A portable ^{87}Rb gradiometer operating in Earth's field *(for detection of biomagnetism)*

Mark Limes

DAMOP 2020

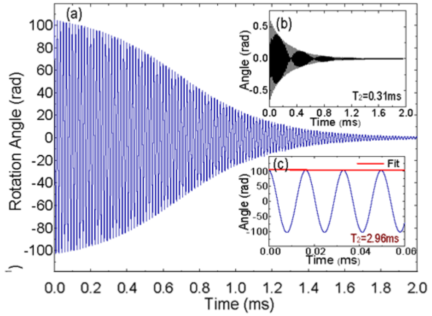
Princeton-area collaboration

Mark Limes, Dave Newby, Jill Foley, Thomas Kornack

- Sensor and controls, design and implementation

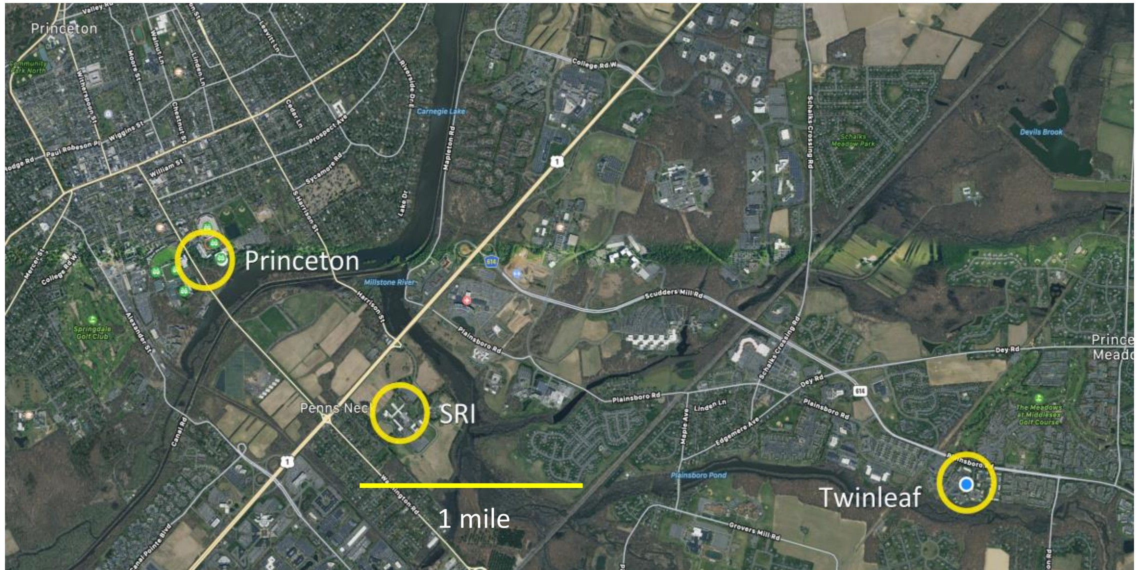
Wonjae Lee, Tao Wang, Gianvito Lucivero, Michael Romalis

- Physical limits of ^{87}Rb gradiometer



Sterling McBride, Kaitlin Moore, Seth Caliga, Alan Braun

- Low-SWAP assemblies



DARPA AMBIIENT

- "Atomic Magnetometers for Biomagnetic Imaging In Earth's Native Terrain"
- Expands upon previous SERF-based successes using developments in microfabrication techniques and laser technology
- Extremely aggressive size, weight, and power (SWaP) metrics
- Physical limits project 1 – 10 fT/cm/rtHz with 3 cm baseline in Earth's field
- No heading error, no dead zones

W. Lee, V. G. Lucivero, M. V. Romalis, M. E. Limes, E. L. Foley, T. W. Kornack (202-) arXiv:

- *This presentation/paper: Proof-of-principle MEG using pulsed pump multipass probe, two vapor cell gradiometer, vacuum packaged cell assembly, and lasers within sensor head*

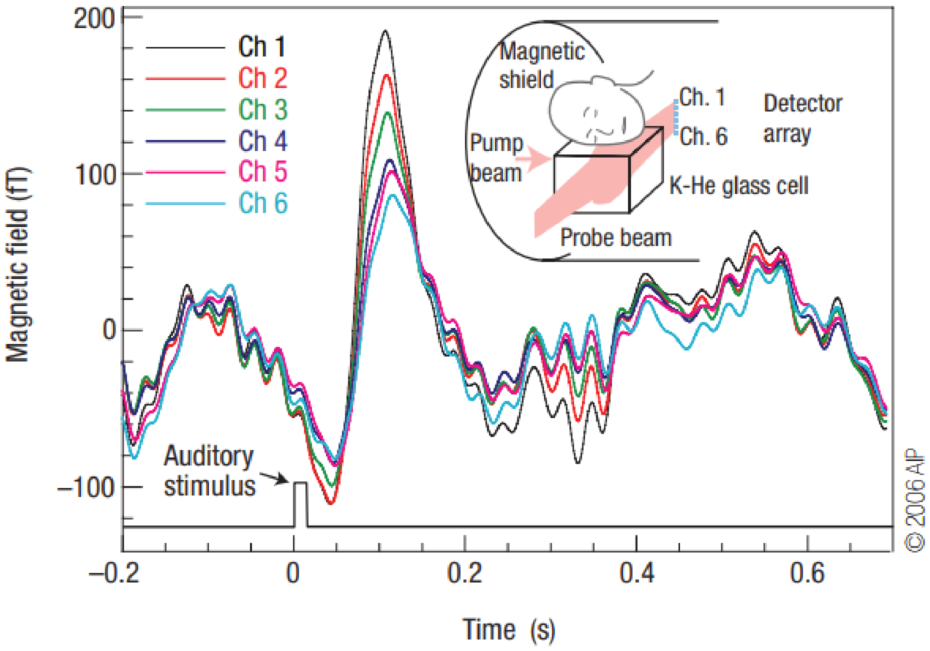
Biomagnetism w/ SERF OPMs

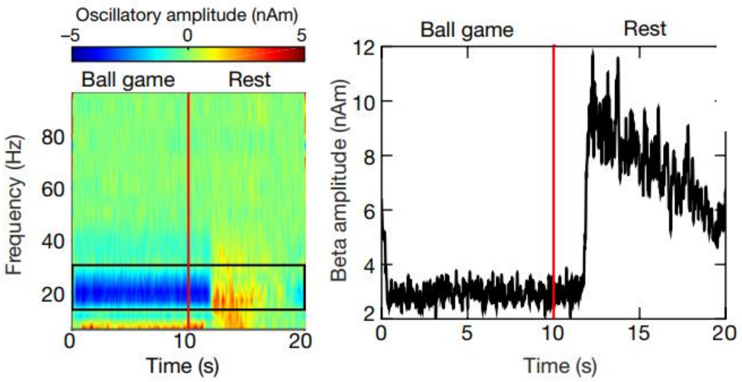
$$\delta B_{SNL} \approx \frac{1}{\gamma}\sqrt{\frac{\Gamma}{Nt}}$$

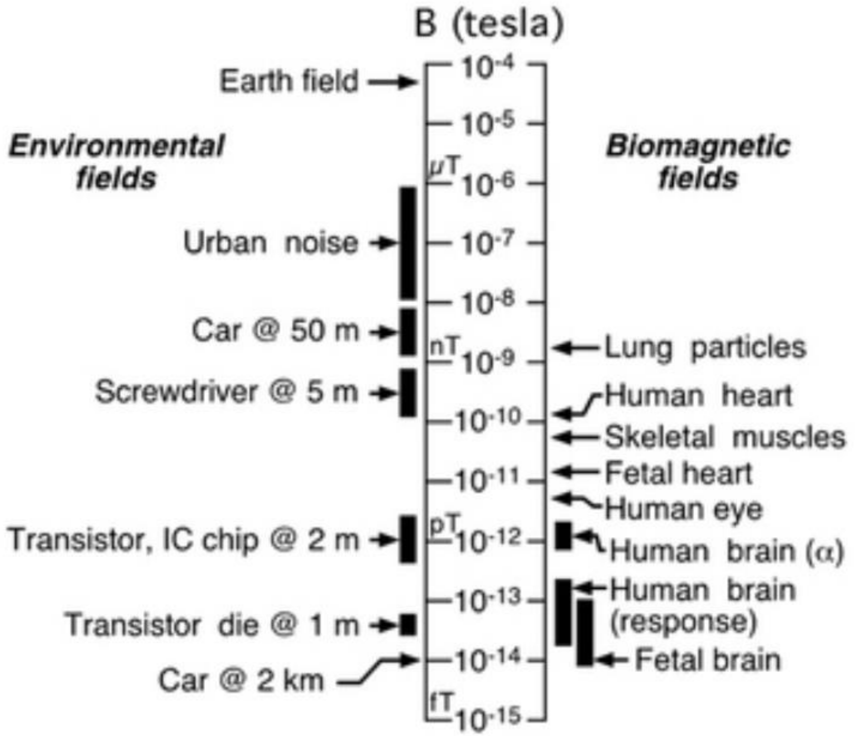
$$\frac{1}{T_{2SE}} \propto \frac{(\gamma B)^2}{\Gamma_{SE}}$$

H. Xia, A. Ben-Amar Baranga, D. Hoffman, and M. V. Romalis, *Appl. Phys. Lett.* **89**, 211104 (2006)
E. Boto, et al. *Nature* **555**, 26147 (2018)

$$\Gamma \propto \cancel{\frac{1}{T_{2SE}}} + \Gamma_{light} + \cdots$$





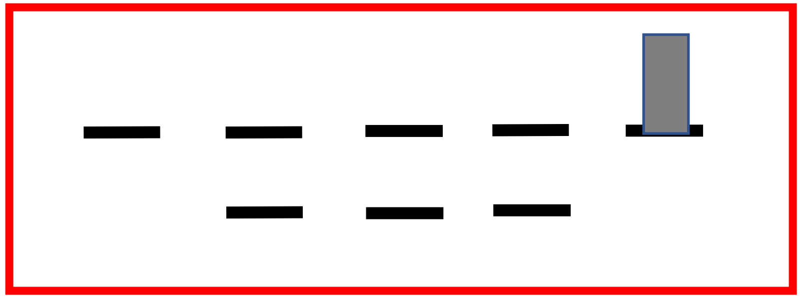


High-sensitivity SERF sensors typically require magnetic shielding

Ambient environments pose a real problem for SERF sensors, as they have *inherently limited linearity and dynamic range*

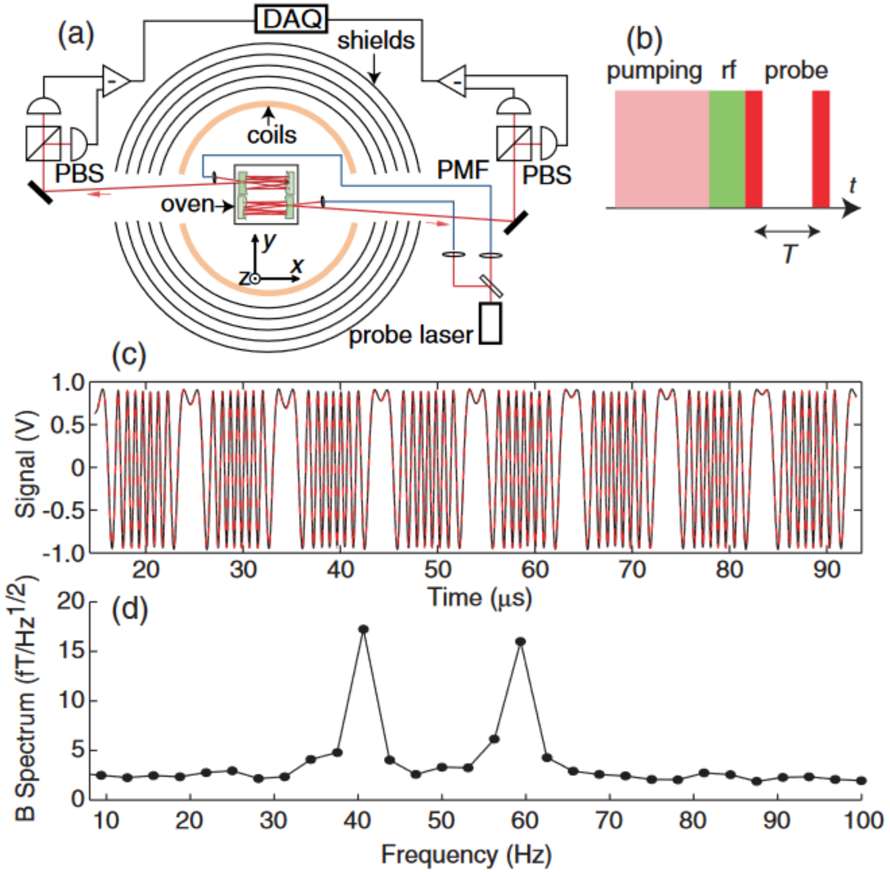
Prior work – multipass cells

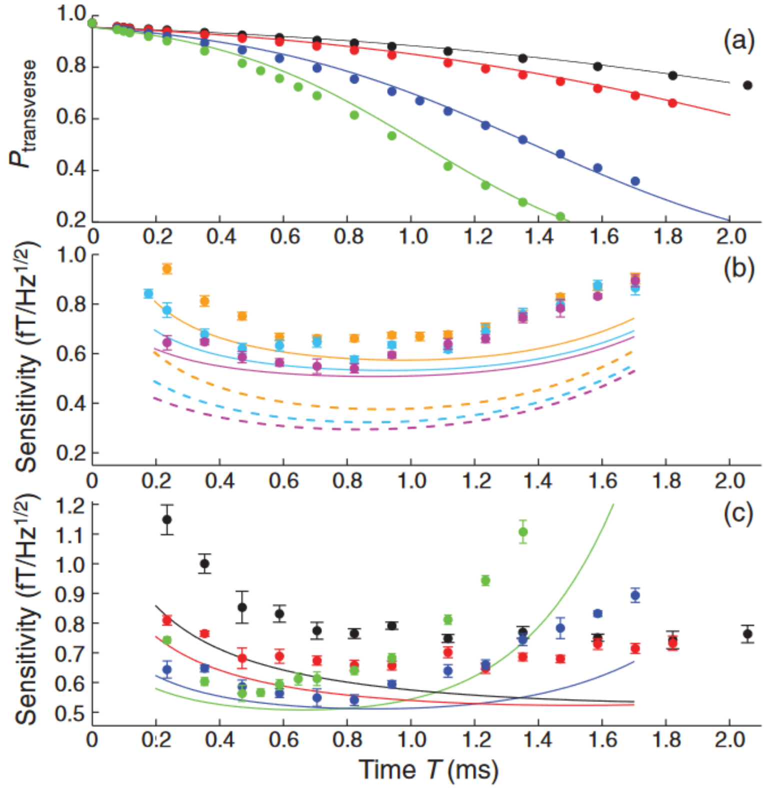
Shuguang Li, P. Vachaspati, Dong Sheng, Nezih Dural, and Mike Romalis *Physical Review A* **84**, 061403(R) (2011)
Dong Sheng, Shuguang Li, Nezih Dural, and Mike Romalis, *Physical Review Letters* **110**, 160802 (2013)



$$\Gamma \propto \frac{1}{T_{2SE}} + \Gamma_{\text{light}} + \cdots$$

- Pulsed pump, RF Tipping and free precession



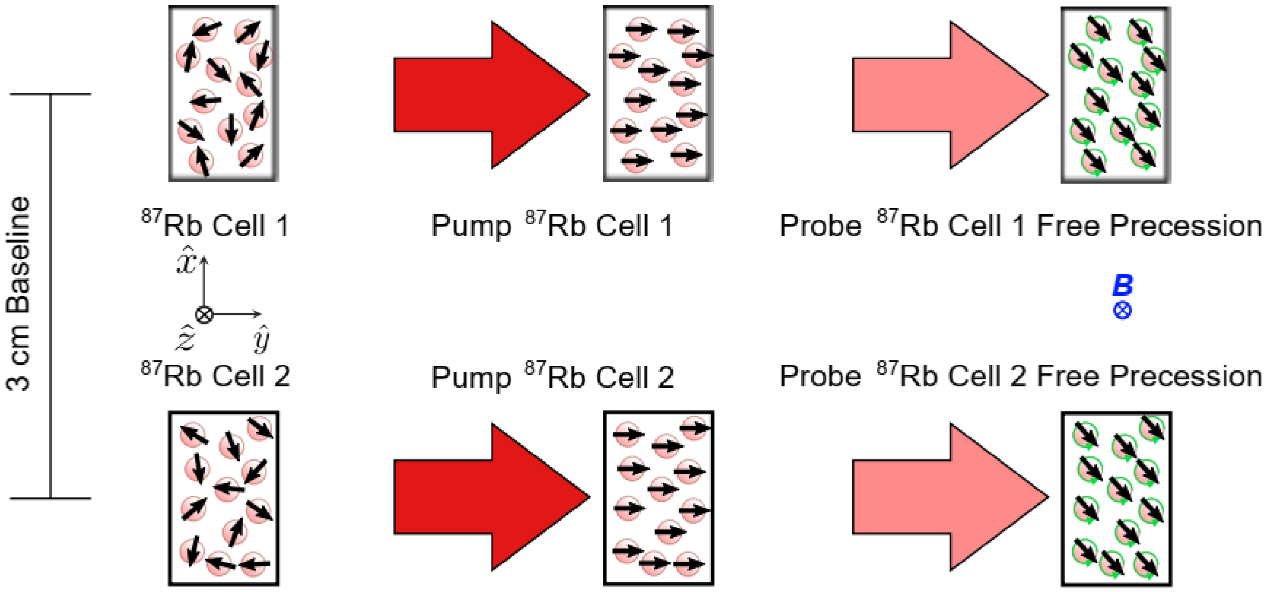


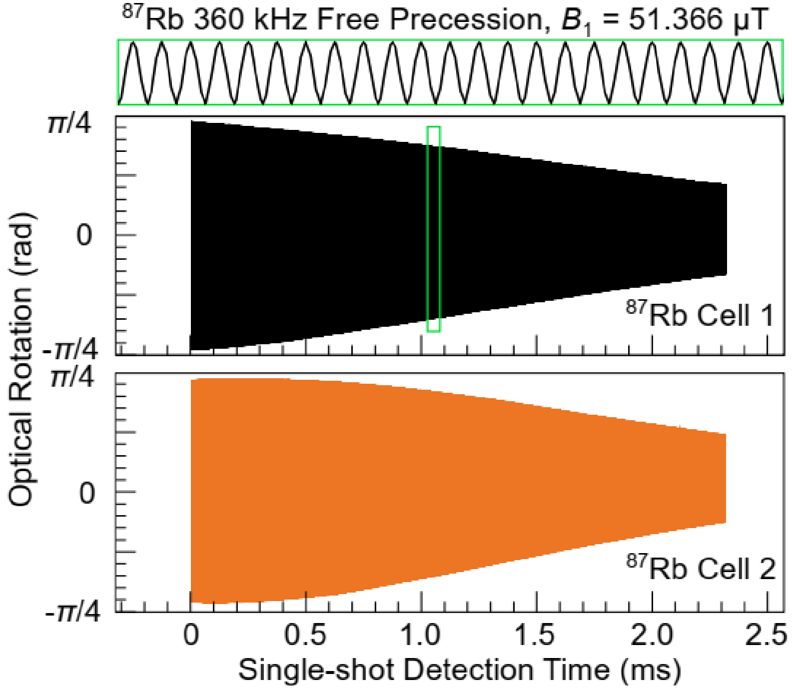
Sub-fT

Pulsed pump, free precession ^{87}Rb gradiometer

M. E. Limes, E. L. Foley, T. W. Kornack, S. Caliga, S. McBride, A. Braun, W. Lee, V. G. Lucivero, M. V. Romalis (2020) arXiv:2001:03534

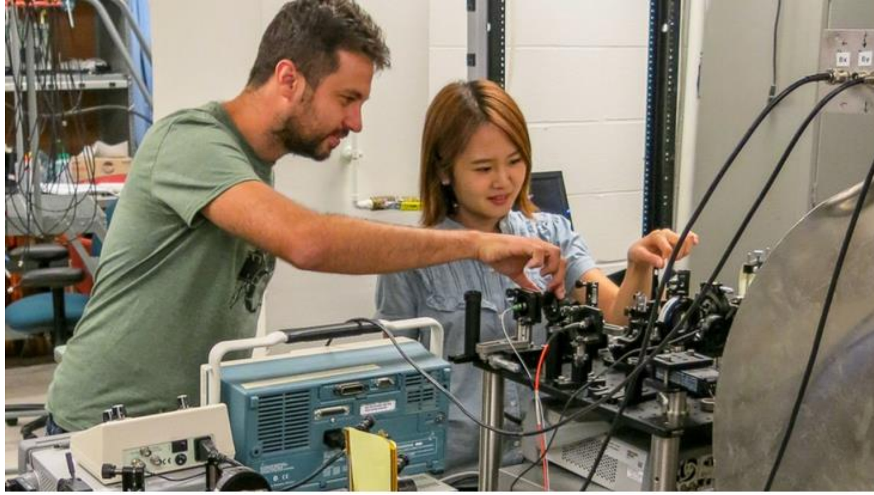
- Ideally 100% spin polarization in plane transverse to *B*, pulse-train pump of <1 us sigma+ pulses at Larmor Freq
- Detection of free precession with multipass detuned probe high optical rotation
- Frequency measurement: linear with high dynamic range



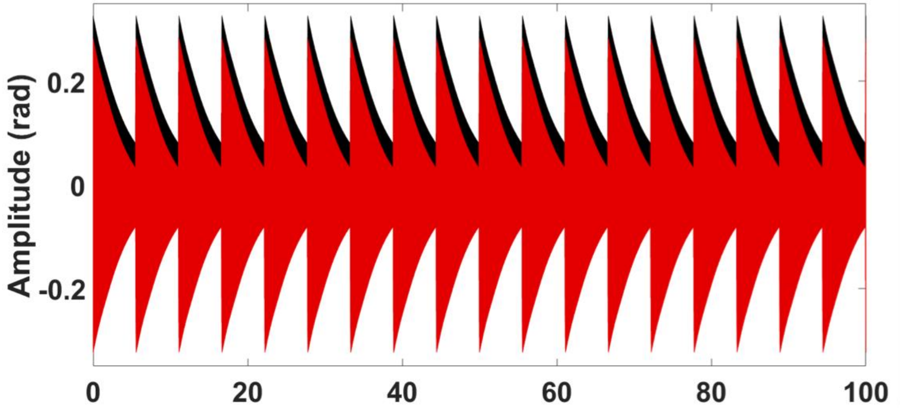


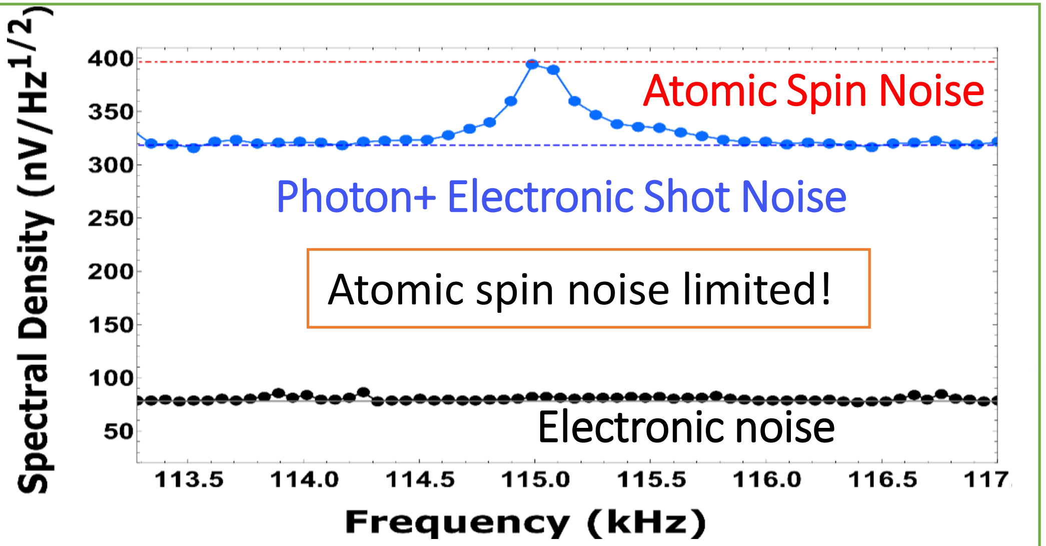
Fundamental limits- shielded

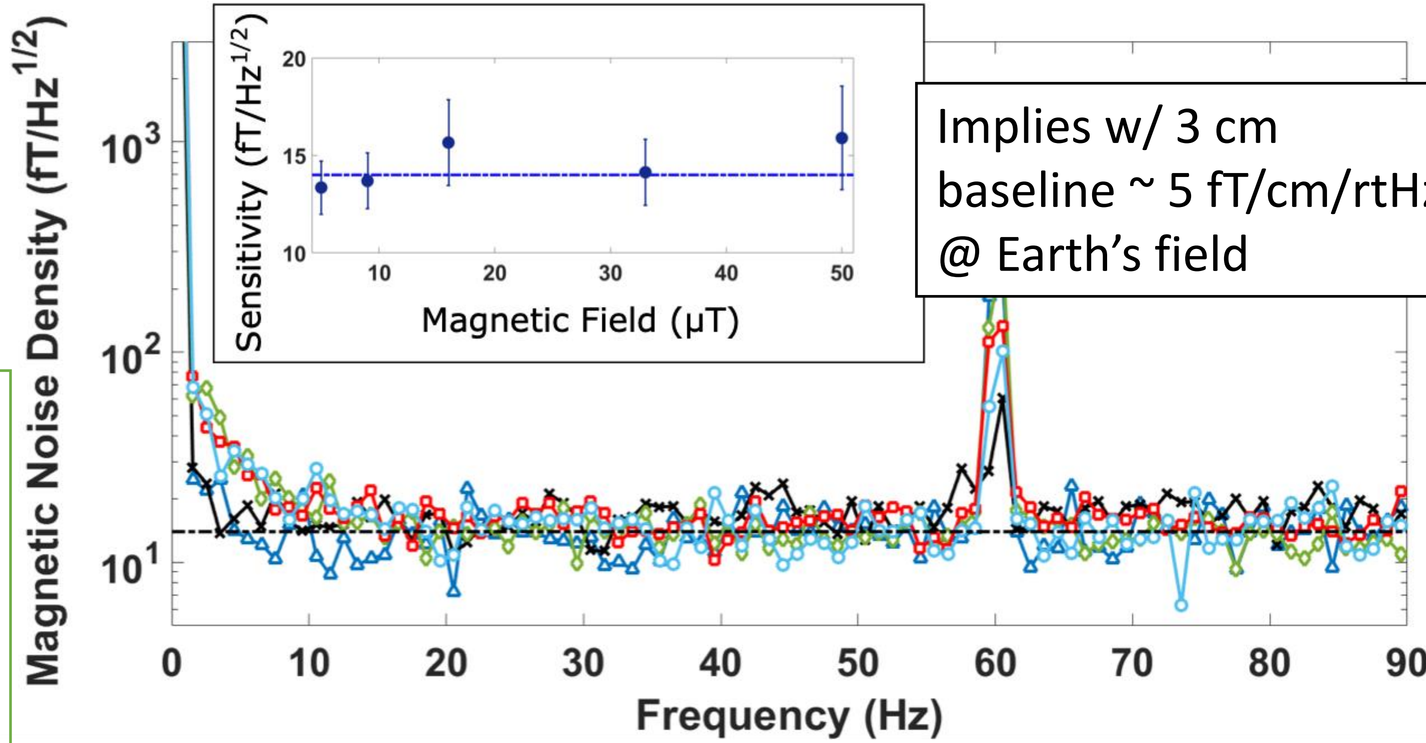
V. G. Lucivero, W. Lee, M. V. Romalis, M. E. Limes, E. L. Foley, T. W. Kornack (2020) arXiv:



- Single cell top-bottom gradiometer (0.2 cm baseline)





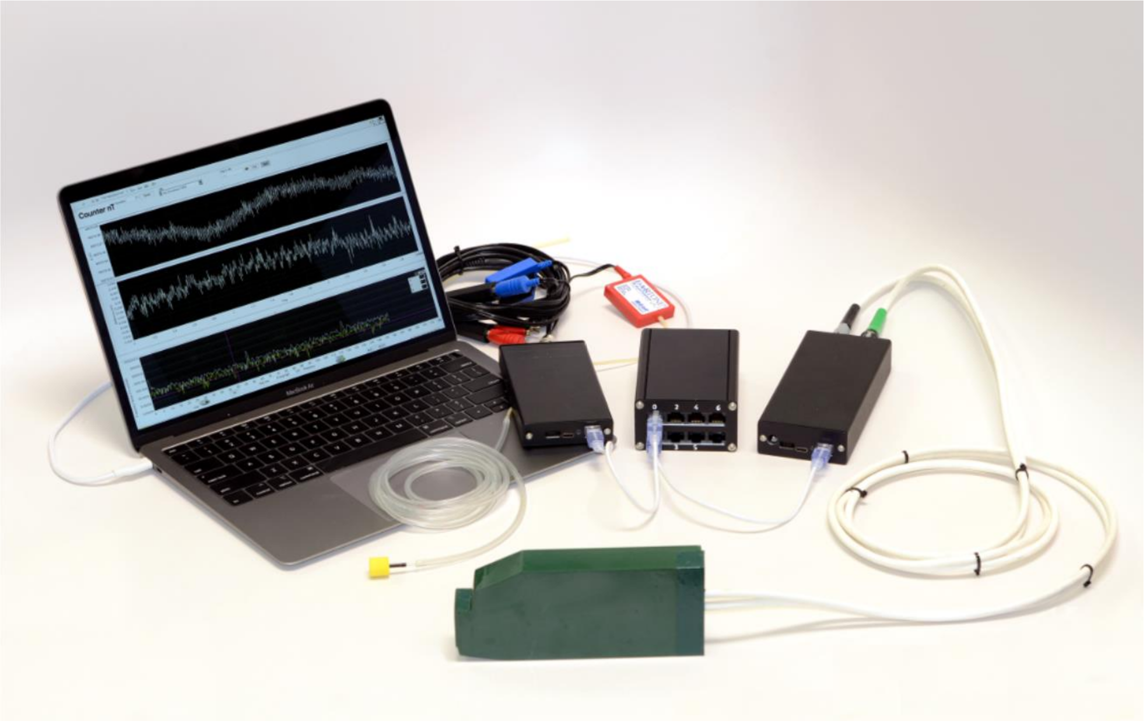


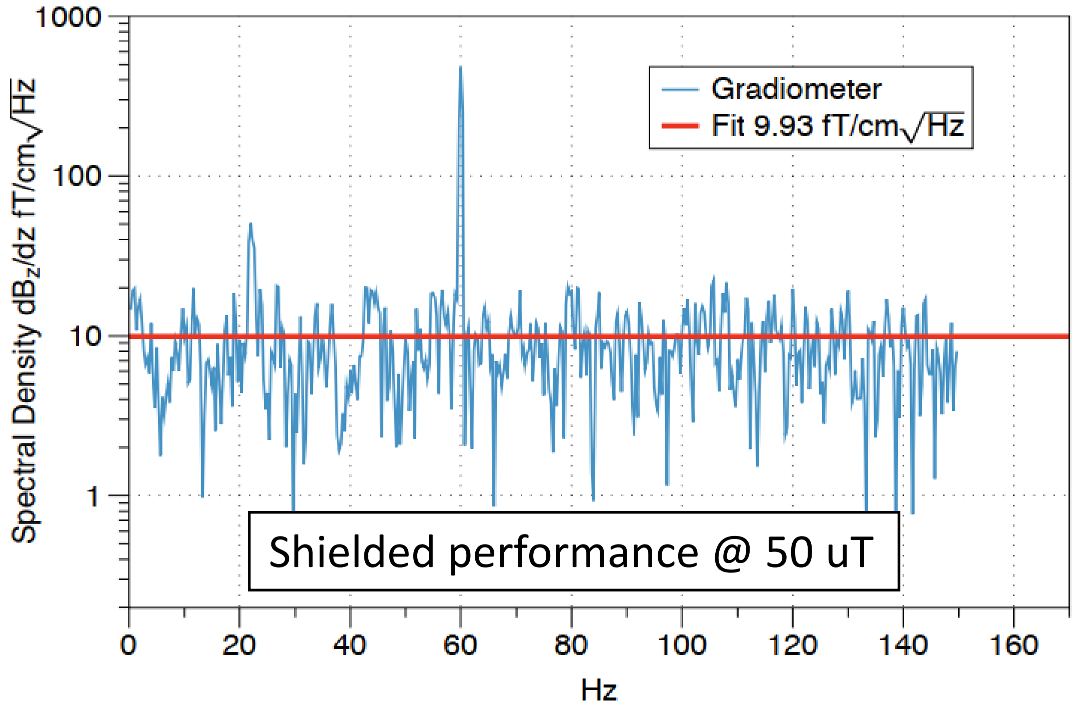
Implies w/ 3 cm baseline ~ 5 fT/cm/rtHz @ Earth's field

$$\sigma_\nu^2 \geq \frac{12(\rho_w^2 + \rho_{nw}^2 C_{nw})C}{(2\pi)^2 A^2 T^3}$$

Portable system for MEG proof-of-principle

M. E. Limes, E. L. Foley, T. W. Kornack, S. Caliga, S. McBride, A. Braun, W. Lee, V. G. Lucivero, M. V. Romalis (2020) arXiv:2001:03534





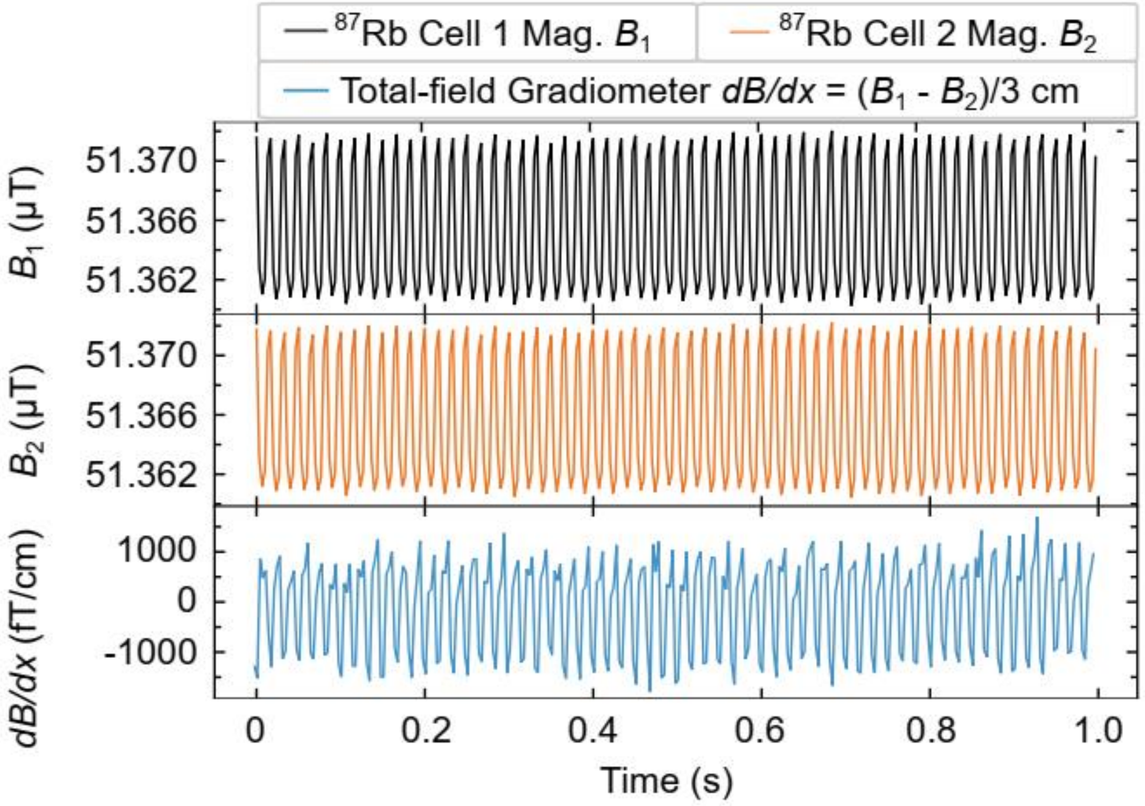
- Vacuum-packaged cells, pump/probe lasers, and photodiode amp (PDA) contained in sensor head

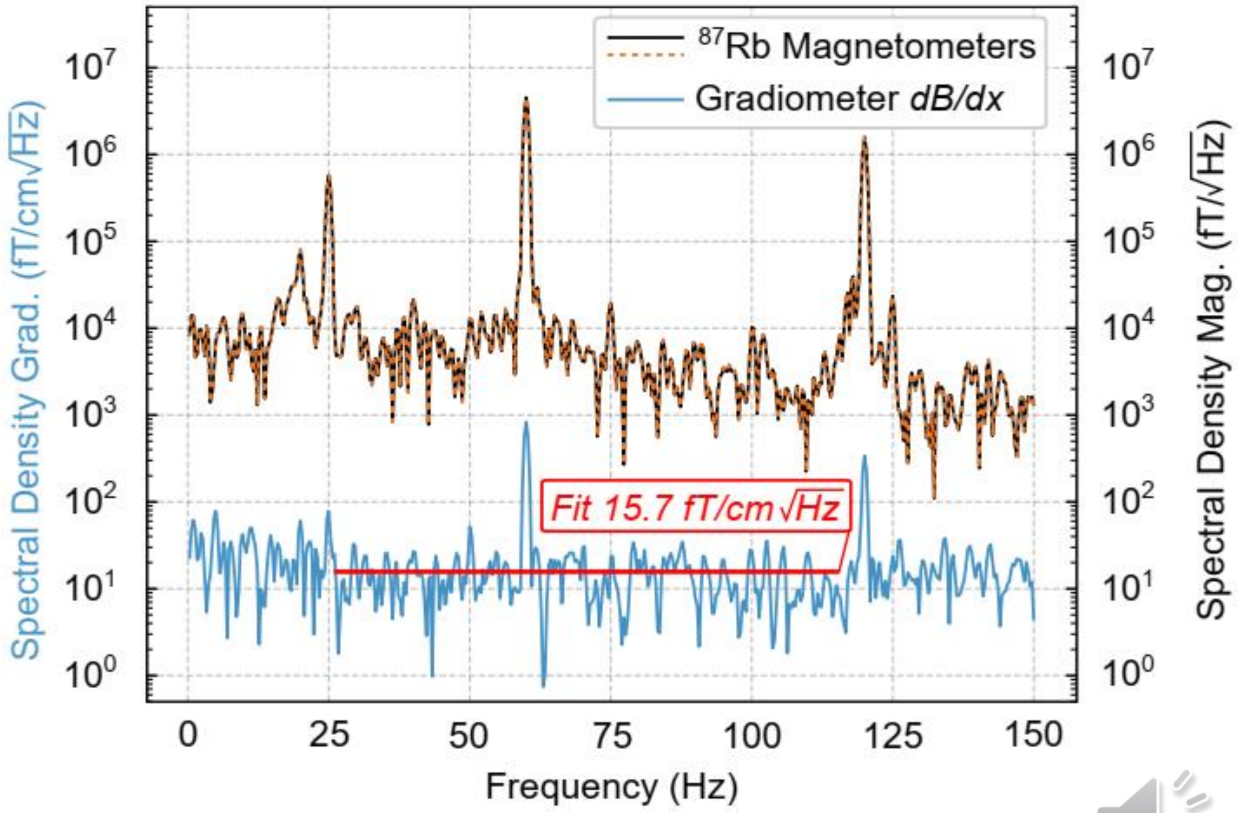
Sensor controlled by custom electronics and detected by custom frequency counter. System able to run off laptop battery (5 W). Data streams at 300 Hz to laptop.

Portable ^{87}Rb gradiometer performance

M. E. Limes, E. L. Foley, T. W. Kornack, S. Caliga, S. McBride, A. Braun, W. Lee, V. G. Lucivero, M. V. Romalis (2020) arXiv:2001:03534

- CMRR > 2000 , unshielded performance 16 fT/cm rtHz





In-the-field MEG

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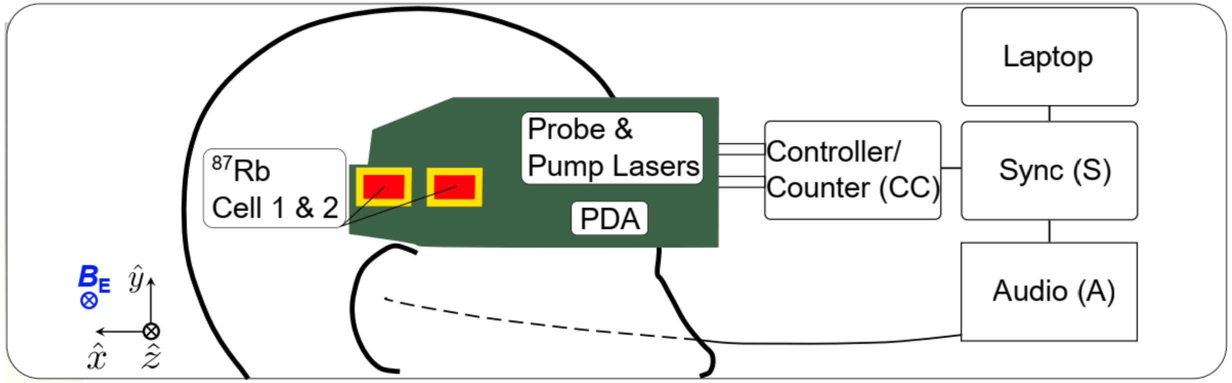
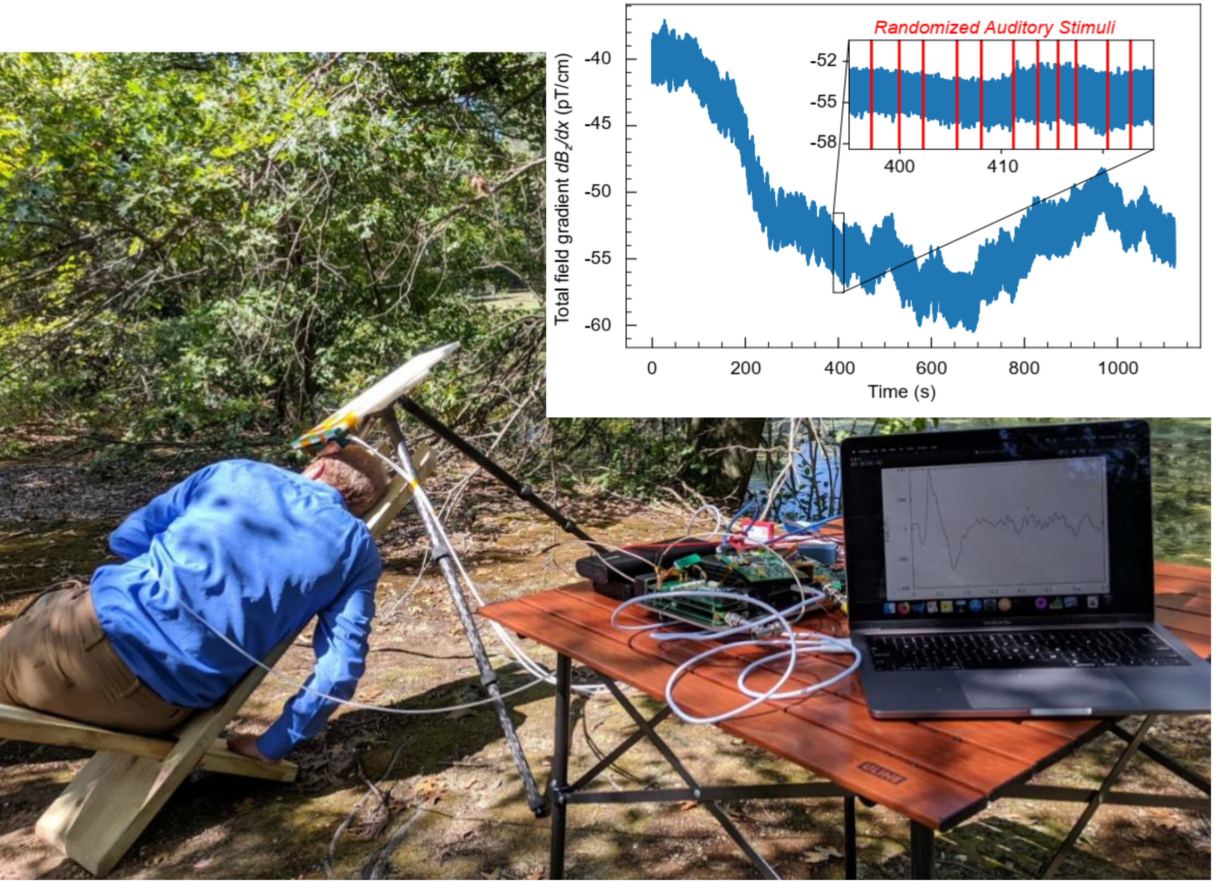
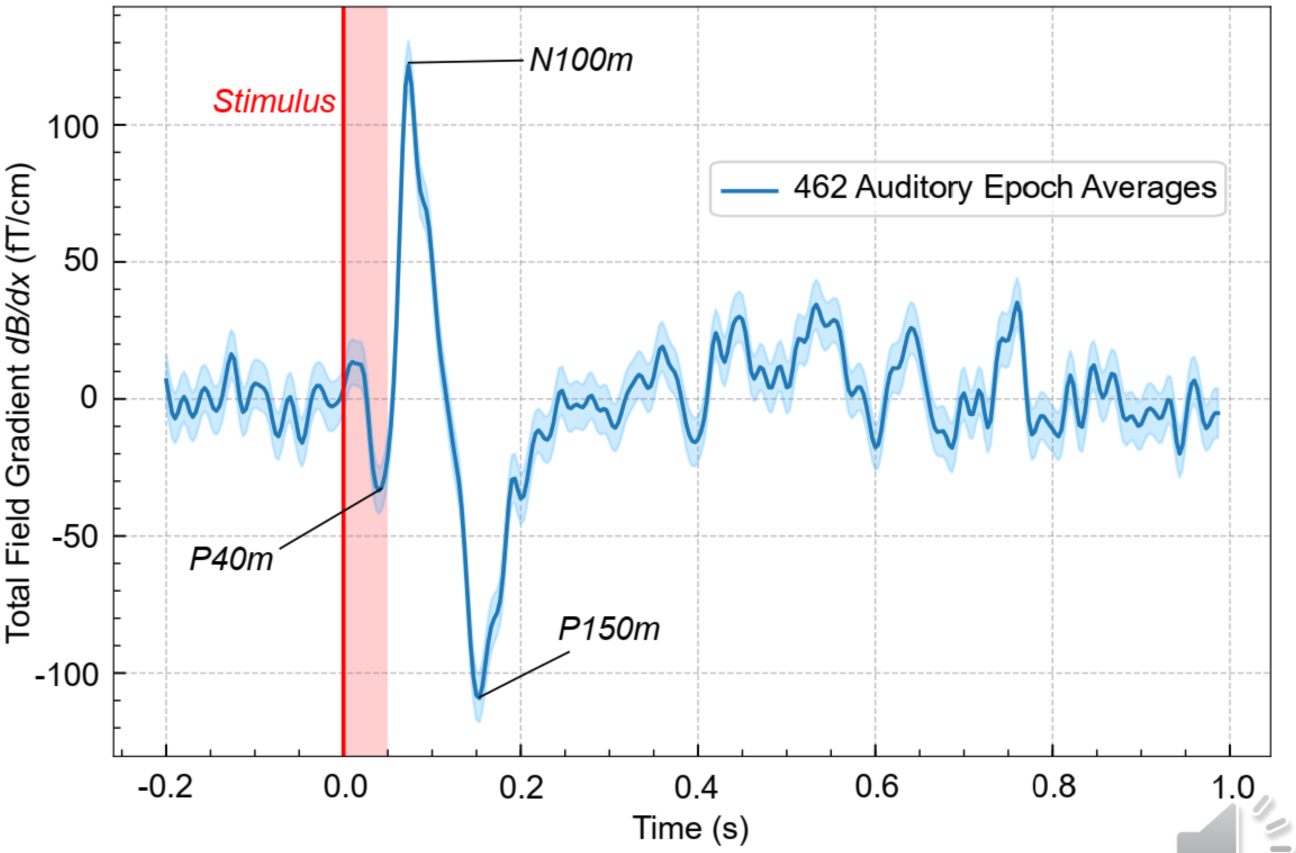
A. Braun, W. Lee, V. G. Lucivero, M. V. Romalis (2020) arXiv:2001:03534



- Magnetoencephalography (MEG): Auditory Evoked Fields





Summary

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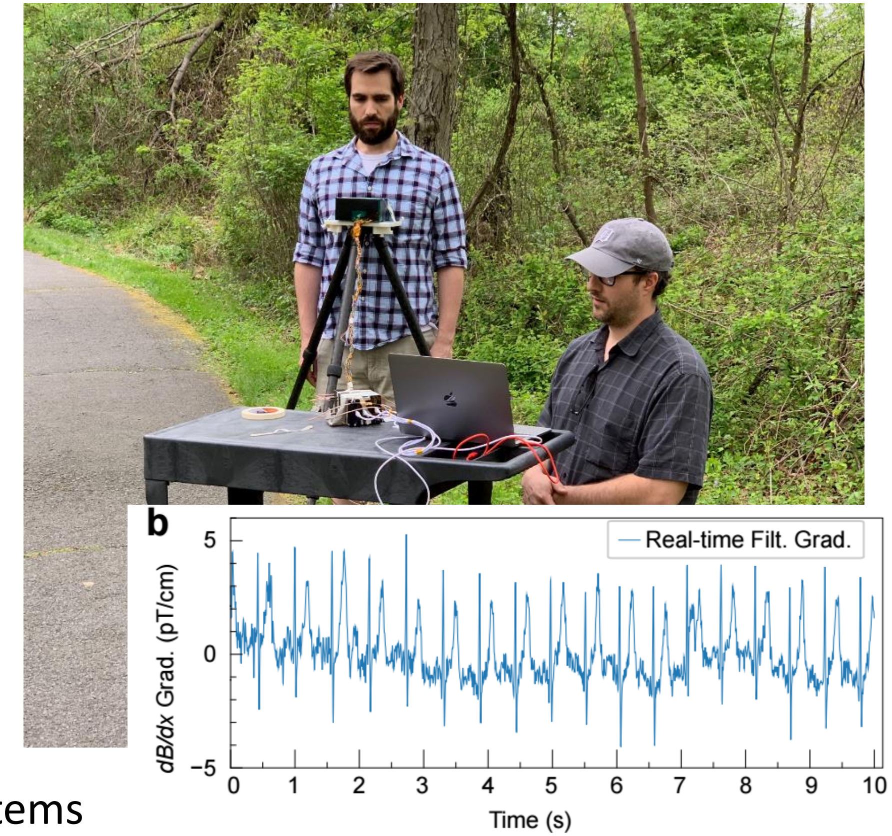
A. Braun, W. Lee, V. G. Lucivero, M. V. Romalis (2020) arXiv:2001:03534



- "Portable magnetometry for detection of biomagnetism in ambient environments"
- Multipass probe and pulsed pump: high optical rotation and SNR
- Frequency detection: linear and high dynamic range
- Works well in unshielded environment!
- Future: Improve performance of sensor to level comparable to SQUID systems

  - *Wonjae Lee* -> **Abstract: K01.00176 : A femtotesla pulsed gradiometer using multipass cells at finite fields**

  -"Vector-izing" sensor *Tao Wang* -> **Abstract: E01.00009 : Pulsed 87Rb vector magnetometer using a fast rotating field**

  -Build Array of sensors to demonstrate low crosstalk, use for current dipole source localization

Commercialization:

- Twinleaf now sells a less aggressive, single pass configuration with no vacuum package that gives ~0.2 pT/rtHz in Earth's field

https://twinleaf.com/scalar/OMG/

OMG Optical Magnetic Gradiometer

PRINCETON UNIVERSITY

Romalis group (c. 2017)

Thanks! DARPA

Twinleaf

www.twinleaf.com

SRI International

See MEG/MCG Paper - arXiv:2001:03534

Questions please contact me at
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