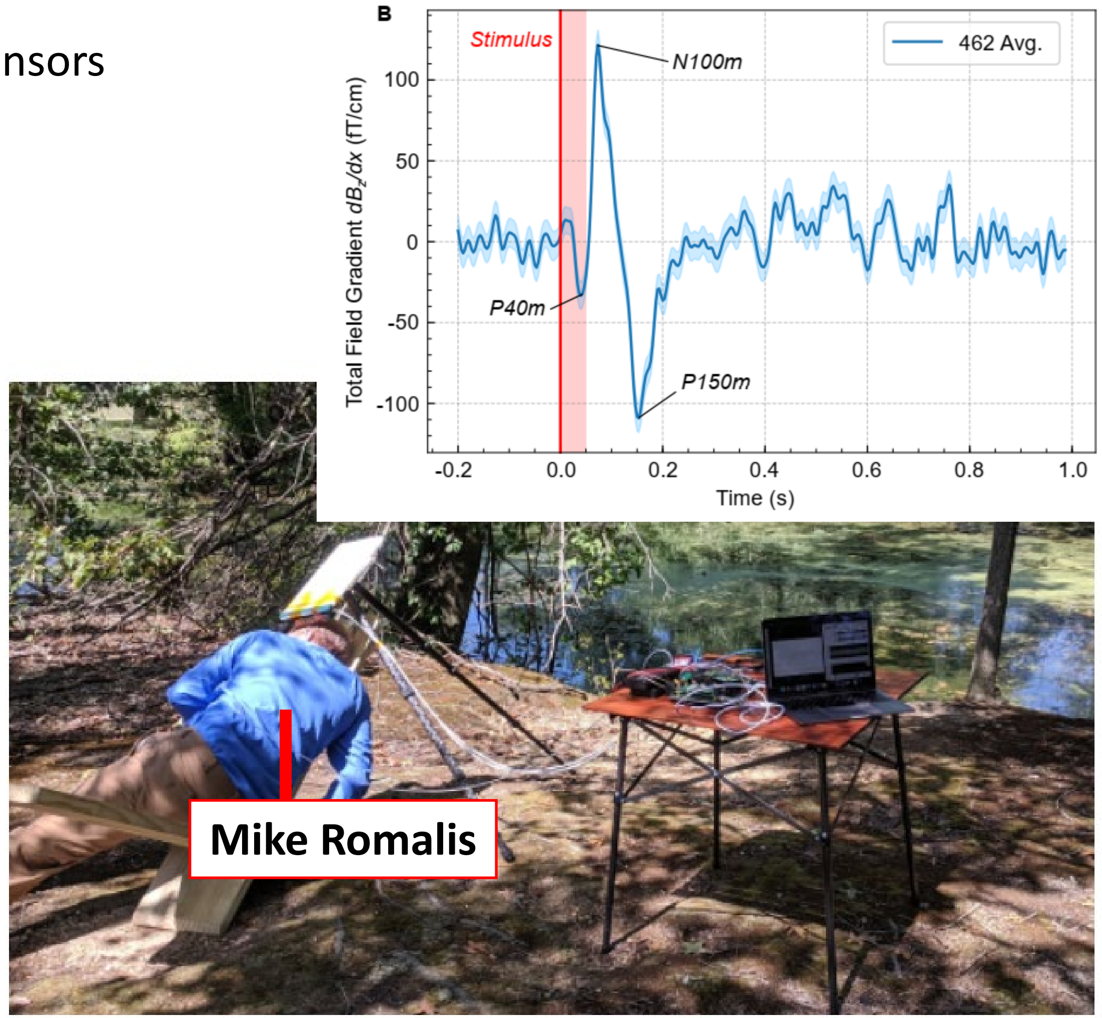




Earth's field magnetometry + In-the-field MEG

- Princeton University, SRI, and Twinleaf collab
- High dynamic range, high common mode rejection across sensors
- Scalar, free-precession atomic magnetometers using ^{87}Rb





M. E. Limes, E. L. Foley, T. W. Kornack, S. Caliga, S. McBride, A. Braun, W. Lee, V. G. Lucivero, M. V. Romalis, Phys. Rev. Applied 14, 011002 (2020)

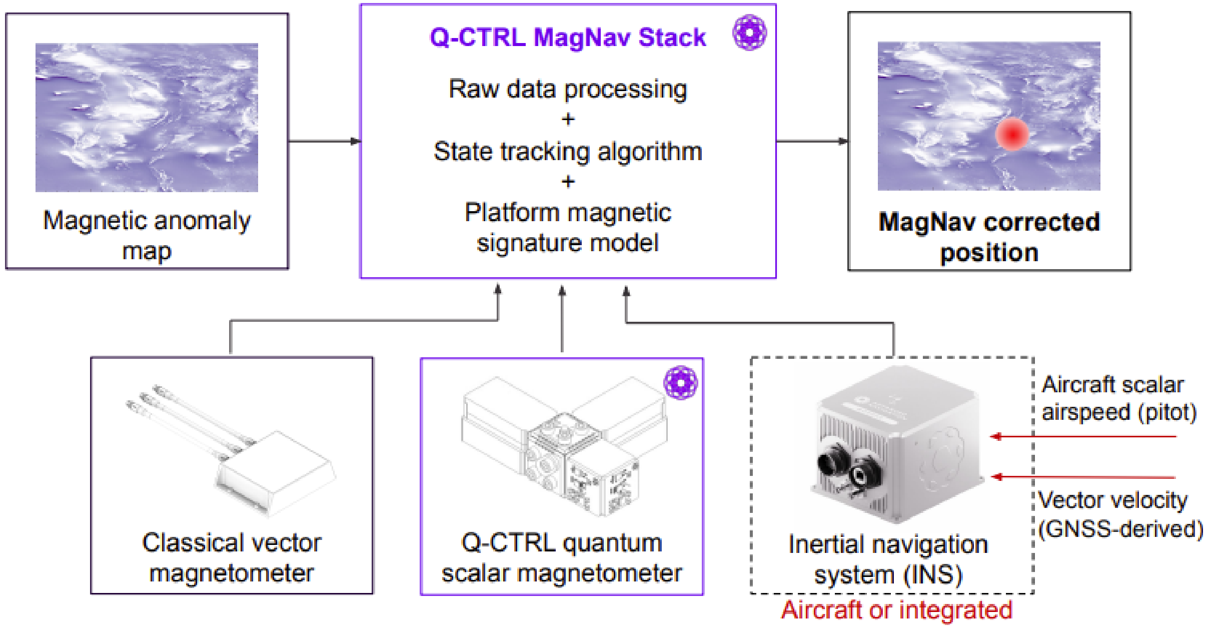
Supported by DARPA AMBIIENT

Lockheed Martin and Q-CTRL: Revolutionizing Navigation with Quantum Technology

AUGUST 27, 2025

Quantum-assured magnetic navigation achieves positioning accuracy better than a strategic-grade INS in airborne and ground-based field trials

Murat Muradoğlu, Mattias T. Johnsson, Nathanial M. Wilson, Yuval Cohen, Dongki Shin, Tomas Navickas, Tadas Pyragius, Divya Thomas, Daniel Thompson, Steven I. Moore, Md Tanvir Rahman, Adrian Walker, Indranil Dutta, Suraj Bijjahalli, Jacob Berlocher, Michael R. Hush, Russell P. Anderson, Stuart S. Szigeti, and Michael J. Biercuk
Q-CTRL, Sydney, NSW Australia



The Q-CTRL magnetometer sensor head achieves an absolute sensitivity of $<80\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ at Earth's field, with a bandwidth of 250 Hz. Each weighs approximately 70 g, has a volume of 144 cm^3, and consumes less than 15 W of power (limited by current electronics). These magnetometers have undergone laboratory vibration tests to 5.7g, and have been validated to provide a stable output in the operational range of $[-30, 50]$°C.

Magnetometer
80 fT/rtHz
BW 250 Hz
144 cc…
15 W, 70 g

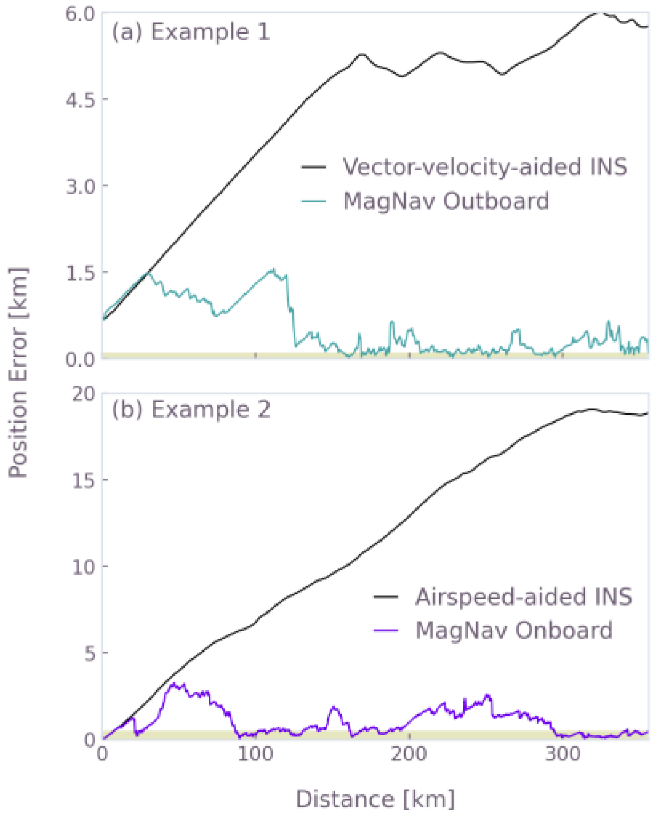
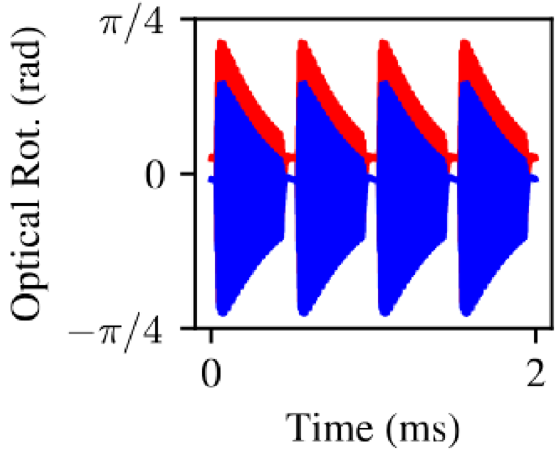


FIG. 4. Demonstration of quantum MagNav achieving a better bounded positioning accuracy when compared against different INS configurations for different flights at 3600 feet altitude, following the approximate trajectory illustrated in Fig. 3a. Note that these data are examples only and do not constitute a head-to-head comparison under identical conditions. (a) Comparison of positioning error using a vector-velocity-aided INS and the Q-CTRL MagNav system. Outboard externally-mounted quantum magnetometers in use. Shaded horizontal band represents 100m accuracy. Relative advantage over the INS at the conclusion of the flight is ∼46×. (b) Similar comparison using onboard quantum magnetometer and comparison against INS aided by scalar airspeed. Shaded band represents 500m accuracy. Relative advantage over the INS at the conclusion of the flight is ∼34×.

Gradient Tolerance

Through Cramer-Rao, optimal sensitivity goes as coherence time T_2

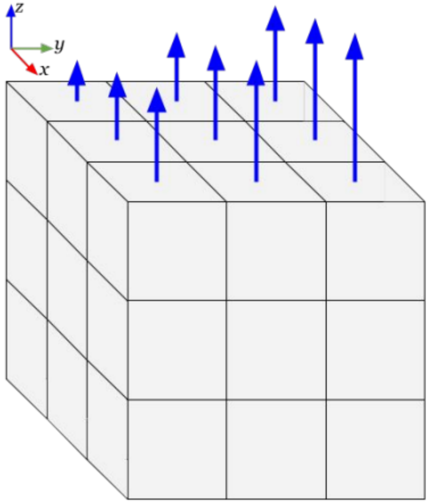
$$\delta B = \frac{\sqrt{12C}}{2\,\pi\gamma \mathrm{SNR}\, T^{3/2}\sqrt{\mathrm{BW}}} \left[\frac{\mathrm{T}}{\sqrt{\mathrm{Hz}}}\right]$$

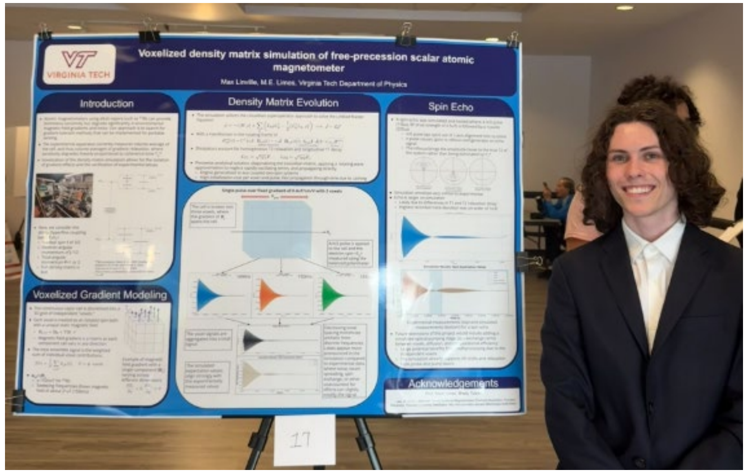


With integration time T (optimal sensitivity for $T \approx 2T_2$),

sensor bandwidth $BW = 1/2T_{rep}$

Gradient relaxation can be significant, through reduction in T_2^* (~proportional loss in optimal sensitivity)

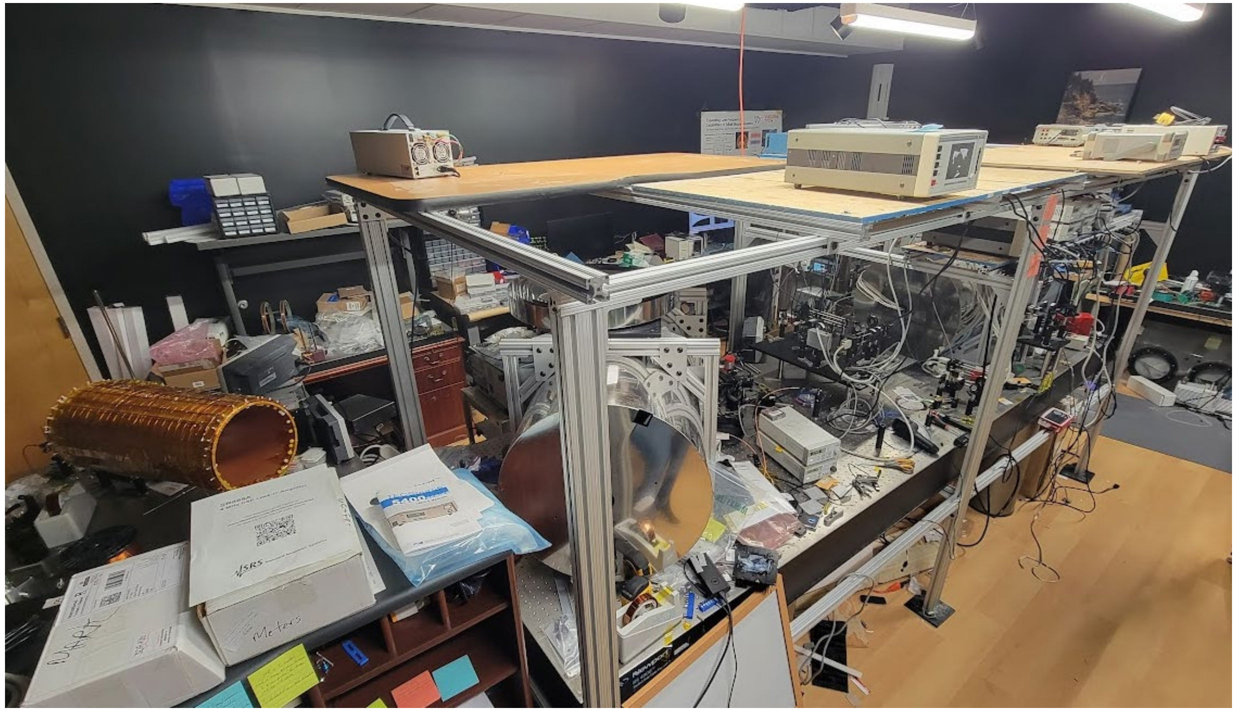




Senior undergrad project, Voxelized density matrix sim of ^{87}Rb to accommodate gradients

Limes Atomic Physics Lab @ Virginia Tech

- Building since July 2024; currently focused on ^{87}Rb, also building up $^{4}He/^{3}He$ MEOP and Cs setups



Hyperfine-resolved Optical Pumping

M. E. Limes, J. Smoot, J. Perez, J. Freeman, C. Amano-Dolan, D. Peters, W. Lee, Phys. Rev. A 113, 033102 (2026)

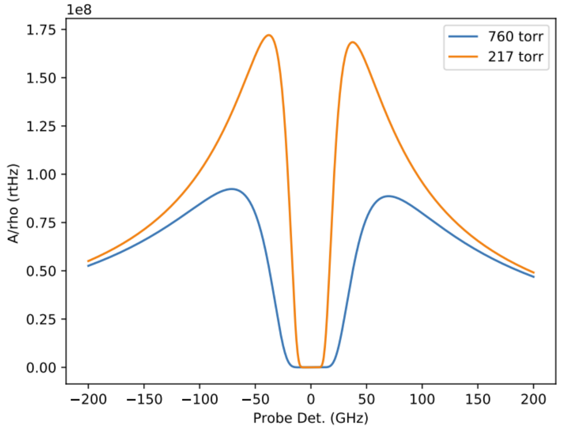
- For precision magnetometry, typically buffer gas pressure, used for non-radiative quenching and slowing diffusion, significantly broadens hyperfine manifolds

- Lowering buffer gas results in higher optical rotation

Lorentzian in High-pressure limit

$$\phi = l\, r_e c f\, n\, P_x\, \mathrm{Im}[V(\nu/2)] = \frac{1}{2} l r_e c f n P_x \frac{\Delta\nu}{\Delta\nu^2 + (\Gamma_L/2)^2}$$

Where V is a Voigt profile



$$\phi_{\mathrm{opt}} \propto \frac{1}{\Gamma_L}, D_1 \text{ full width is} \sim 17.8\ \frac{\mathrm{GHz}}{\mathrm{amg}} \text{ for } \mathrm{N_2}$$

Romalis, Miron, Cates, PRA, DOI:10.1103/PhysRevA.56.4569

Hyperfine-resolved Optical Pumping

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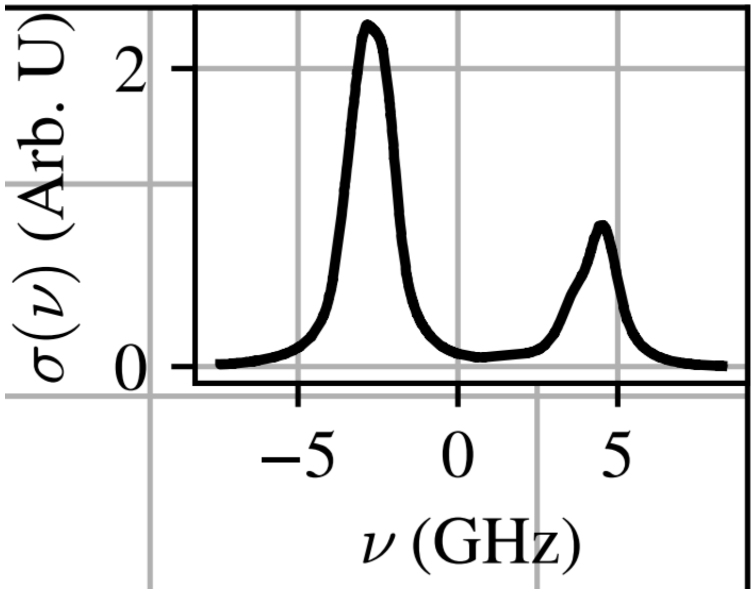
- Lowering buffer gas results in higher optical rotation at low pressures as well

$$\phi = l\, r_e c f\ n\, P_x\ \mathrm{Im}[V(\nu/2)]$$

Can we get high sensitivity with very low buffer gas, where hyperfine manifold is resolved?

Here, we consider at ~ 20 torr buffer gas regime, with wall diffusion relaxation comparable to probe broadening

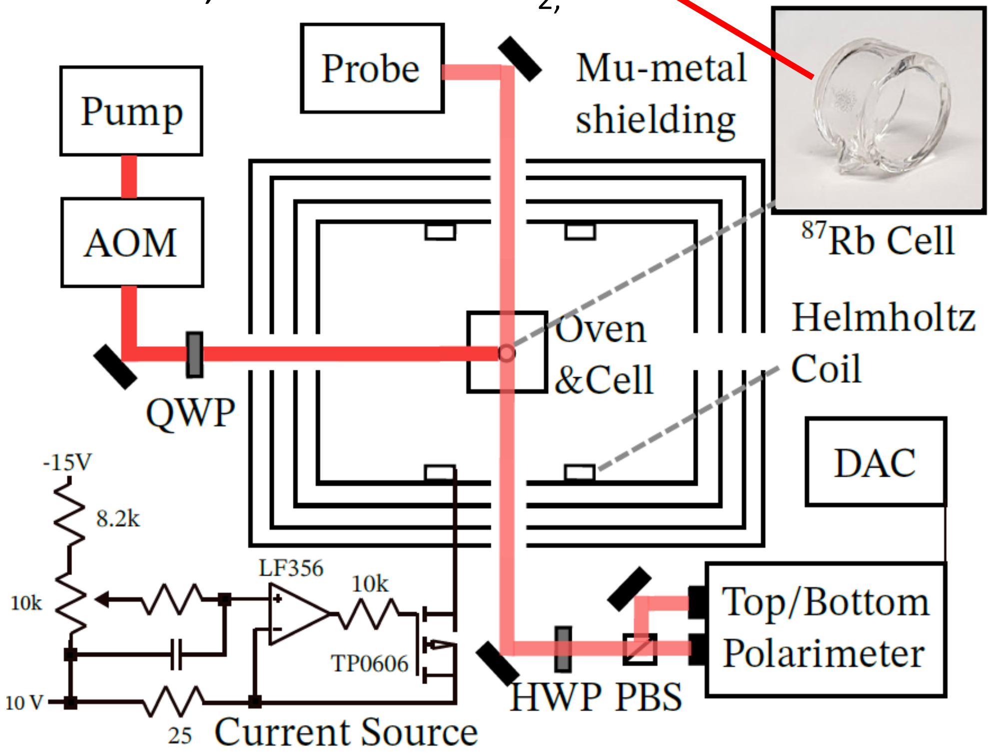


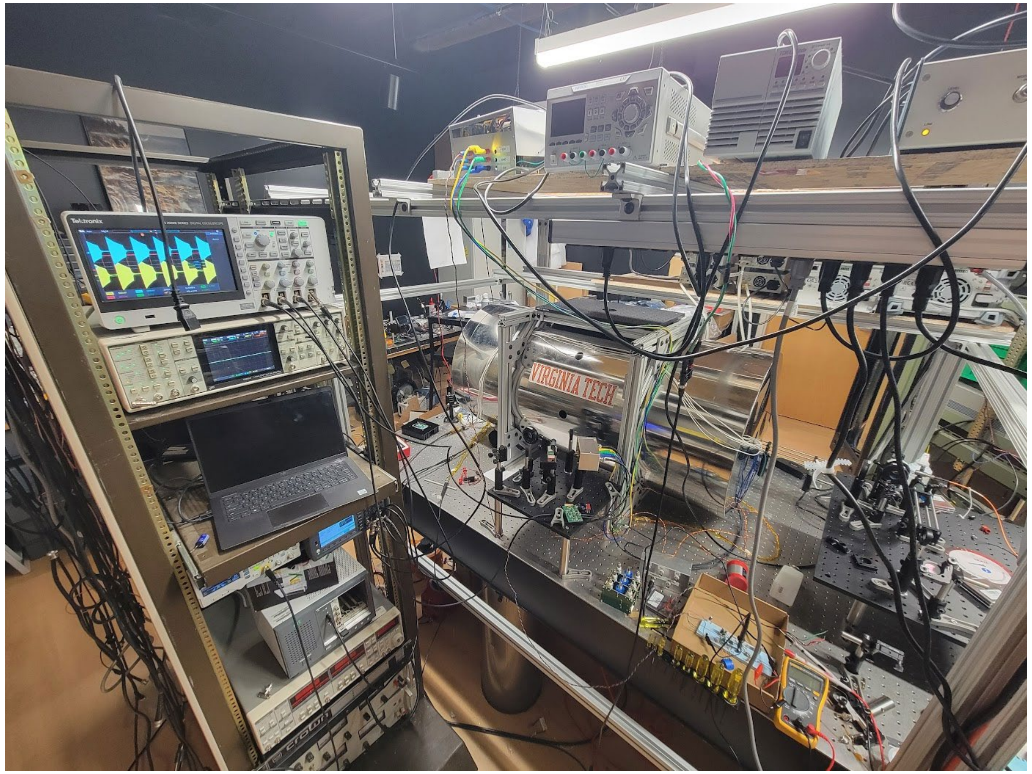
Experimental set-up

M. E. Limes, J. Smoot, J. Perez, J. Freeman, C. Amano-Dolan, D. Peters, W. Lee, Phys. Rev. A 113, 033102 (2026)

Cell: 6 mm width, 10 mm diameter
0.47 cc, 25 Torr 3:2 Ar:N_2, ^{87}Rb

1) Pump along Earth-scale field, 2) shut off pump, tip spins with $\pi/2$ pulse,
3) watch free precession with linearly polarized detuned probe

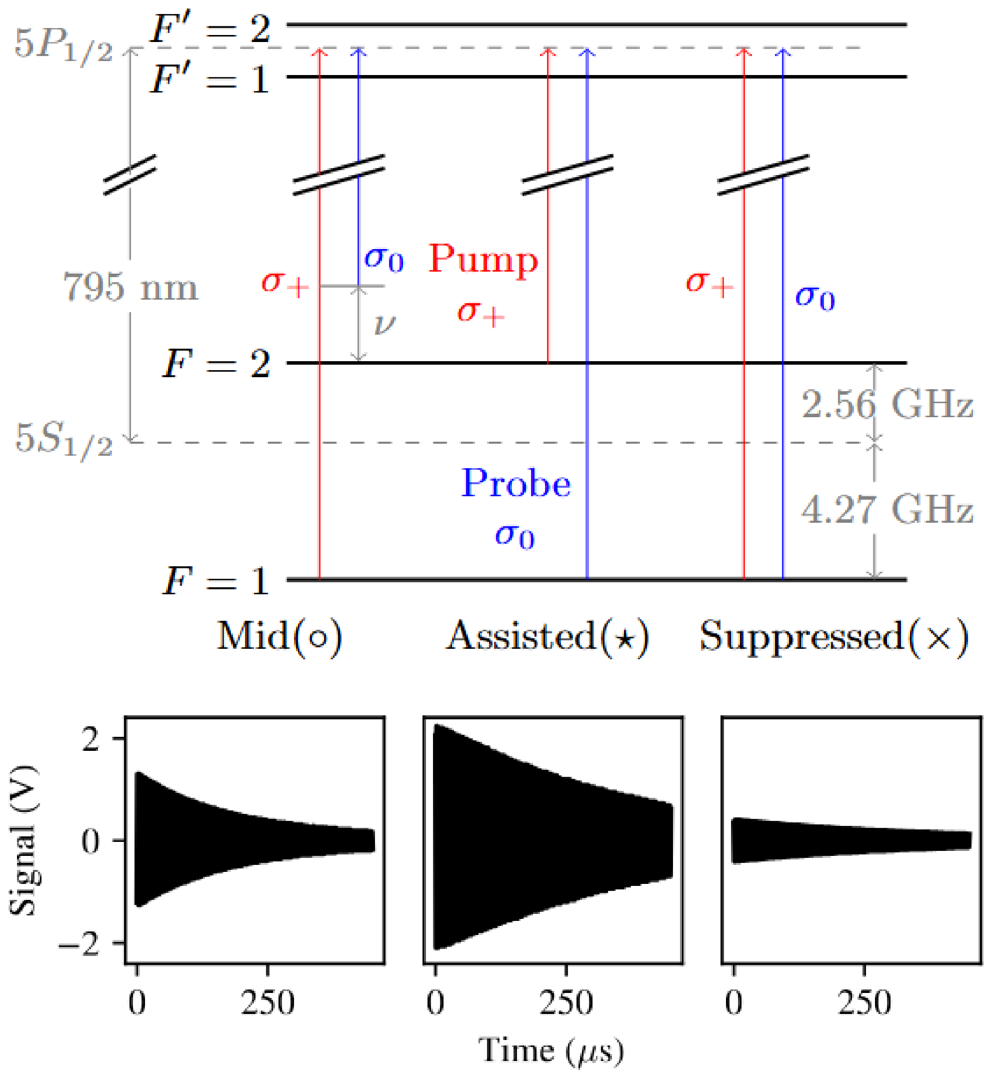




Photodigm DBR Pump & Probe, custom two-channel balanced polarimeter, and NI-5922 DAC

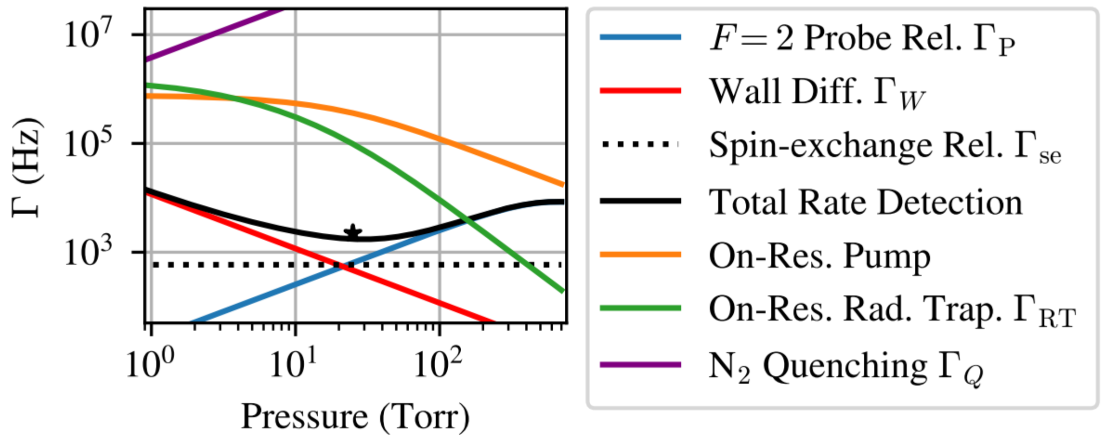
Probe-Assisted Depopulation Pumping

M. E. Limes, J. Smoot, J. Perez, J. Freeman, C. Amano-Dolan, D. Peters, W. Lee, Phys. Rev. A 113, 033102 (2026)



- At low pressures, address F=2 and F=1 separately with narrow linewidth light
- Can tune probe to deplete F=1 and pump F=2

- Wall relaxation and probe-broadening limited



Probe-Assisted Depopulation Pumping

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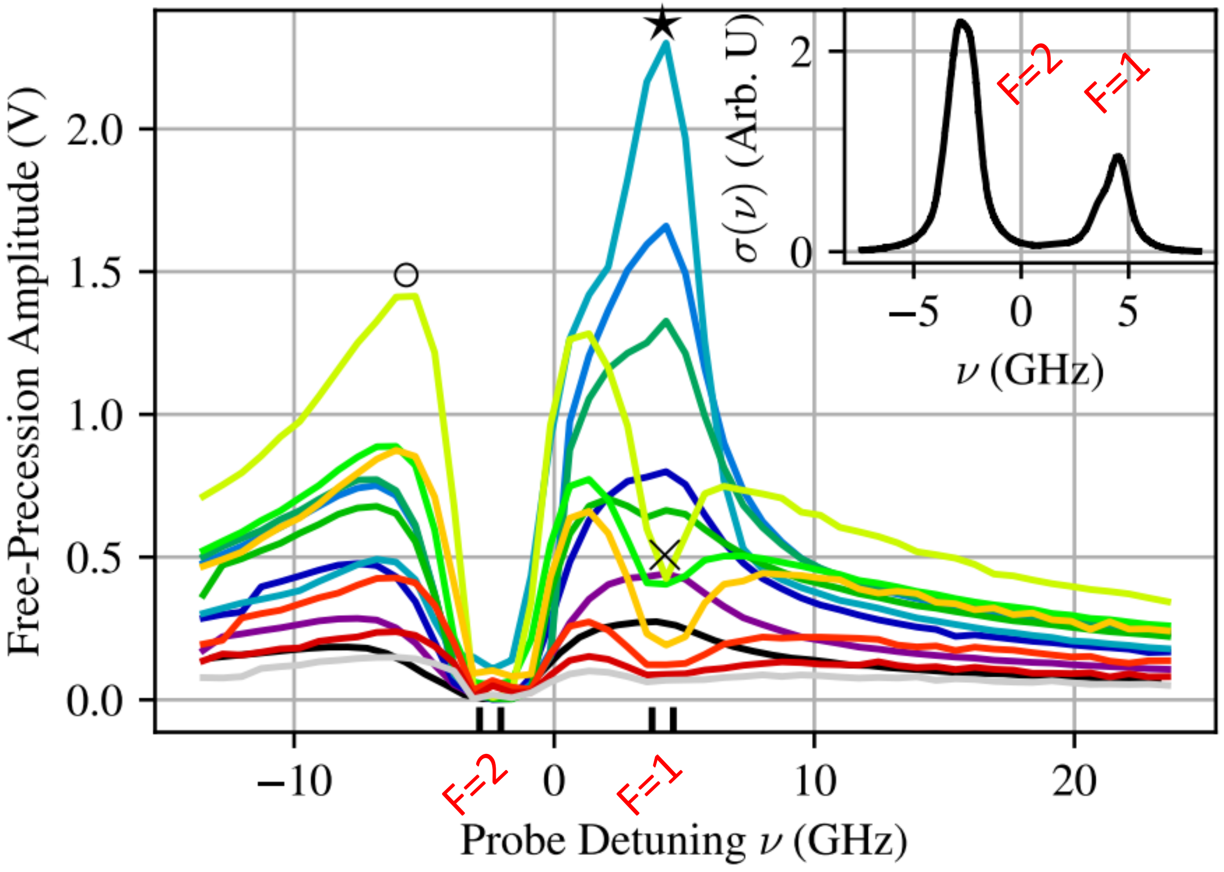
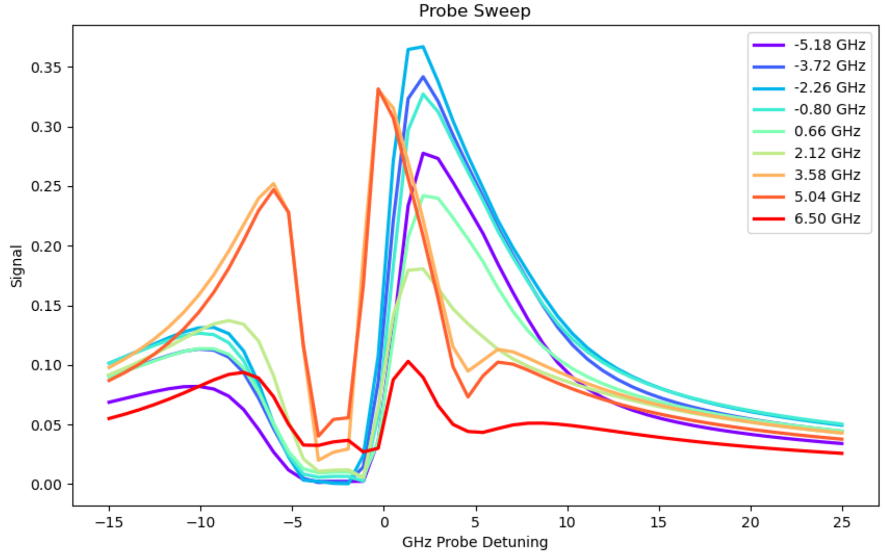
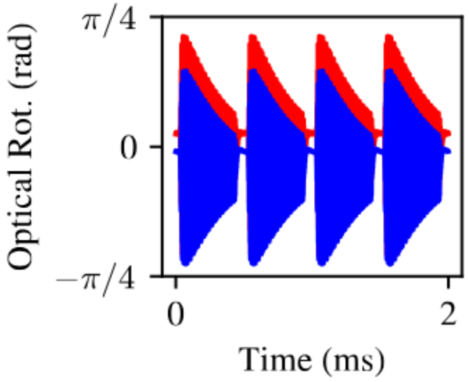


- 5 – 10 mW pump and probe , varying wavelength detuning
- Density matrix Simulations (developed by Brady Talbert) nominally exhibits low-pressure behavior, and indicates pump light starved

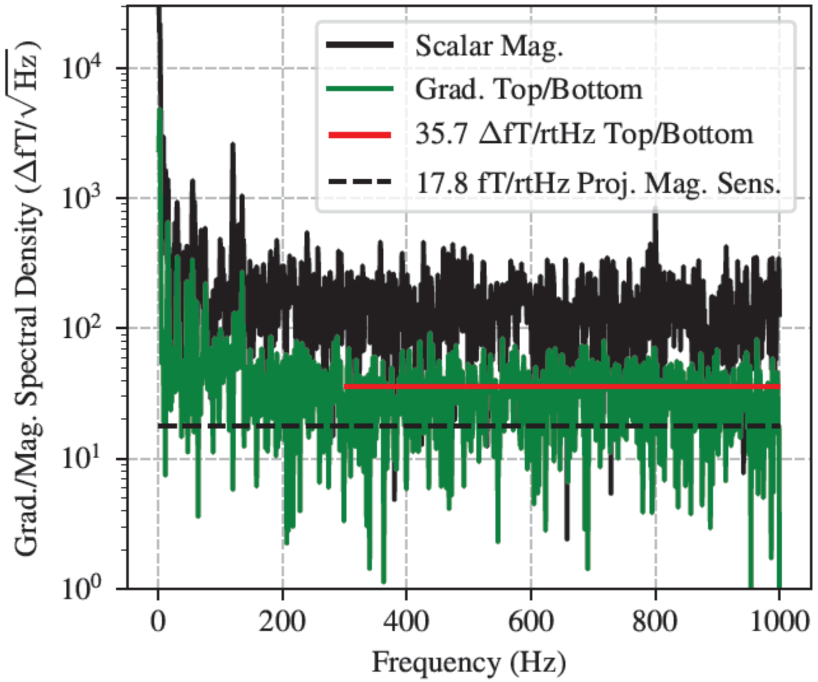


Low Pressure Magnetometer Sensitivity

M. E. Limes, J. Smoot, J. Perez, J. Freeman, C. Amano-Dolan, D. Peters, W. Lee, Phys. Rev. A 113, 033102 (2026)

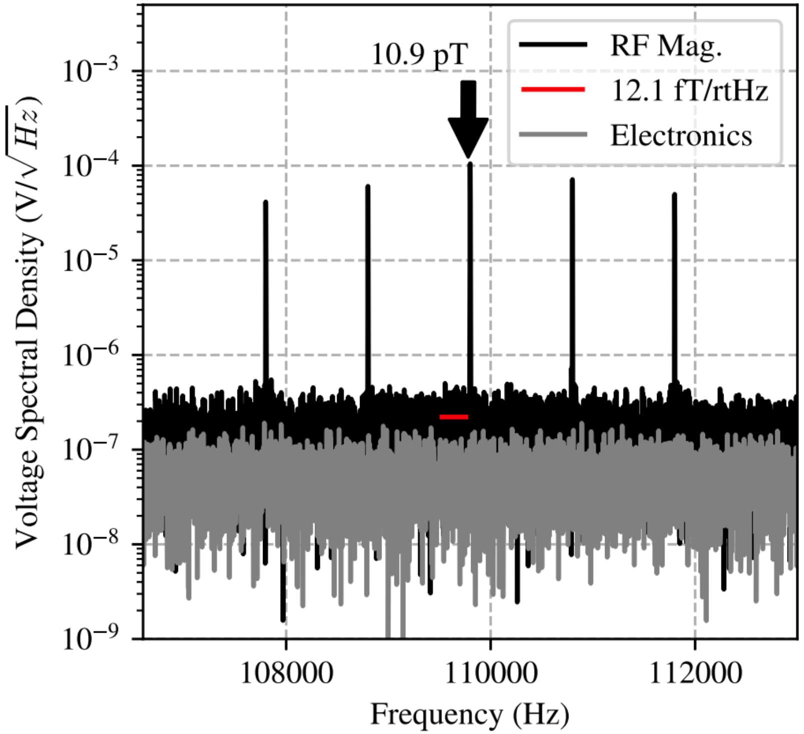


Single pass, ^{87}Rb pulsed pump and probe with 6 mm path length



Earth's field data @ 45 µT

Scalar mode



RF Mag. Data at 110 kHz

RF mode

Gradient Tolerance

- Data projects clinically relevant, single-pass, two-cell gradiometer with short baseline of <10 fT/cm Hz$^{1/2}$

- Short interrogation time -> Higher bandwidth and Higher gradients across cell

$$\frac{dB}{dz} = \frac{\Delta\phi}{\gamma LT}$$

With $\Delta\phi$ phase spread, γ is gyromagnetic ratio, and L is the size of cell across z

For example: signal height loss of $sinc(\Delta\phi) = \frac{1}{e}$ results from 160 nT/cm over 0.4 ms

Acknowledgements

- Currently looking at effect of light shifts and higher light powers in low pressure cells, gradients, diffusion, and spin-temperature distributions
- Poster #38 Tues. session: B. Talbert *"Light Shifts in Free-Precession Alkali Magnetometry at Earth-Scale Fields"*

- Thanks!
- Group: Grad Students: Brady Talbert (Physics)

  Julia Rodrigues (ECE) (*in Aug.*)

  Alexander Burkholder (ECE) (*in Aug.*)

  Undergrads: Jeb Smoot (Physics),

  Max Linville (Physics/ECE)