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Unshielded Operation of a Miniaturized Radiofrequency Magnetometer in Earth's Field

LDRD

CQuIC
Center for Quantum Information and Control

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I: Introduction

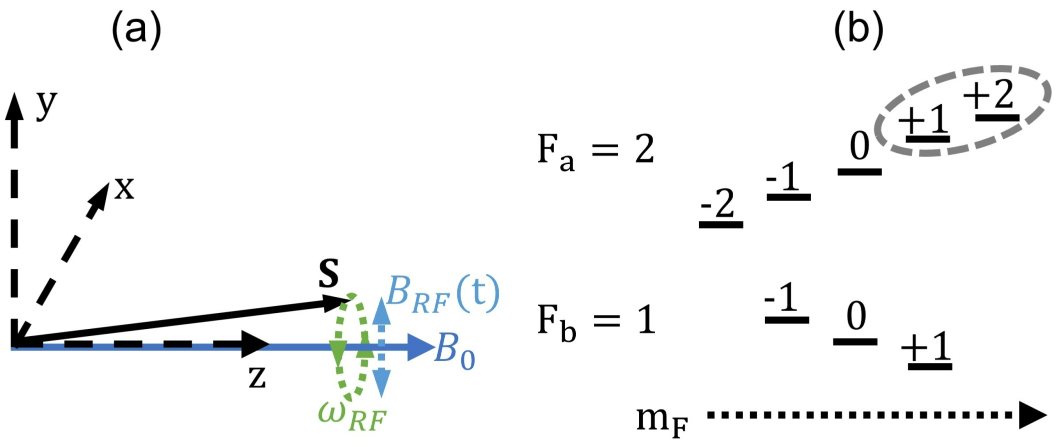
Motivation: Unshielded Radiofrequency (RF) Sensing

Many potential applications for high sensitivity RF sensing in very low frequency (VLF) and low frequency (LF) ranges:

- Remote sensing
  - A. N. Garroway, M. L. Buess, J. B. Miller, B. H. Suits, A. D. Hibb, G. A. Barrall, R. Matthews, and L. J. Burnett,Remote sensing by nuclear quadrupole resonance (2001).
  - C. Deans, L. Marmugi, and F. Renzoni, Active underwater detection with an array of atomic magnetometers, Appl. Opt. 57, 2346 (2018).
- Electromagnetic induction imaging and defect imaging
  - A. Wickenbrock, F. Tricot, and F. Renzoni, Magnetic induction measurements using an all-optical 87rb atomic magnetometer, Applied Physics Letters 103, 243503 (2013), https://doi.org/10.1063/1.4848196.
  - A. Wickenbrock, S. Jurgilas, A. Dow, L. Marmugi, and F. Renzoni, Magnetic induction tomography using an alloptical 87rb atomic magnetometer, Opt. Lett. 39, 6367 (2014).
  - A. Wickenbrock, N. Leefer, J. W. Blanchard, and D. Budker, Eddy current imaging with an atomic radiofrequency magnetometer, Applied Physics Letters 108,183507 (2016), https://doi.org/10.1063/1.4948534
  - C. Deans, L. Marmugi, S. Hussain, and F. Renzoni, Electromagnetic induction imaging with a radio-frequency atomic magnetometer, Applied Physics Letters 108,103503 (2016), https://doi.org/10.1063/1.4943659.
  - P. Bevington, R. Gartman, and W. Chalupczak, Enhanced material defect imaging with a radio-frequency atomic magnetometer, Journal of Applied Physics 125, 094503 (2019), https://doi.org/10.1063/1.5083039.
  - C. Deans, Y. Cohen, H. Yao, B. Maddox, A. Vigilante,and F. Renzoni, Electromagnetic induction imaging with a scanning radio frequency atomic magnetometer, Applied Physics Letters 119, 014001 (2021), https://doi.org/10.1063/5.0056876.

Radiofrequency (RF) magnetometry.

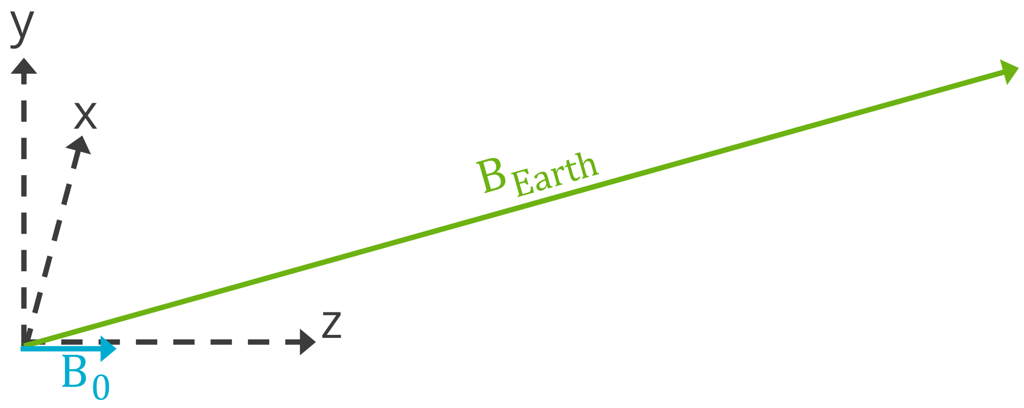
- Method from I. M. Savukov, S. J. Seltzer, M. V. Romalis, and K. L. Sauer, Tunable atomic magnetometer for detection of radio-frequency magnetic fields, Phys. Rev. Lett. 95, 063004 (2005).
- Bias field $\mathbf{B}_0 = \frac{2\pi}{\gamma} f_{RF}$ applied along longitudinal (z) axis.
  - γ is gyromagnetic ratio.
  - f_{RF} is RF sensing frequency.
- Atomic spin $\mathbf{S}$ polarized along longitudinal axis by optical pumping.
- RF field polarized in transverse (xy) plane causes resonant Larmor precession of atomic spin at $\omega_{RF} = 2\pi f_{RF}$.



Above: Dynamics of an RF optically pumped magnetometer (OPM). (a) Atomic spin $\mathbf{S}$ polarized along z axis via optical pumping. RF field causes resonant Larmor precession. (b) Hyperfine level diagram of an $I = \frac{3}{2}$ alkali species with resonant transition highlighted.

The Problem of Unshielded Operation

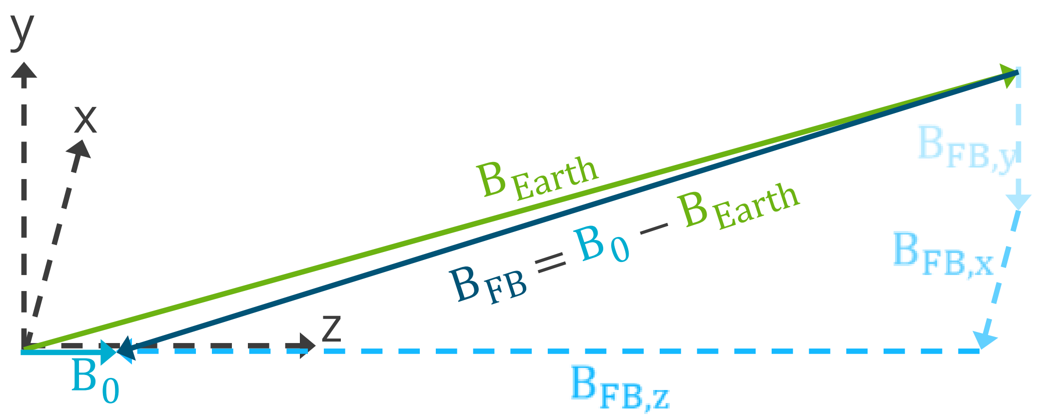
- Low frequency field must be maintained such that $\mathbf{B} \approx B_0 \mathbf{e}_z$.
- For $f_{RF} = 300$ kHz in ^{87}Rb, $\gamma = 7$ Hz/nT , $B_0 \approx 43$ μT.
- $B_{Earth} \approx 25 - 65$ μT
- $B_0 \sim B_{Earth}$ on the high end. $B_{Earth} \gg B_0$ for sensing at lower frequencies!
- Need method to cancel B_{Earth} and hold B_0 at the correct magnitude and direction to implement an RF magnetometer.



Above: Problem of unshielded operation. Earth's magnetic field is typically much larger than the required bias field, and not generally in the correct direction. Something must be done to control external fields, establish the correct bias for RF sensing.

The Solution: Another Magnetometer

- Need another magnetometer! Use to provide feedback that can cancel out external field
  - Must be vector magnetometer, provide signals for three independent directions.
  - Must operate in Earth's field.
- Set of control coils provides feedback to cancel external fields.
  - Easily controlled by applied voltage.
  - Proportional-integral-differential (PID) servo to derive feedback voltages.
- Either another OPM or different type (e.g. fluxgate).



Above: The solution-apply feedback via control coils to cancel external Earth's field.

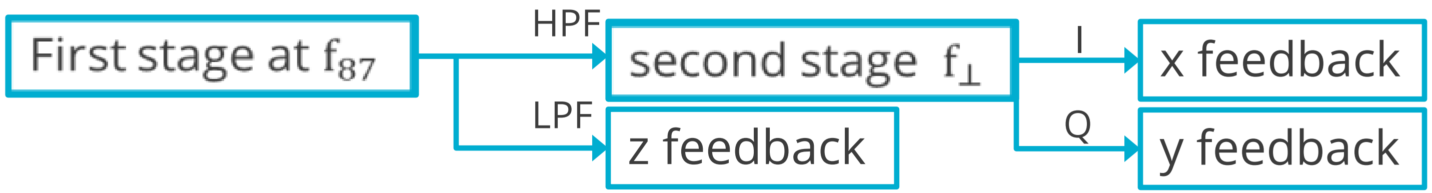
II: Our Platform

Potential of Duel Isotopes for Comagnetometry

- Natural Rb has 72.2% ^{85}Rb and 27.8% ^{87}Rb.
  - ^{85}Rb has nuclear spin 5/2, ^{87}Rb has nuclear spin 3/2.
- Ratio of gyromagnetic ratios : $\frac{\gamma_{85}}{\gamma_{87}} = \frac{\frac{\gamma_e}{2(\frac{5}{2}+1)}}{\frac{\gamma_e}{2(\frac{3}{2}+1)}} = \frac{3}{2}$.
  - Isotopic responses are separated in frequency at sufficient bias field.
  - γ_e : gyromagnetic ratio of bare electron.
- Can use the extra isotope for our 2nd magnetometer. We use ^{85}Rb for RF sensing due to higher fraction. ^{87}Rb is used for feedback magnetometer.
  - Both responses in the *same* signal, from the *same* lasers. Just need filtering to discriminate.

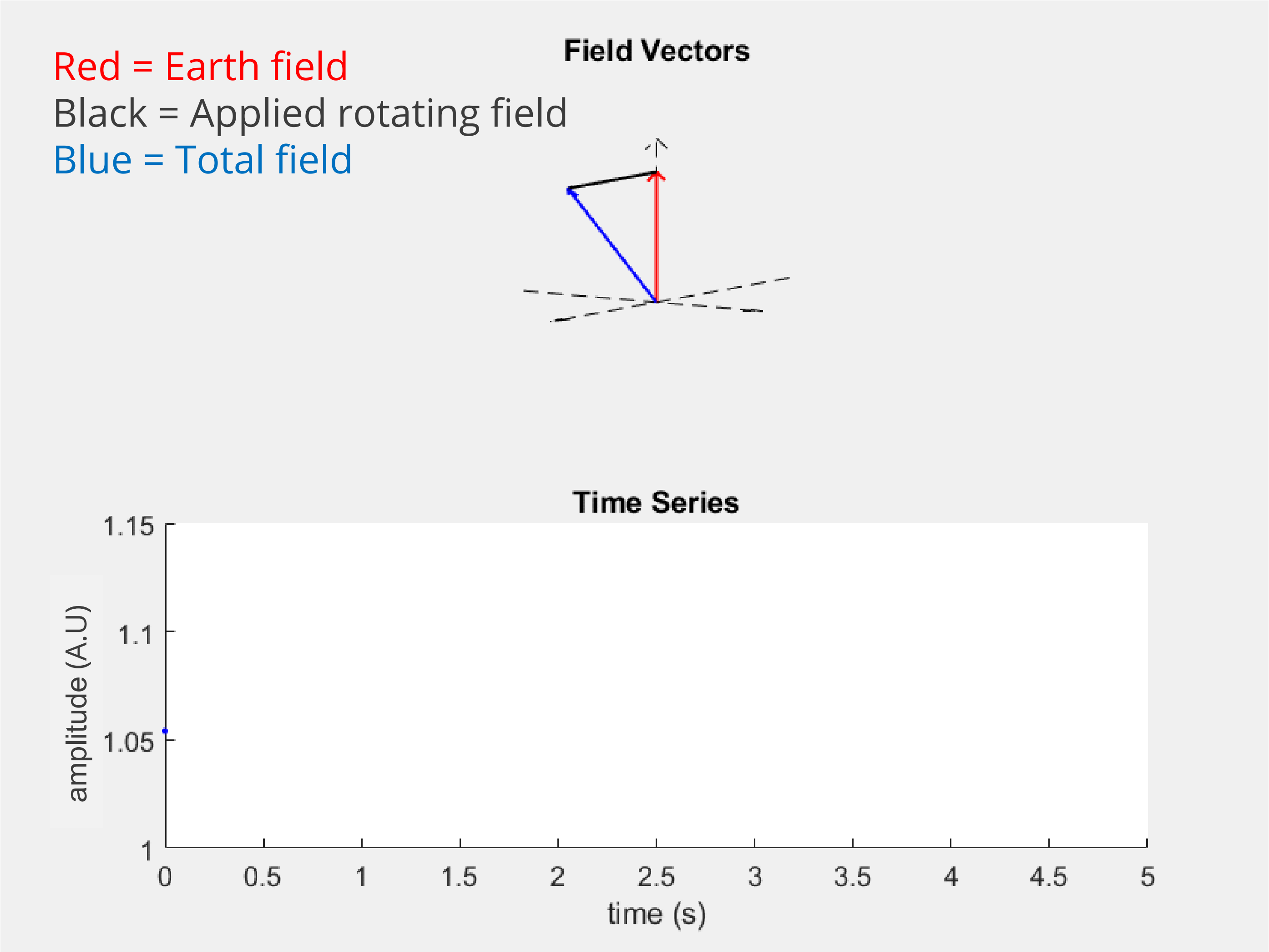
Feedback Variometer with ^{87}Rb

- We use a modified version of the OPM *variometer* developed in E. B. Alexandrov, M. Balabas, V. N. Kulyasov, A. E. Ivanov, A. S. Pazgalev, J. L. Rasson, A. K. Vershovski, and N. N. Yakobson, Three-component variometer based on a scalar potassium sensor, Measurement Science and Technology 15, 918 (2004).
- *Total* feedback comes from excitation of ^{87}Rb at 3/2 the desired RF sensing frequency.
  - Controls the total field amplitude $|B| = \sqrt{B_z^2 + B_x^2 + B_y^2}$. Maintains $|B| \approx B_0$.
  - Feedback to longitudinal (z) axis.
- Transverse feedback from introducing small rotating modulation at frequency $f_\perp$ in transverse plane.
  - Combines with offset fields in xy plane to produce amplitude modulation of total error signal at $f_\perp$. See next slide
  - Modulation phase depends on direction. In-phase (I) and in-quadrature (Q) components provide feedback for x & y directions, respectively.
- Requires *cascaded* lock-in demodulations:



Variometer in Action

- Total error signal modulated at $f_{\perp}$ when Earth's field has transverse component.
- Phase of amplitude modulation depends on physical direction. Splits into in-phase (I) and in-quadrature (Q) components to control x & y axes, respectively.
- Rotating field ~ 1/10 of Earth field to enhance variometer sensitivity

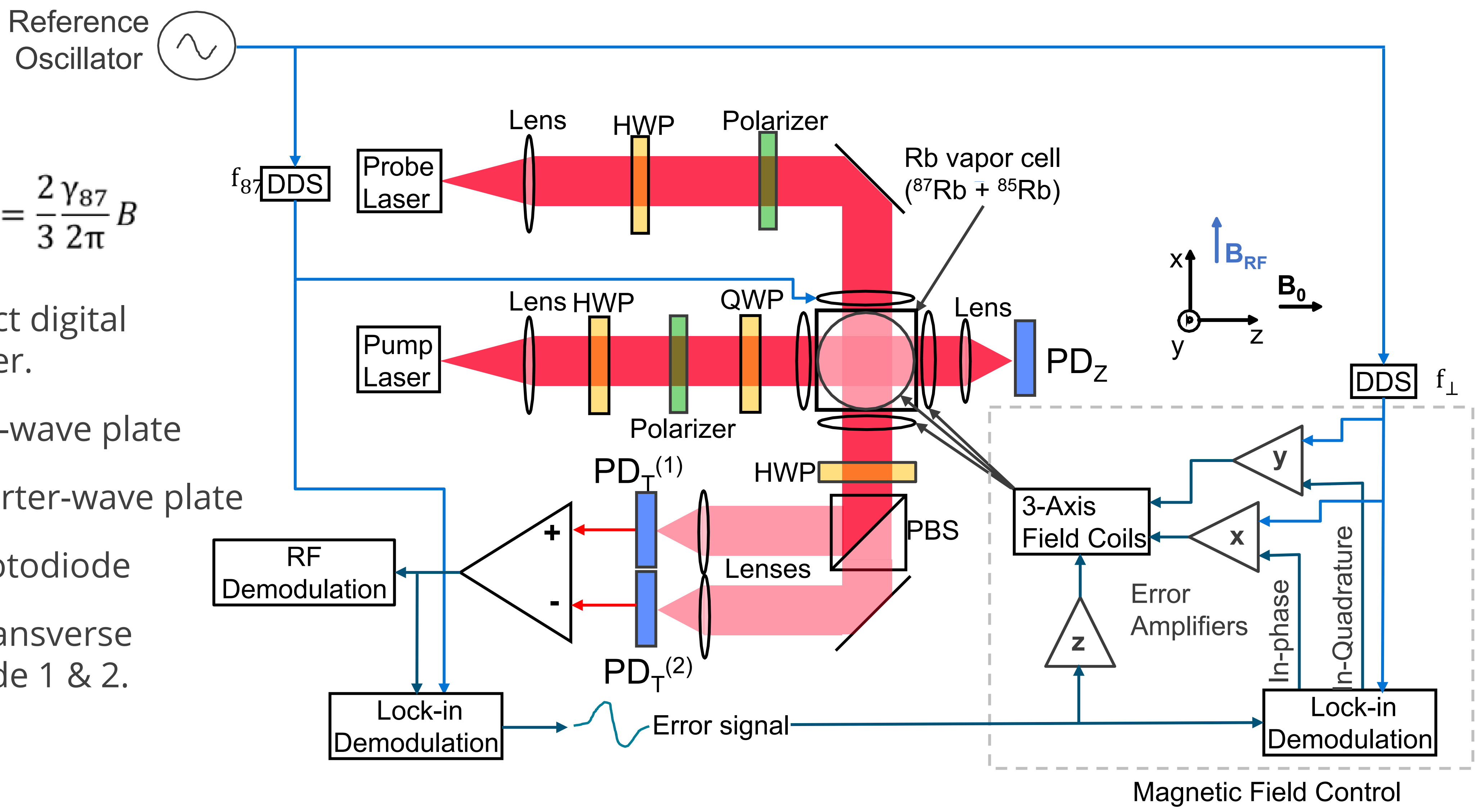


Animation by Neil Claussen

Basic Layout

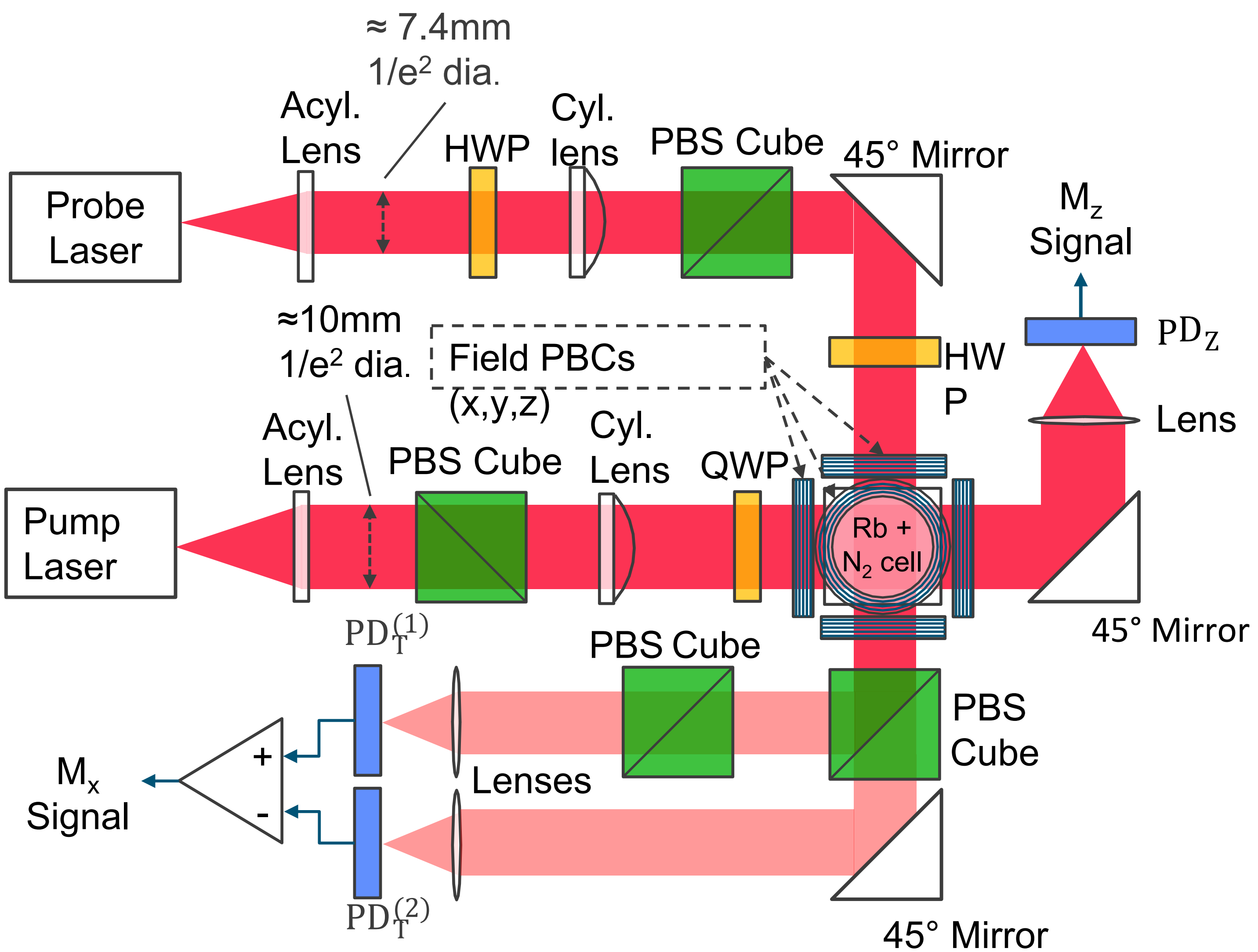
$$f_{85} = \frac{2}{3} f_{87} = \frac{2}{3}\frac{\gamma_{87}}{2\pi} B$$

- DDS: direct digital synthesizer.
- HWP: half-wave plate
- QWP: quarter-wave plate
- PD_Z: z photodiode
- $PD_T^{(1,2)}$: transverse photodiode 1 & 2.



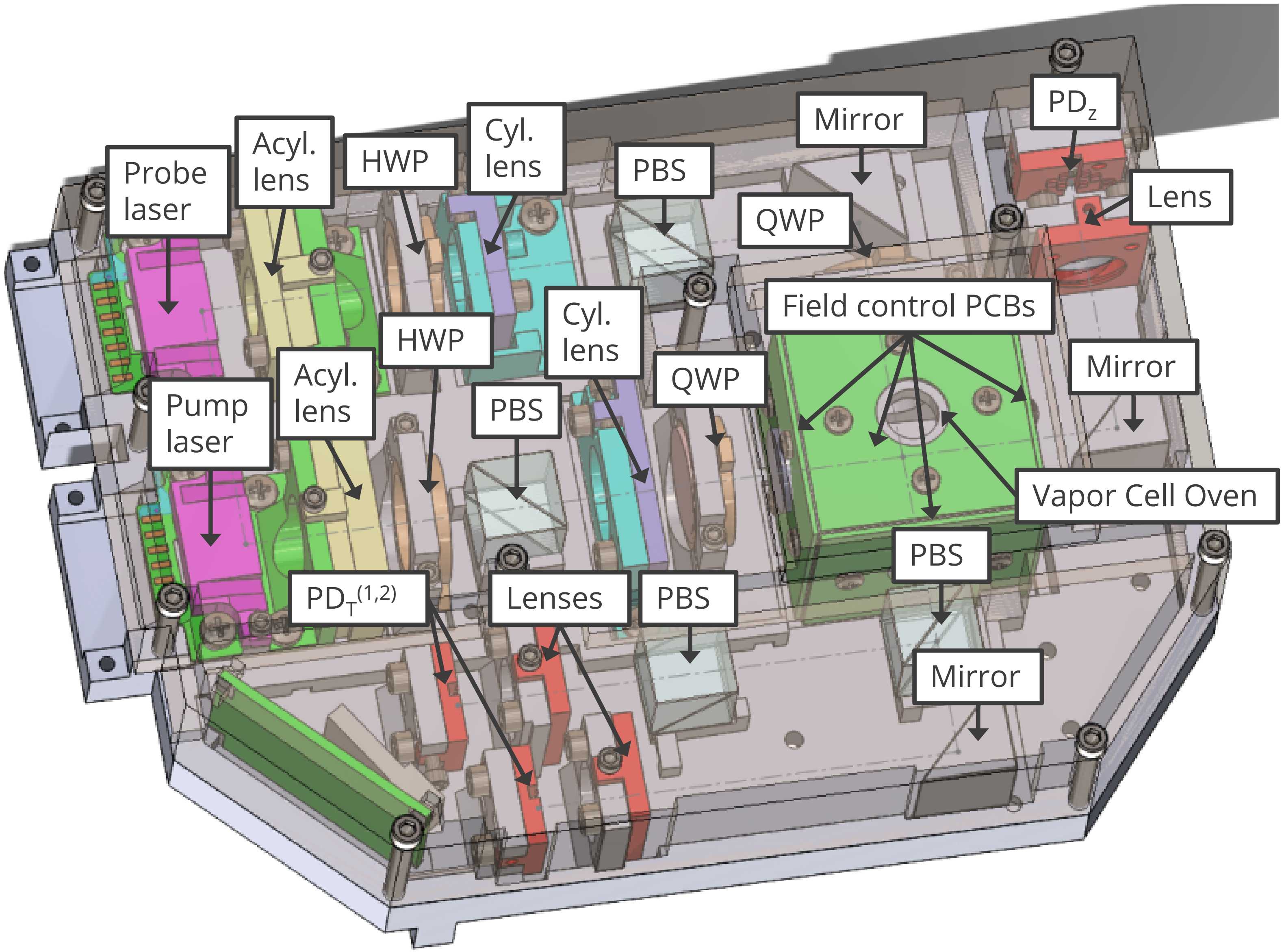
Miniaturization

- Final optical layout for miniaturized package shown at right
- Collimated via acylindrical and cylindrical lenses.
- Fits entire optical layout into a <600 cm^3 volume.
- Oven windows and vapour cell intentionally tilted to address optical feedback
- Vapor cell volume ≈ 1 cm^3.



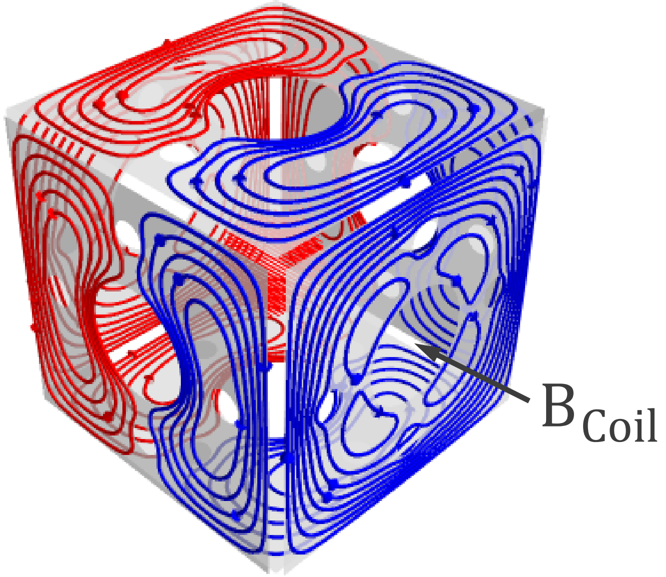
Miniaturized Layout

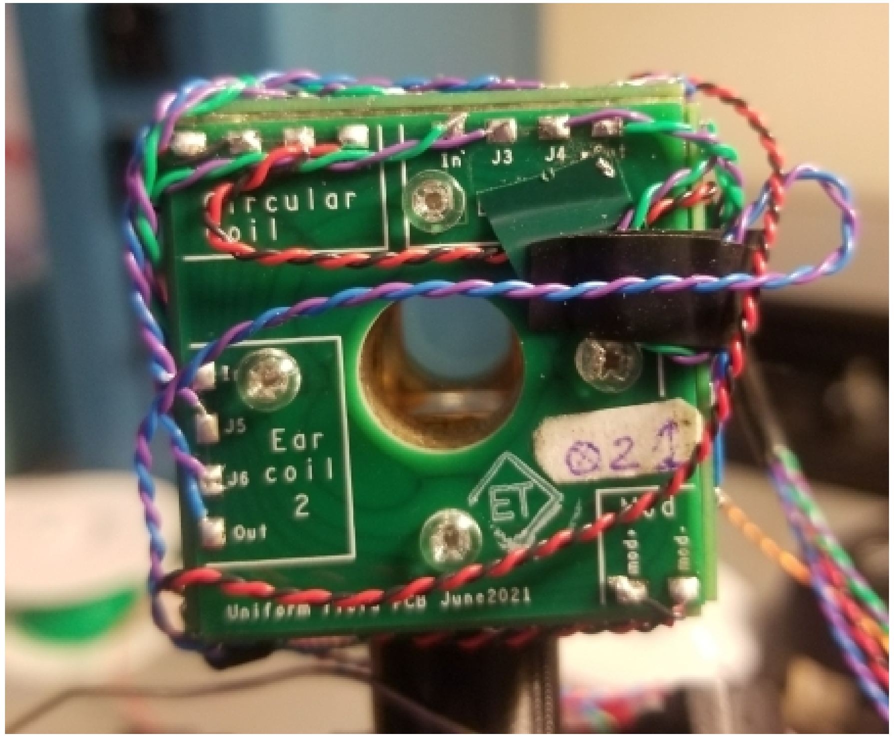
- Right: Annotated *SolidWorks* design of the 3D printed miniaturized physics package.
- 3D printed from ABS and Ultem (for cell oven).



Field Control PCBs

- Used bfieldtools package to design compact PCB's for field control.
  - Each PCB has 6 layers.
  - Thanks to Joonas Iivanainen
- All faces contribute to every direction.
- Produce highly uniform(~0.5%) fields

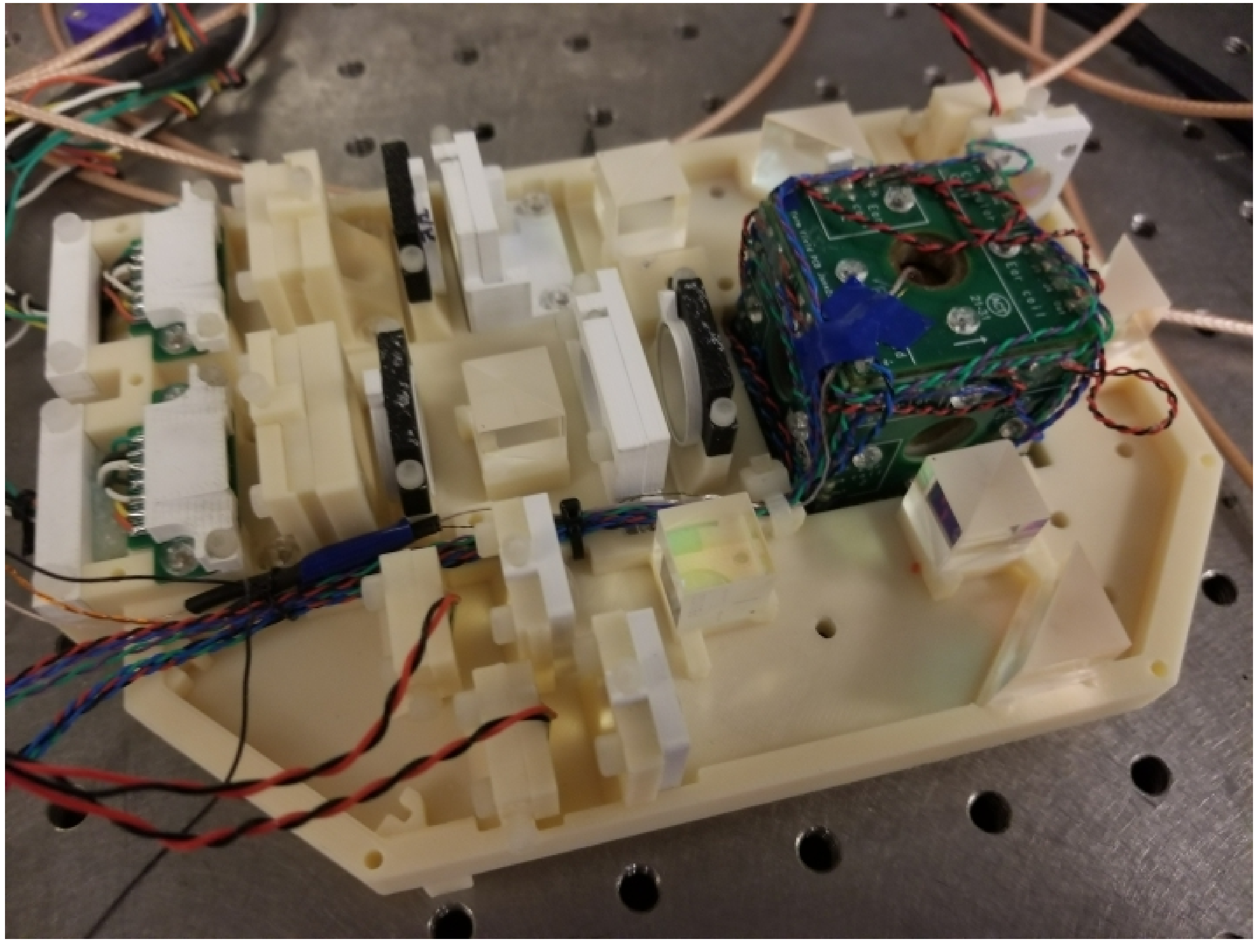




Above: The PCB's assembled around the natural Rb+N_2 cell and heater.

Left: Current distribution over 6 faces for a single field direction. Blue is clockwise about the outward surface normal, red is counter-clockwise.

Miniaturized Layout in Real Life



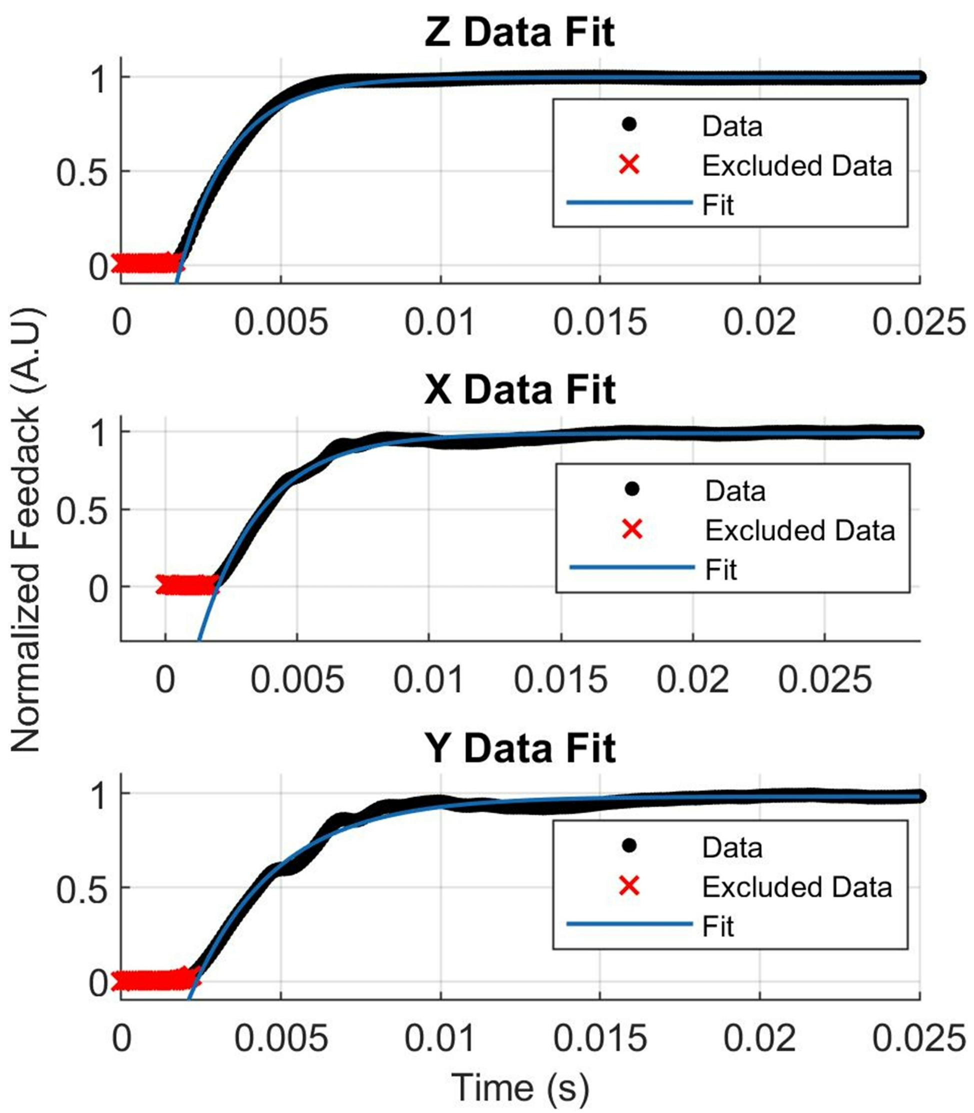
Above: The actual physics package, assembled without its protective cover.

III: Results

Inside and out.

Feedback Performance

- Right: normalized feedback response of each channel to a square wave input.
  - Decaying exponential fit used to extract feedback bandwidth.
- Maximum slew rate tested by applying 1 Hz linear ramp and increasing amplitude until the system became unstable.
  - Validated by doubling the ramp rate and halving the amplitude.

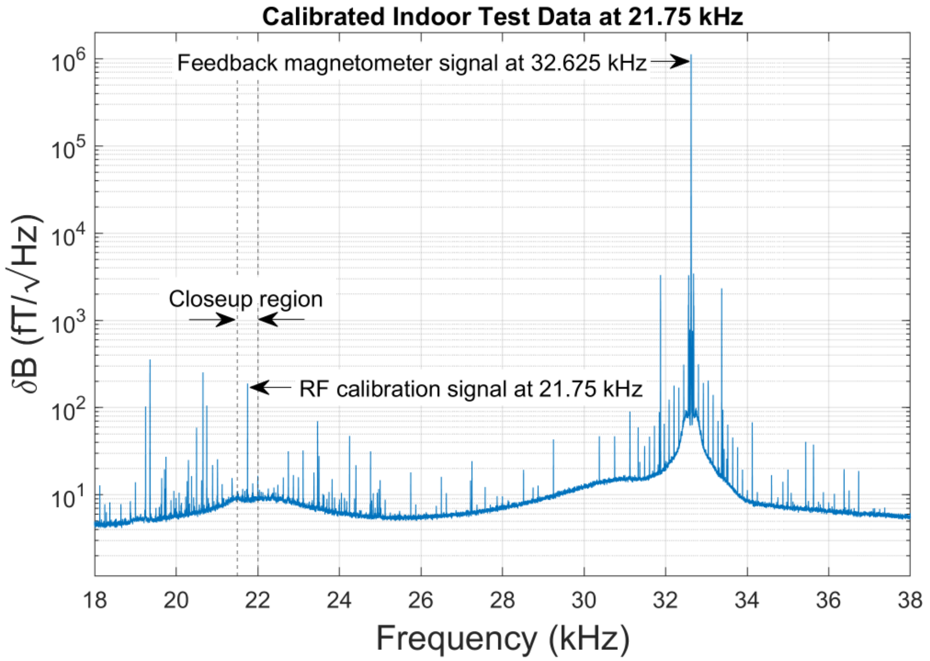


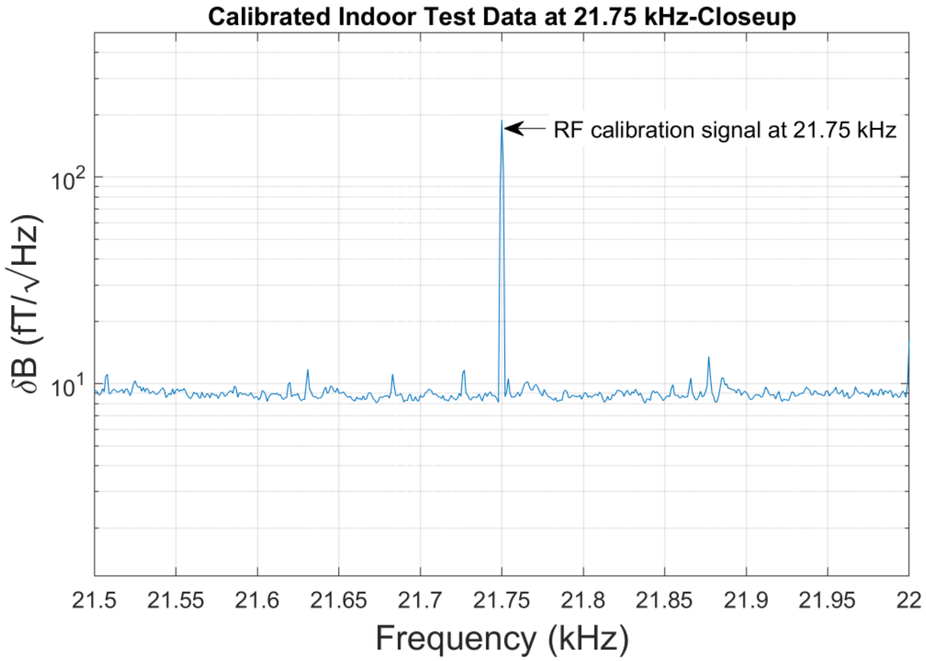
Feedback Performance: The Numbers

Direction	Feedback Bandwidth (Hz)	Maximum Slew Rate (μT/s)	Variometer Sensitivity (pT/√Hz)
z	96	33	5.8
x	67	8	1,000
y	60	8	1,300

Above: Table showing the feedback performance numbers determined by the methods outlined on previous slide.

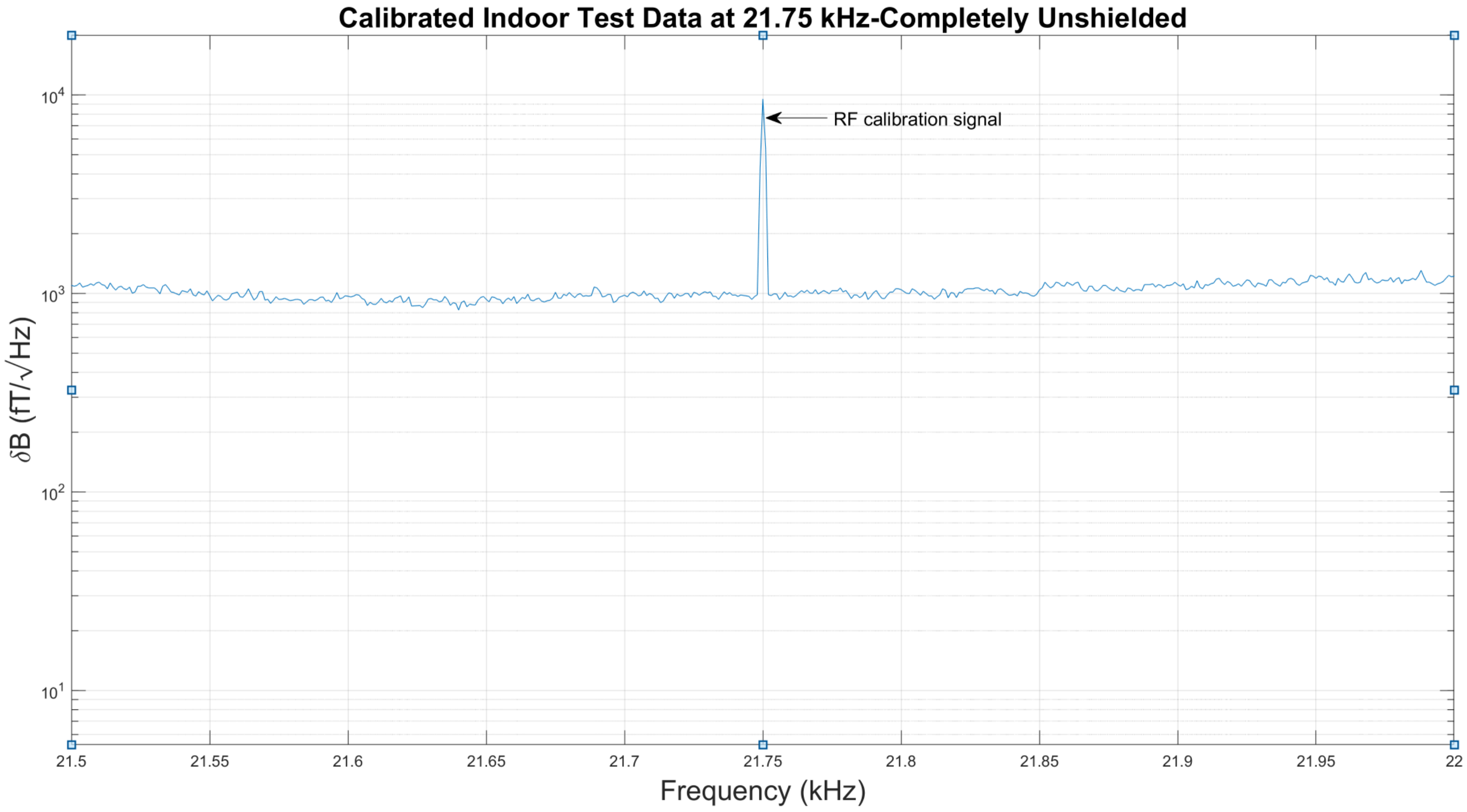
Results in the Lab-Noise Floor Limit





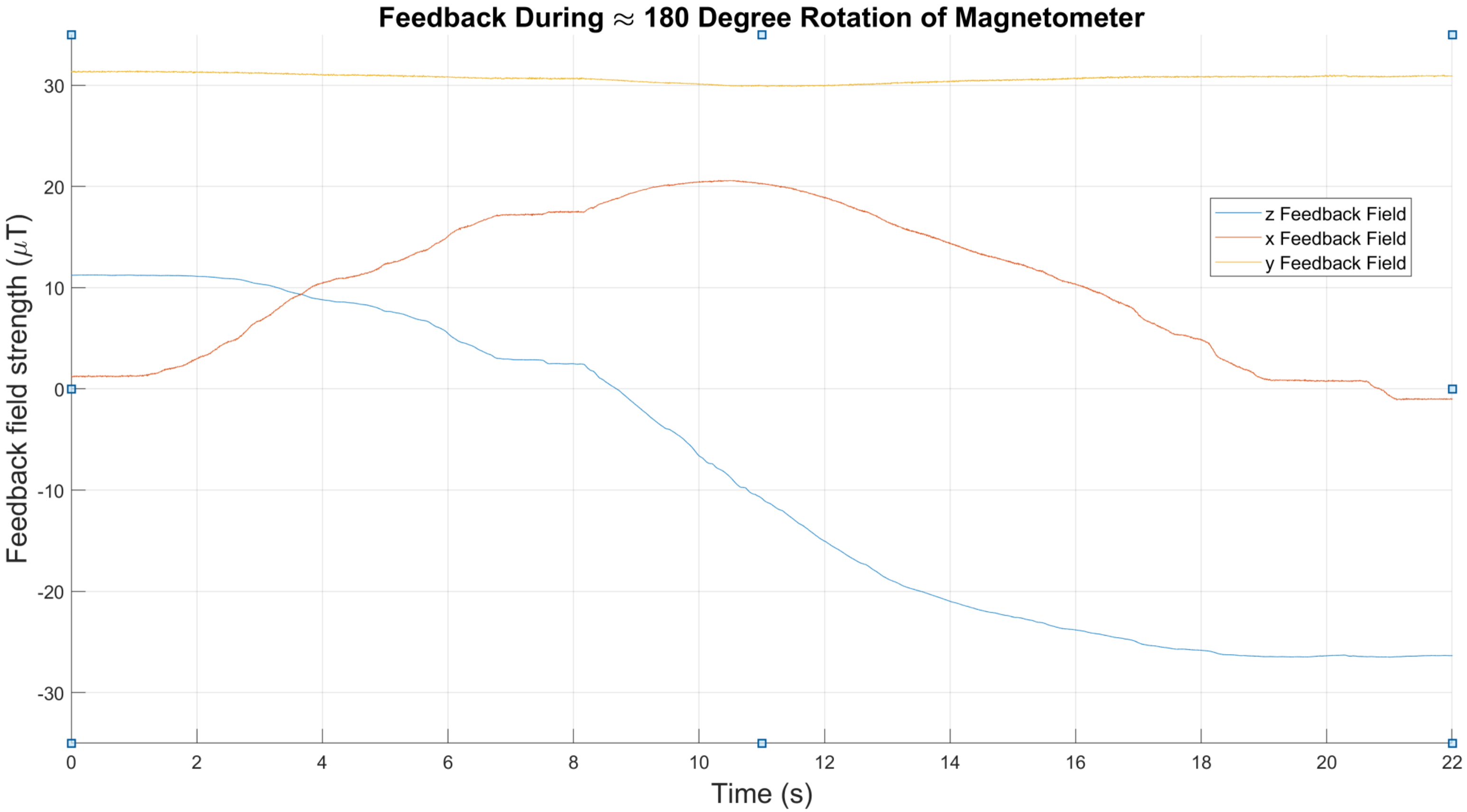
Above: Amplitude spectral density data taken in the lab. The magnetometer was placed inside ¼" Aluminum shield to limit RF noise to determine fundamental noise floor, which was found to be $\approx 9\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$.

Results in the Lab-Completely Unshielded



Above: Amplitude spectral density showing the RF noise floor of $\approx 1\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$ when operating completely unshielded in our lab.

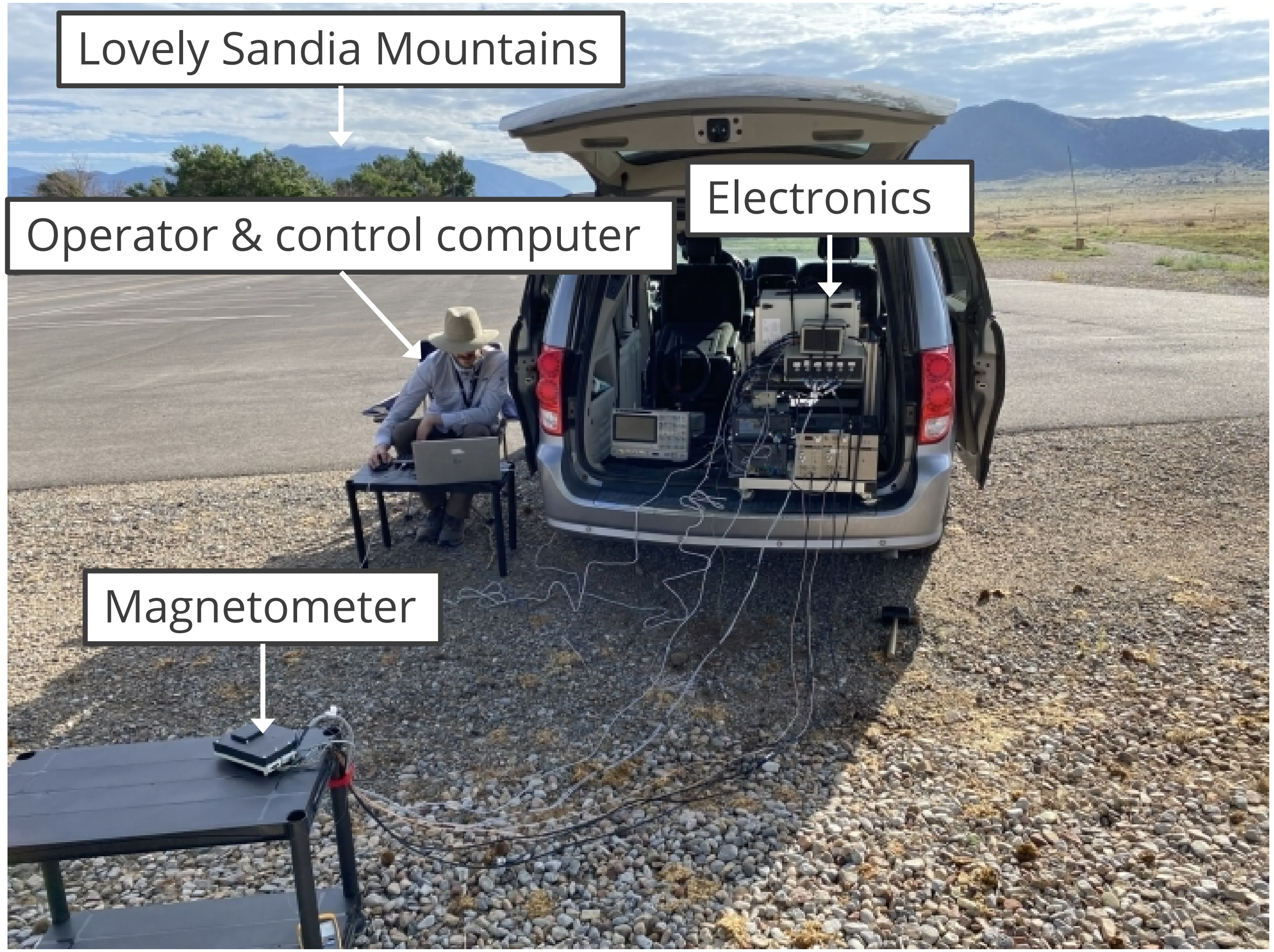
Feedback During Rotation



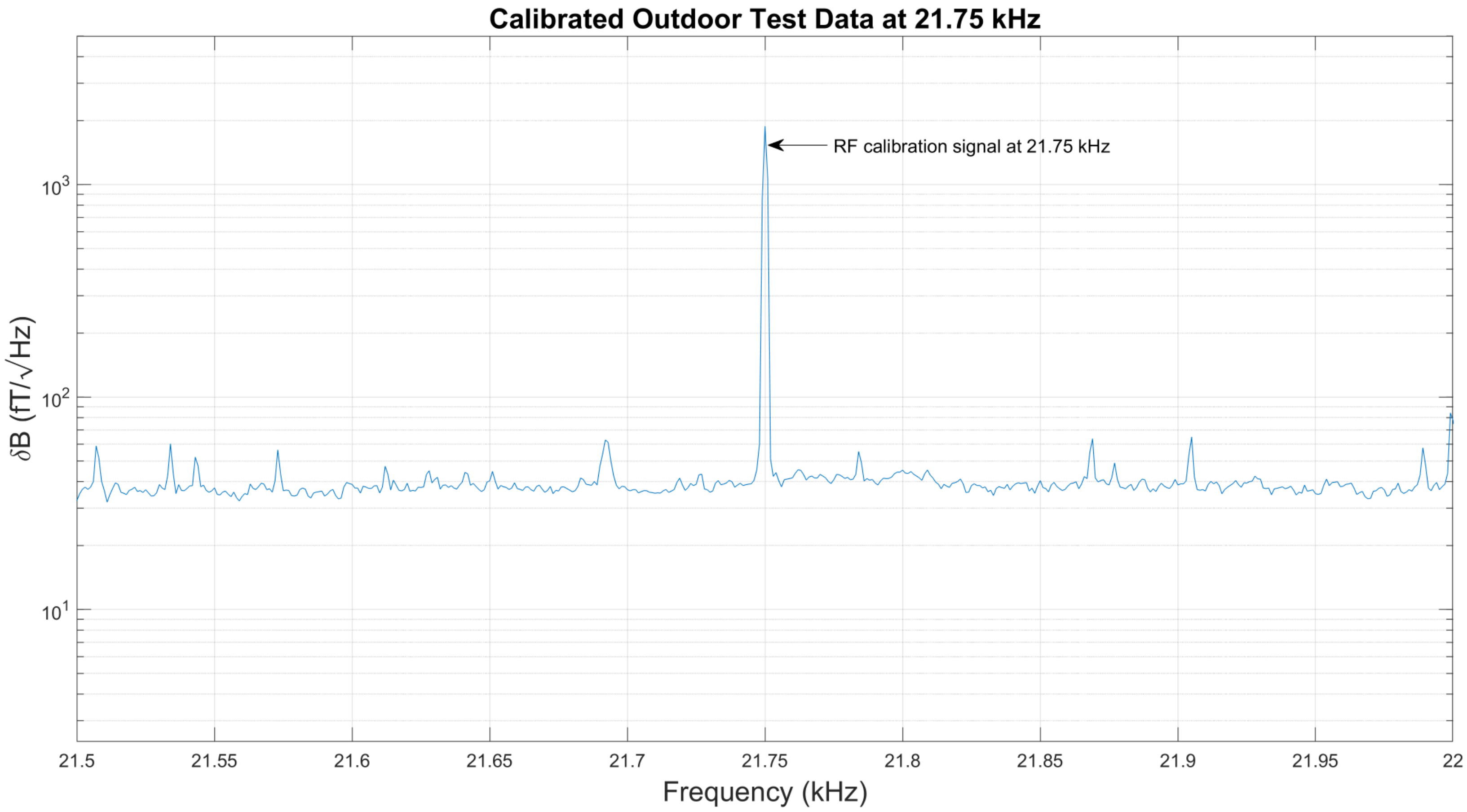
Above: Calibrated variometer feedback signals recorded during a rotation of ≈ 180° in the azimuthal (xz) plane. Start and end positions have the longitudinal axis approximately aligned along north-south.

Results Outdoors-Mobile Test Platform

Right: Outdoor testing arrangement. Power provided by a Yeti® Goal Zero 3000x portable power station, not shown. Cables connecting the physics package to the electronics are 3 m long.



Results Outdoors-RF Sensitivity



Above: Amplitude spectral density showing the RF sensitivity of $\approx 40\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$. Because this is significantly above the fundamental noise floor found indoors, we conclude this is the true environmental noise in the outdoor spectrum.

IV: Summary

Summary

- We have developed a fieldable RF magnetometer with $\approx 9\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$ fundamental sensitivity.
  - Based on ^{85}Rb in natural Rb vapor.
- Feedback provided by a comagnetometer co-located within the same vapor cell.
  - Based on variometer using ^{87}Rb in natural Rb vapor.
  - Considerable reduction in physics package volume to <600 cm^3.
  - Reduces gradient errors.
  - Bandwidth, slew rate depend on rotating variometer modulation amplitude, PID parameters.
- System approaches the fundamental noise limit.
  - Best possible for natural ^{85}Rb in a $\approx 1\ \mathrm{cm}^3$ vapor cell at resonant OD of 25-30 is $\approx 6\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$.
  - Best lab demonstration was $\approx 2\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$ in K by Savukov et al.

V: Acknowledgements

Acknowledgements

- Thanks to Peter Schwindt for giving me the opportunity to work on this project, and his continuing mentorship.
- Thanks to Neil Claussen for his work on various technical aspects of the project.
- Thanks to Joonas Iivanainen for his compact coil design via bfieldtools.
- Thanks to Jeffrey Bach for his support on RF engineering, signals analysis, for lending laboratory equipment.
- Thanks to Lee Marshall for consulting on electronics design.

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Above: Peter Schwindt (image by Arne Wickenbrock)

Below: Neil Claussen