SAND2022-9679C

Sandia National Laboratories

CENTER 5200

Advanced quantum sensing technologies & underground utility detection

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ARPA-E Undergrounding Workshop, 19 July 2022

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Agenda

- Overview of current underground sensing technologies from geophysics
  - EMI, GPR, passive magnetic, etc.
- Topside vs. down-hole sensing considerations
- Quantum sensing modalities for underground detection:
  - RF magnetometry
  - Gravimetry
- Recent progress in sensor development at Sandia

Geophysical interrogation of the urban subsurface – a Maxwell perspective

Strategy: Correlate anomalies in electromagnetic material properties (susceptibility, conductivity, permittivity) with the presence of anthropogenic artifacts (pipes, rebar, etc.) or naturally occurring heterogeneities such as voids or bedrock variability.

Challenges: tradeoff between depth sensitivity and signal fidelity; ambient background noise overwhelming subtle signals of interest; false positives; cumbersome data collects, non-uniqueness.

Electromagnetic Spectrum

Electro/Magneto-statics — Freq = DC — Depth ~100s m — mHz

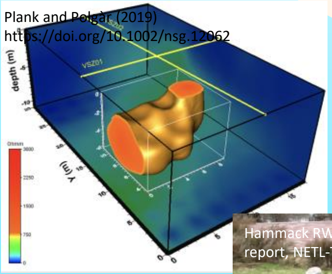
Time- or frequency-domain induction — Hz — 10s m — kHz

Ground Penetrating Radar — MHz — 1-10 m — GHz


https://archive.epa.gov/esd/archive-geophysics/web/html/resistivity_methods.html

1
- Deploy an array of electrodes on/in ground
- Energize various pairs as “sources” while measuring voltage differences between remaining pairs

Imaging karst voids with DC voltages


Plank and Polgar (2019) https://doi.org/10.1002/nsg.12062

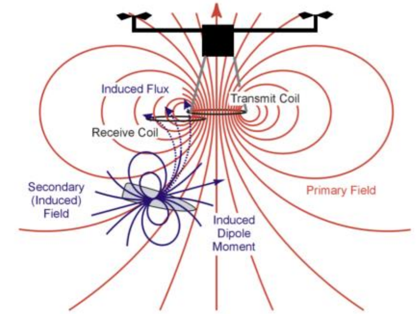
2 Broadband EM uses a time-varying source signal that can be either direct or inductively coupled to the ground

3 Data can be electrode voltages and/or magnetic field fluxes. Various combinations are available.

COTS GPR and EM Induction Sensors


https://www.sensoft.ca/

Prototype UAV packages

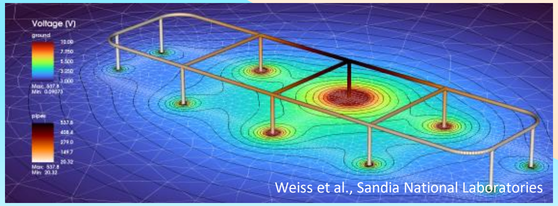


Barrowes et al. (2019), ERDC/CCREL-19-DRAFT

Magnetic Prospecting for Abandoned Wells


Hammack RW and GA Veloski, NETL report, NETL-TRS-5-2016 (2016).

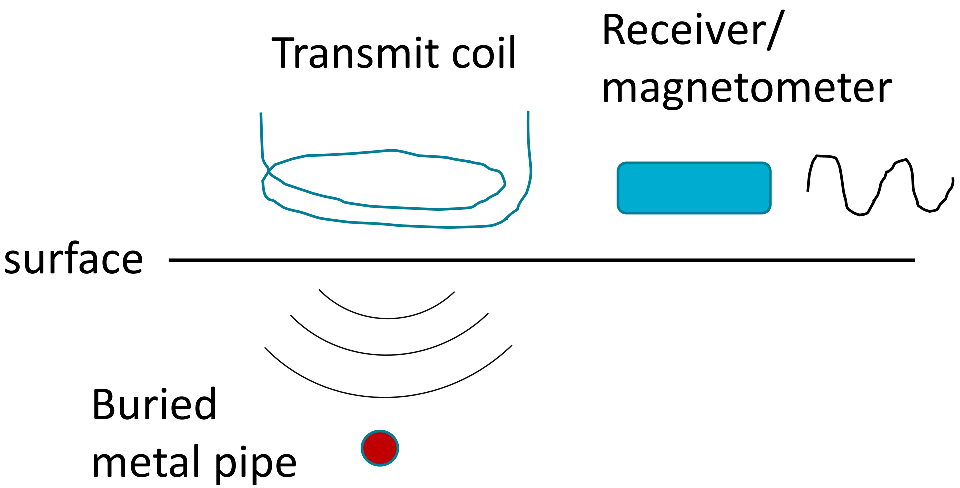
Direct excitation of pipe assemblages


Weiss et al., Sandia National Laboratories

Needs and Opportunities

- Real-time data integration/analysis/visualization
- Physics-informed ML for multi-modal data (seismic + EM?) data reduction.
- Exploitation of “noise” for better resolution
- Optimization for drone/other data collect platforms

Electromagnetic induction (EMI)



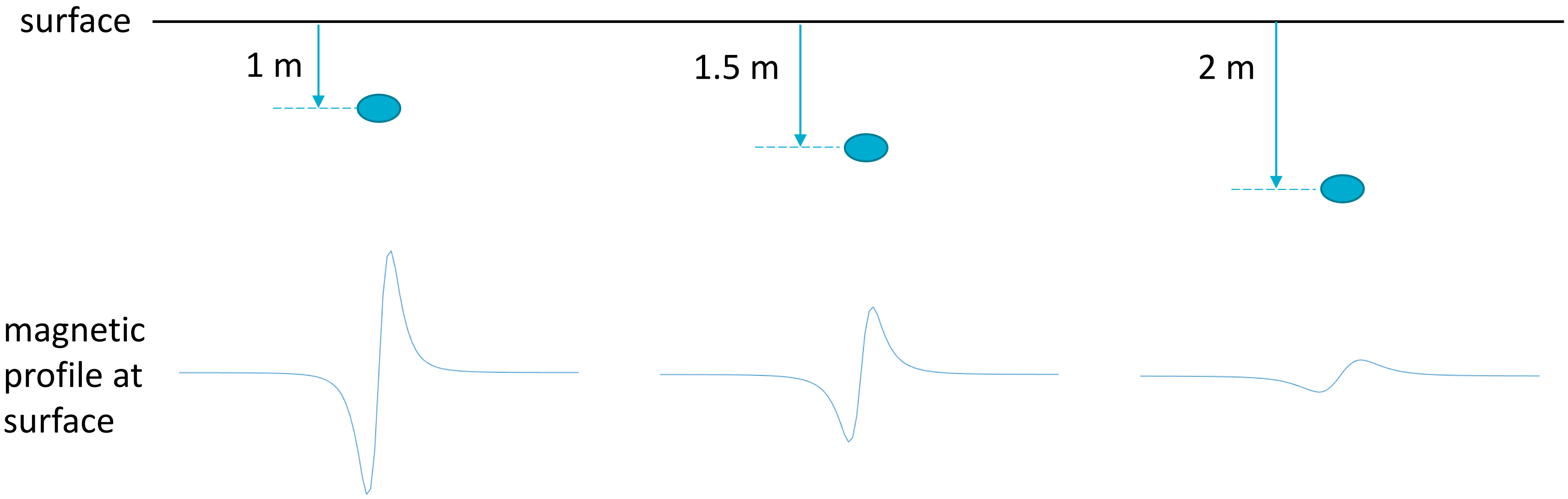
Faraday's Law

$$V_{ind} = -\frac{d\Phi_B}{dt}$$

$$\Phi_B = \oint_S \vec{B} \cdot d\vec{A}$$

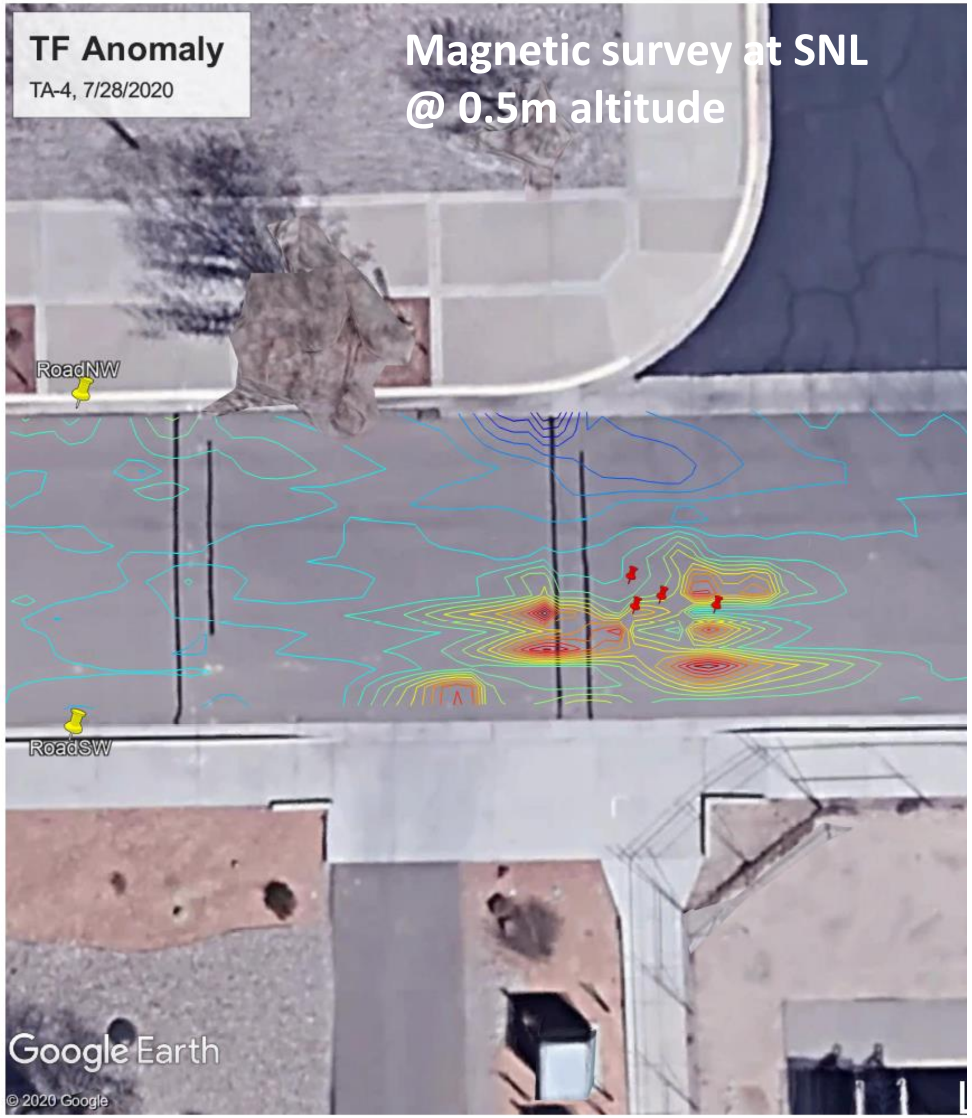
- EMI = active technique to detect conductors by inducing current in buried object via Faraday's Law.
  - Time and frequency domain methods
- Advantage: works for all metals, ferrous or non-ferrous (aluminum, copper, etc.)
- Disadvantage: Range and detection swath are limited by physics of transmission and reception of induced magnetic field.
- $1/R^6$ range dependence of signal when R>>d (d=transmit coil diameter).
- Additional loss of signal due to attenuation in soil
  - Skin depth $\propto 1/\sqrt{f}$
  - Low frequency penetrates deeper
  - f = 50-480 kHz (tune for depth)
- EMI commonly used to detect buried cables, pipes at >2 m depth (up to 10 m) with reduced spatial resolution in horizontal plane

Depth dependence of magnetic signature (dipole)



- Amplitude decreases *nonlinearly* with depth ($1/R^3$ for dipole, $1/R$ for cable)
- Width of profile is *proportional* to depth

Passive magnetic sensing

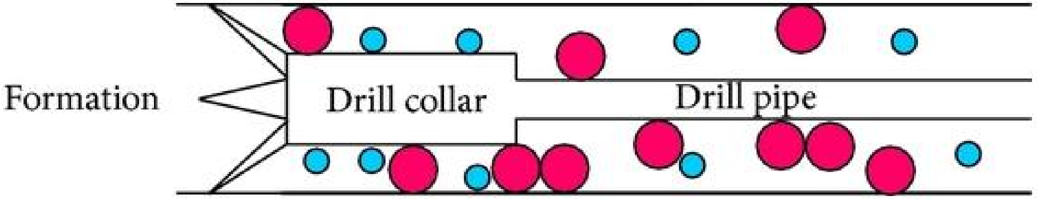


- Passive magnetic sensing relies on magnetism of the buried object
- Advantage: Greater detection depth
  - $1/R^3$ range dependence of signal for dipole source
  - No loss from soil attenuation
- Disadvantages:
  - Only works for iron-containing (ferrous) metals
  - Signal can be confused by nearby surface magnetic objects (clutter).
- Greater detection depth is possible than with EMI, but with low spatial resolution due to spreading effect of dipole fields

Topside vs. down-hole sensing

Geometrics magnetic survey

Horizontal drilling



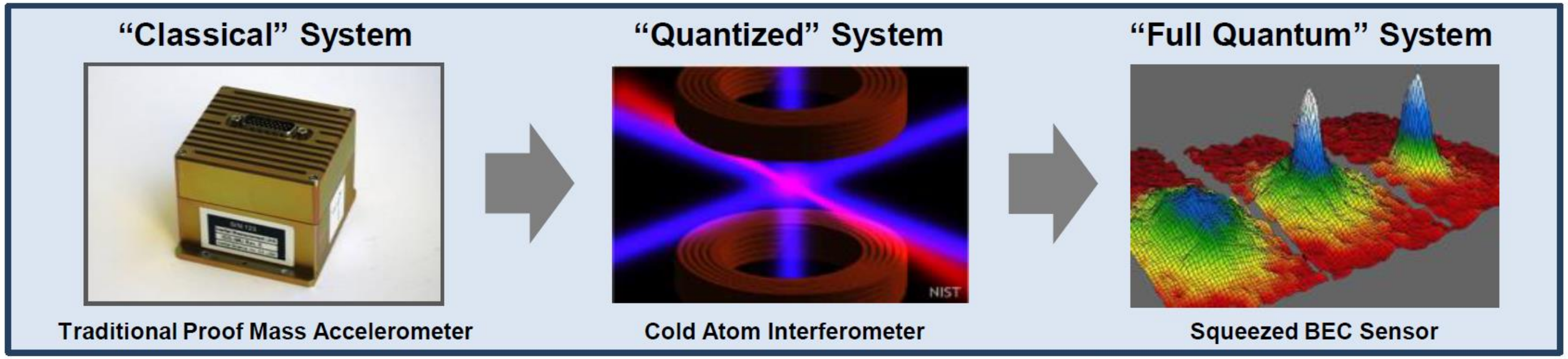
- Topside sensors can have higher SWaP and lower TRL
- Data collection includes GPS position
- Facilitates mapping

- Down-hole sensors are highly size-constrained (3-4 inch pipe ID)
- Rugged against shock & vibe, drilling mud
- No GPS data – better for obstacle avoidance than mapping
- Goal: prevent cross-bore events!

What is quantum sensing?

1. Use of a quantum object to measure a physical quantity (classical or quantum). The quantum object is characterized by quantized energy levels. Specific examples include electronic, magnetic or vibrational states of superconducting or spin qubits, neutral atoms, [neutrons] or trapped ions.
2. Use of quantum **coherence** (i.e., wavelike spatial or temporal superposition states) to measure a physical quantity. **Quantum 1.0**
3. Use of quantum **entanglement** to improve the sensitivity or precision of a measurement, beyond what is possible classically. **Quantum 2.0**

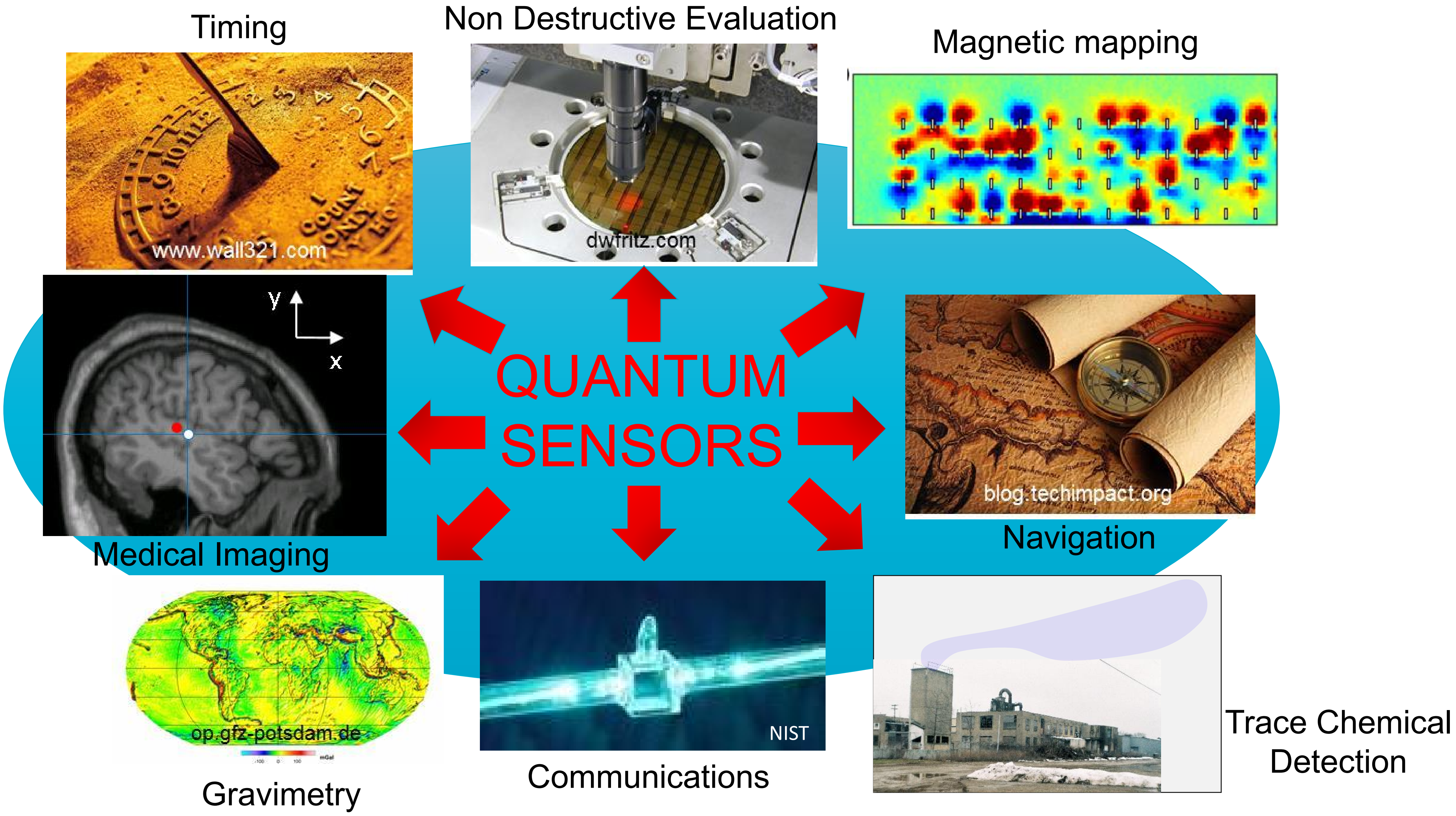
https://doi.org/10.1103/RevModPhys.89.035002



Quantum 1.0 Quantum 2.0

U.S.A.F. Scientific Advisory Board, *Utility of Quantum Systems for the Air Force,* 2015.

Potential application impact



White House Office of Science and Technology Policy

- March 2022 report: Bringing Quantum Sensors to Fruition

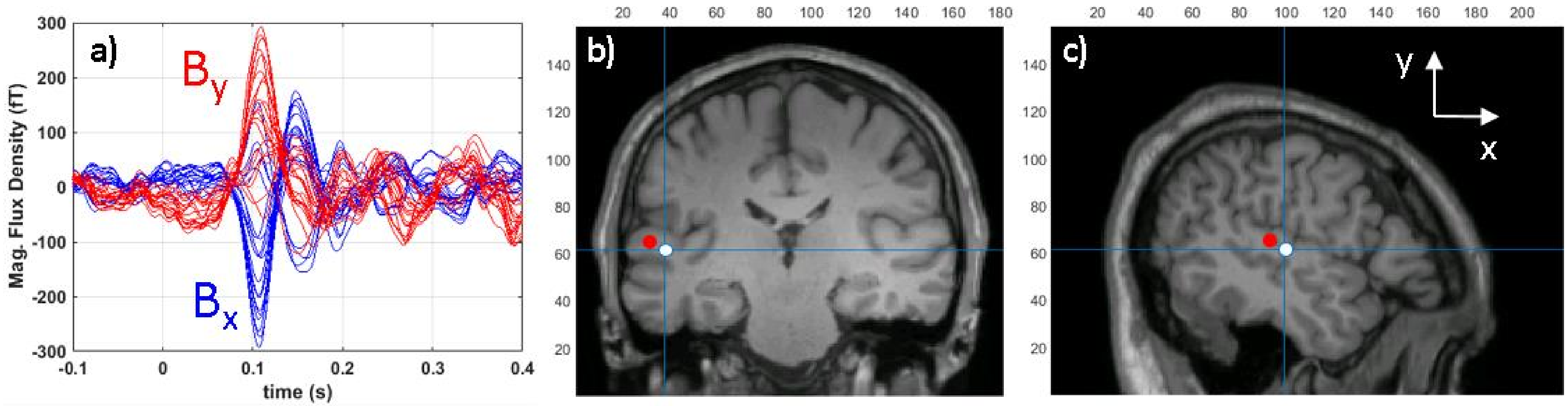
Box 7: Recommendations to Facilitate the Development and Utilization of Quantum Sensors

1. **Agencies leading QIST R&D should accelerate the development of new quantum sensing approaches and prioritize appropriate partnerships with end users to elevate the technology readiness of new quantum sensors.**
2. **Agencies that use sensors should conduct feasibility studies and jointly test quantum prototypes with QIST R&D leaders to identify promising technologies and to focus on quantum sensors that address their agency mission.**
3. **Agencies that support engineering R&D should develop broadly applicable components and subsystems, such as compact reliable lasers and integrated optics, to facilitate the development of quantum technologies and promote economies of scale.**
4. **Agencies should streamline technology transfer and acquisition practices to encourage the development and early adoption of quantum sensor technologies.**

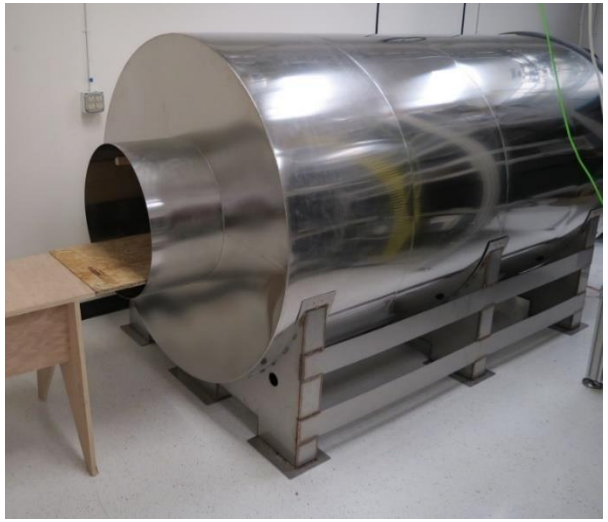
Optically pumped magnetometers (OPMs) at Sandia

- OPMs for magnetoencephalography (MEG)
  - National Institutes of Health
- OPMs for the detection of signatures from capacitive discharges units (CDUs)
  - National Nuclear Security Administration (NNSA): NA-22
- Development of a OPM gradiometer
  - DARPA: Atomic Magnetometer for Biological Imaging In Earth's Native Terrain (AMBIIENT)
- RF OPM for Low Frequency (10 kHz to 500 kHz) detection
  - Internally funded: LDRD
- Nitrogen-vacancy centers in diamond
  - Internally funded: LDRD
  - High spatial resolution magnetometry
    - Electrical circuit failure analysis

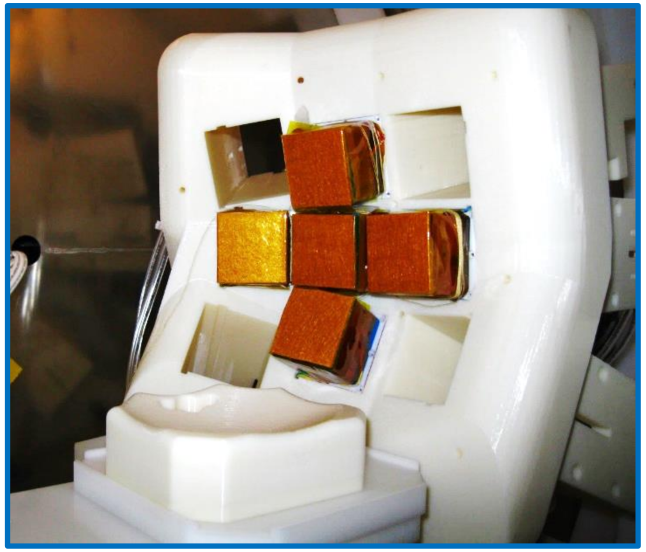
Magnetoencephalography (MEG): localize auditory activity



Magnetic Shield



5-sensor, 20-channel array



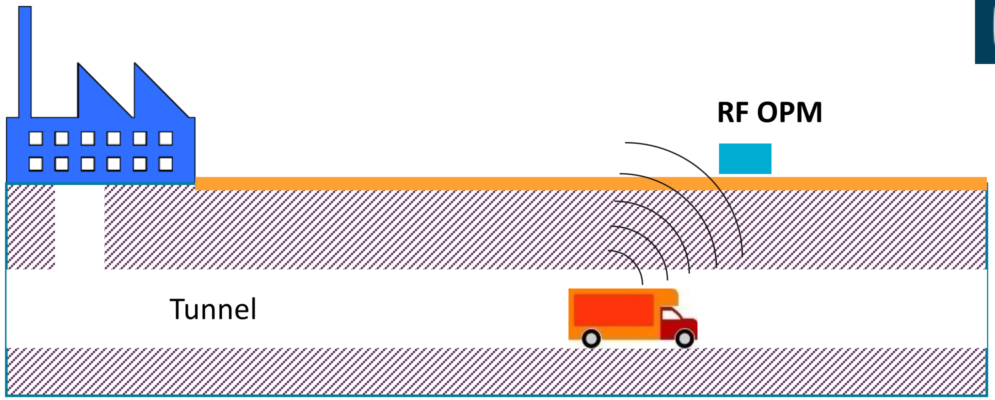
- Auditory stimulation
  - 1000 Hz tone, every 1 to 1.5 s
  - 456 trials
- White dot: OPM location
- Red dot: SQUID MEG location

- Sandia expertise with MEG can be applied to underground utility mapping

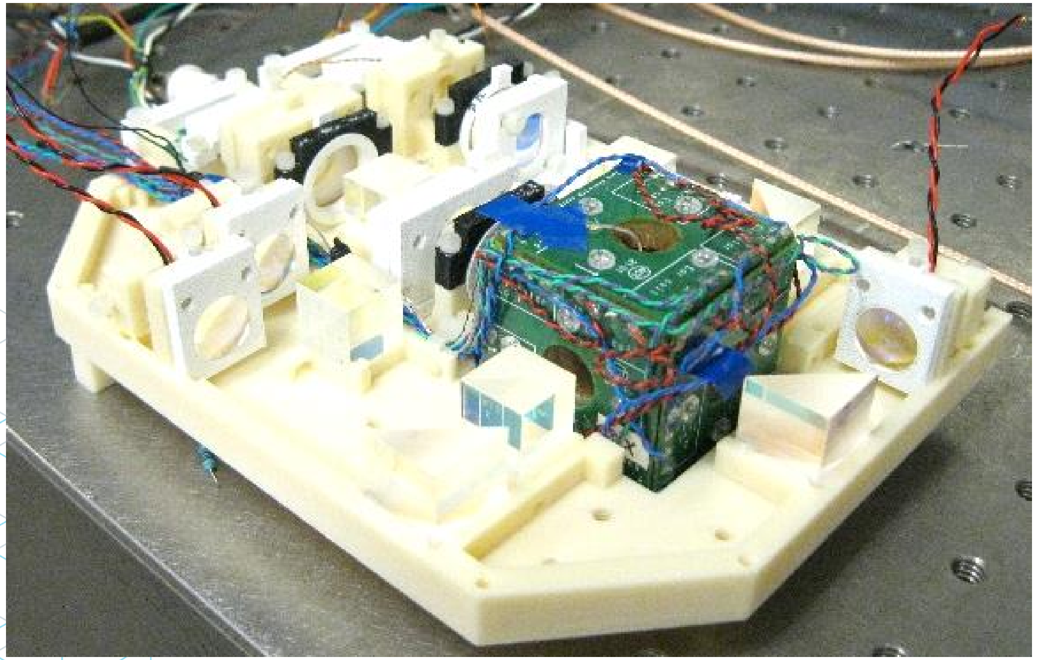
RF magnetometer

- Quantum sensor suitable for signal transmission through soil and utility detection
- VLF (3-30 kHz) can penetrate buildings, soil, water
- Compact sensor head: 0.6 L
- Unshielded operation: active feedback to lock onto desired frequency

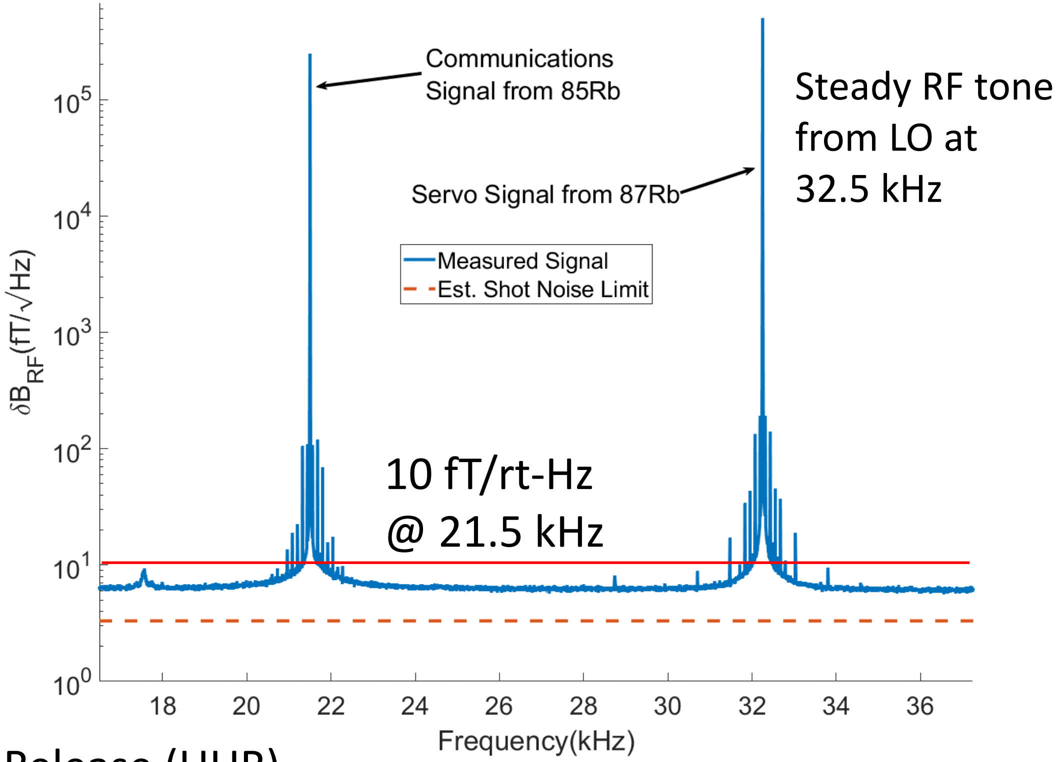
J. Dhombridge et al., submitted to PRA (2022).



Miniaturized sensor head

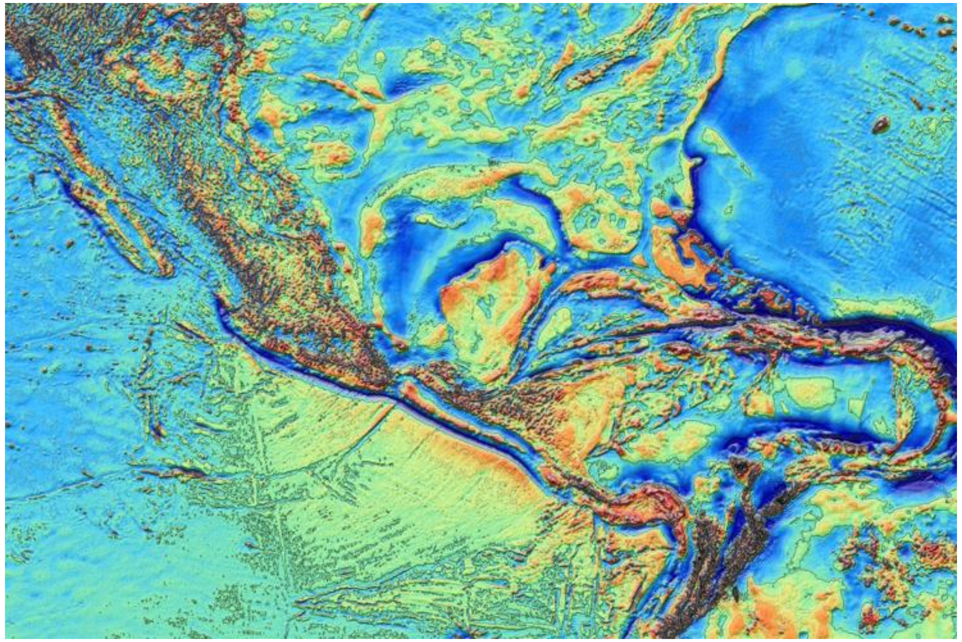


Sensor performance vs. frequency

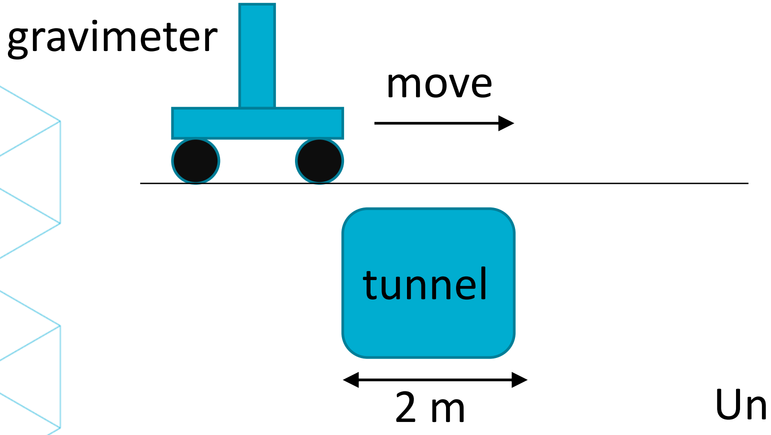


Gravity anomaly mapping with quantum gravimeter

Combined Gravity Anomaly (North America)



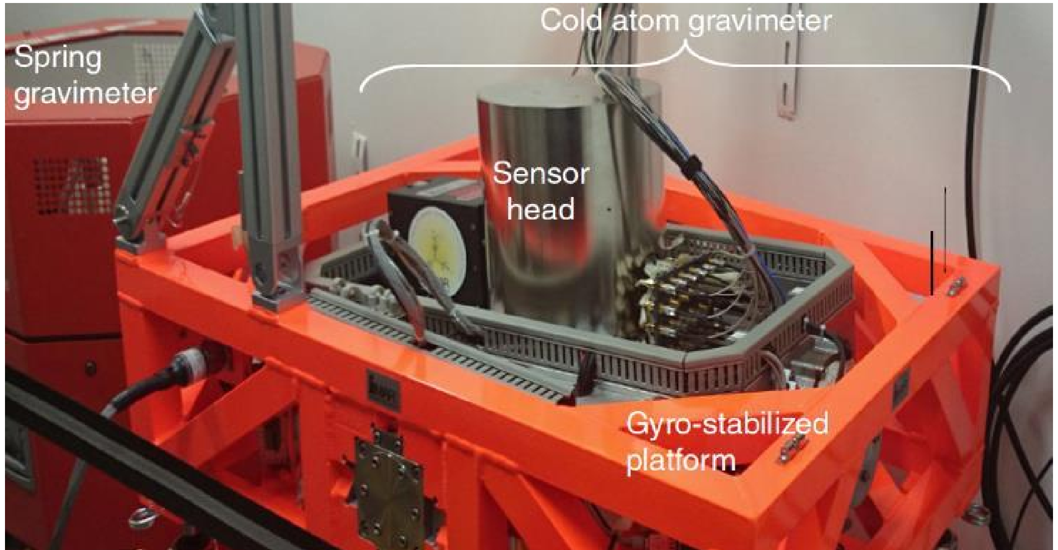
Sandwell et al., Science, 346, 6205 (2014).



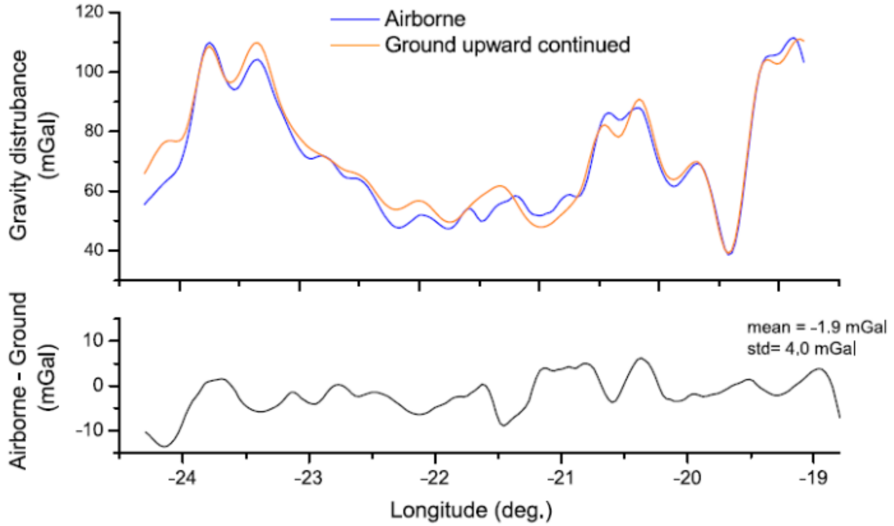
- Gravity anomalies due to mass variations underground can be detected by sensitive gravimeter (accelerometer)
  - Cannot be shielded
  - Less sensitive to clutter than mag
- Techniques pioneered by oil & gas industry for large scale resource exploration
- Current quantum gravimeters are large
  - 7 kg weight, 13 L volume
  - Suitable for topside mapping
  - Further miniaturization/ruggedization needed!
- Mass anomaly modeling capability exists at SNL-CA
  - Can apply to utility detection problem
  - Few cm resolution desirable
  - 50 cm spatial resolution demonstrated in tunnel detection (Stray et al., Nature, 602, 590 (2021).

Airborne gravimetry with atom interferometer

- Gravity measurements over Iceland
- Gimballed platform to maintain vertical
- Feed forward technique
  - Dynamic range = 1000 fringes or ~0.1 g at T = 20 ms
- Data rate = 10 Hz
- Errors: 1.7 to 3.9 μg
- ONERA – The French Aerospace Lab



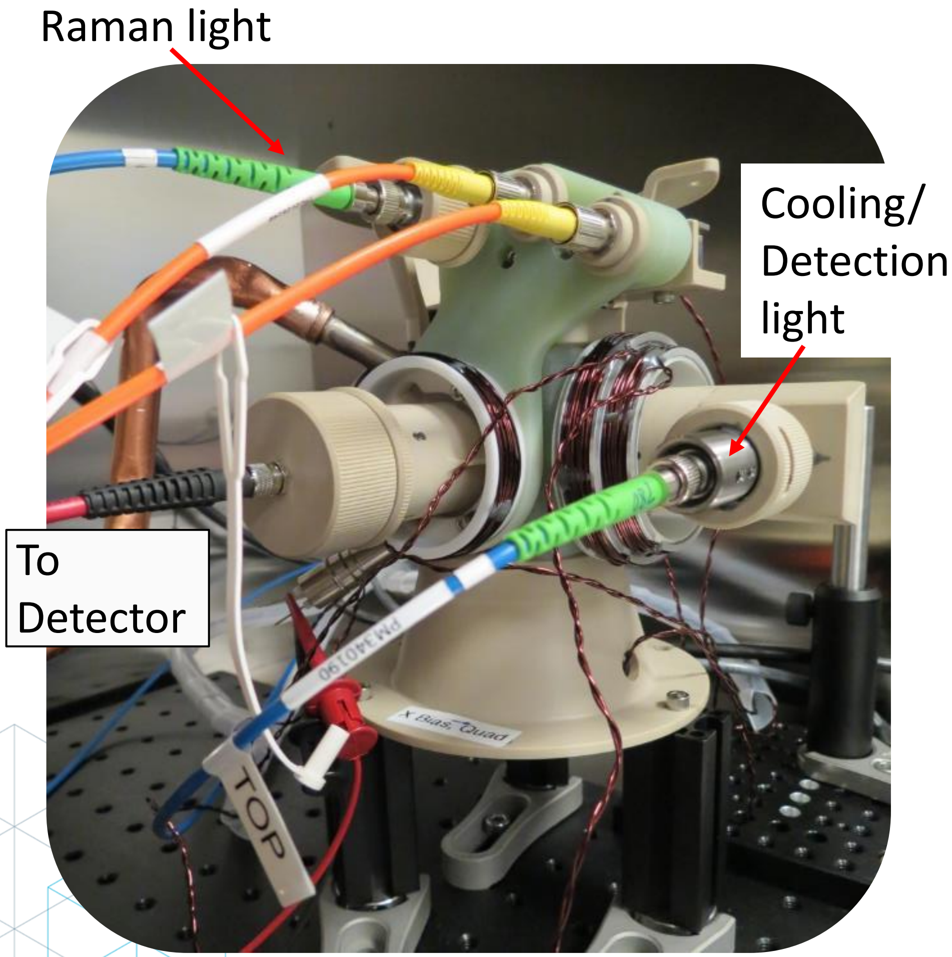
Bidel, Y., Zahzam, N., Blanchard, C. *et al.* Absolute marine gravimetry with matter-wave interferometry. *Nat Commun* **9,** 627 (2018).



Aircraft: Bidel, Y., Zahzam, N., Bresson, A. *et al.* Absolute airborne gravimetry with a cold atom sensor. *J Geod* **94,** 20 (2020).

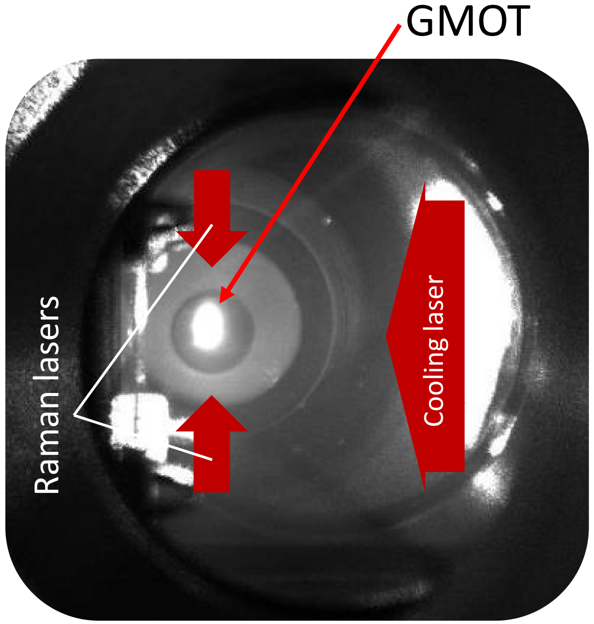
Ship: Bidel, Y., Zahzam, N., Blanchard, C. *et al.* Absolute marine gravimetry with matter-wave interferometry. *Nat Commun* **9,** 627 (2018).

Sandia compact atom interferometer sensor head

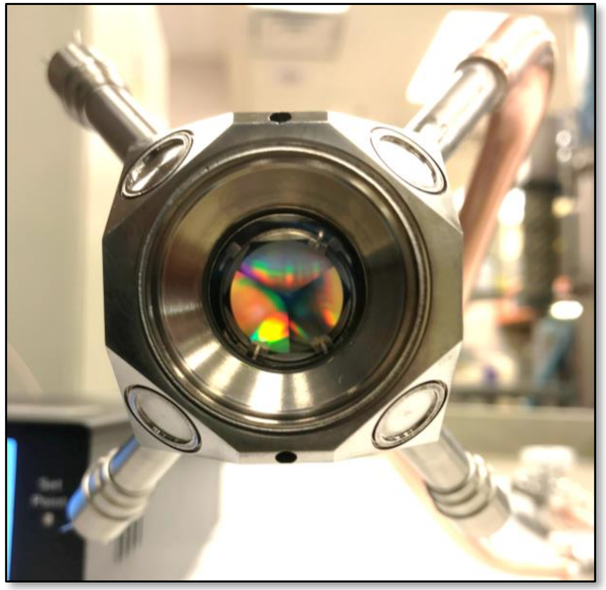


Same Raman configuration used in McGuinness, et al., APL (2012)

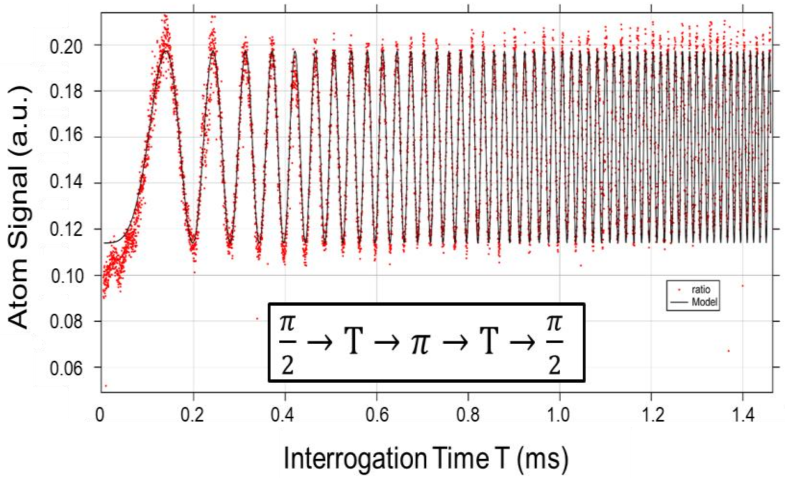
- Grating magneto optical trap (GMOT)
- Grating replaces one window of vacuum package
- Vacuum maintained by ion pump, fused silica windows
- Atom number: 10^7 laser cooled to 18 μK.



Ti Vacuum Package with Grating



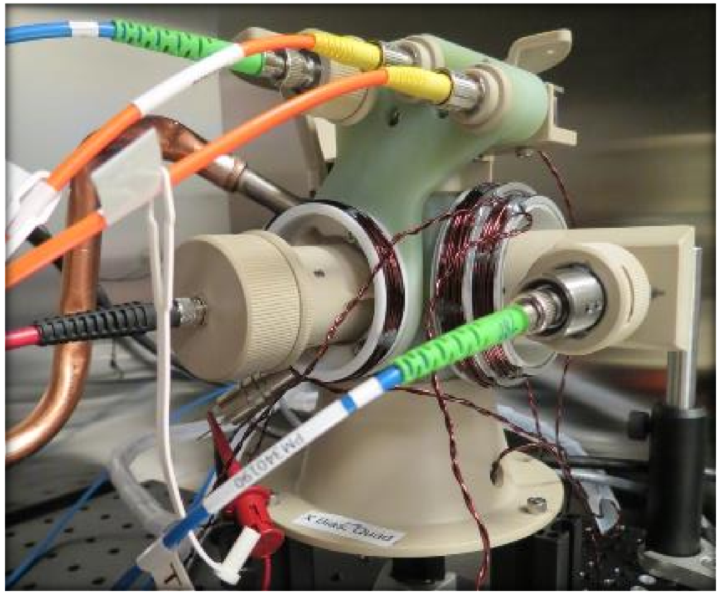
Gravimeter Signal



Unclassified Unlimited Release (UUR)

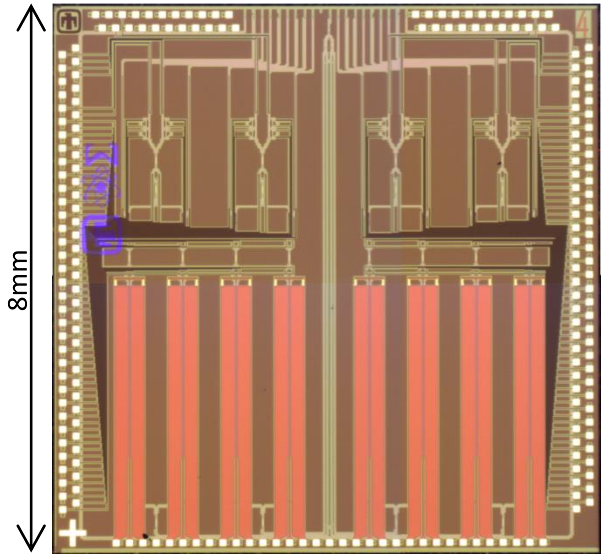
Inertial sensing with atom interferometry

- Strategic-grade accelerometer: 0.25 μg
- 50 Hz data rate
- Targeting a fieldable sensor
- Developing chip-scale laser system (PIC) for extreme miniaturization



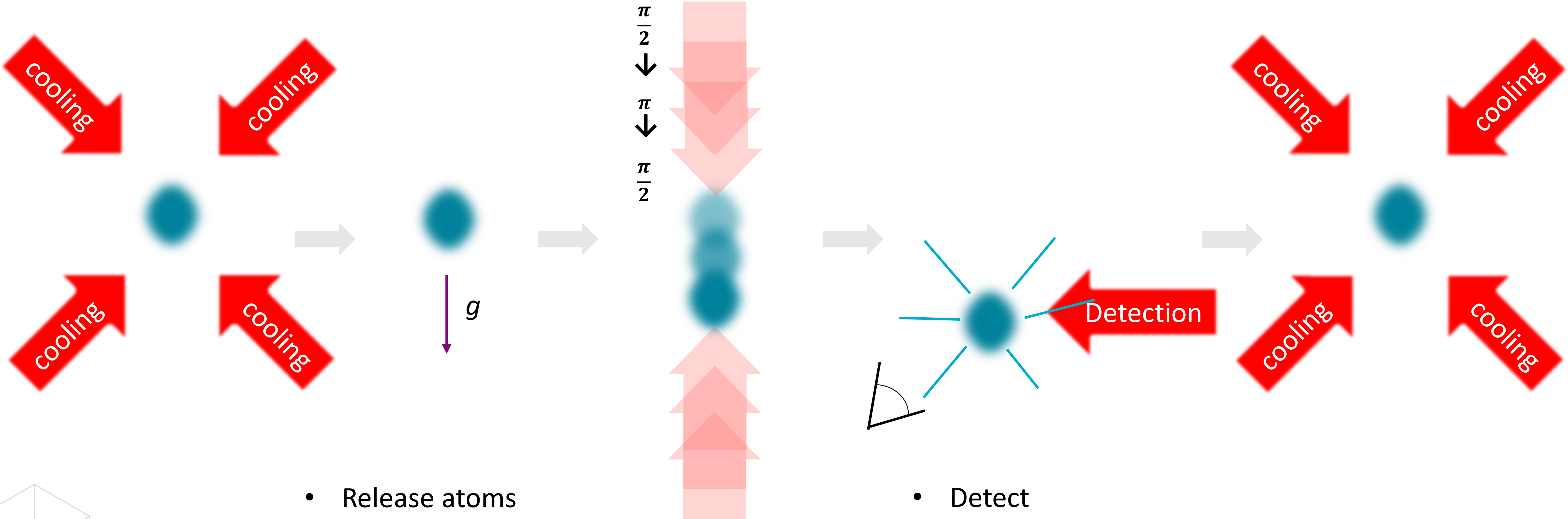
GMOT Grating

Photonic Integrated Circuits



Unclassified Unlimited Release (UUR)

High data rate atom interferometry



- Release atoms
- Detect
- Laser cooled atoms (4.3 ms, $T \approx 15\ \mu$K, $N \approx 10^6$)
- Raman pulse sequence (14 ms, T = 7 ms) $\frac{\pi}{2} \rightarrow \mathrm{T} \rightarrow \pi \rightarrow \mathrm{T} \rightarrow \frac{\pi}{2}$
- Recapture (1.7 ms)

Example, (40 Hz)$^{-1}$ cycle = measure acceleration every 25 ms

H. J. McGuinness, et al.,
Appl Phys Lett **100**, 011106 (2012).