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CENTER 5200

Advanced quantum sensing technologies & underground utility detection

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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:
  - 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

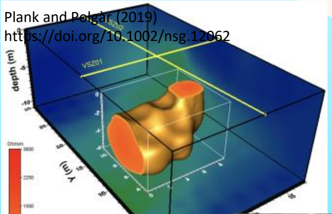
Time- or frequency-domain induction
Hz
10s m
kHz

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 Polgàr (2019)
https://doi.org/10.1002/nsg.12062

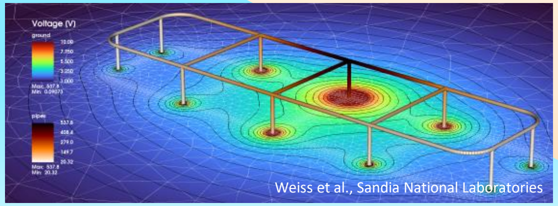
② Broadband EM uses a time-varying source signal that can be either direct or inductively coupled to the ground

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

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

Magnetic Prospecting for Abandoned Wells

Direct excitation of pipe assemblages

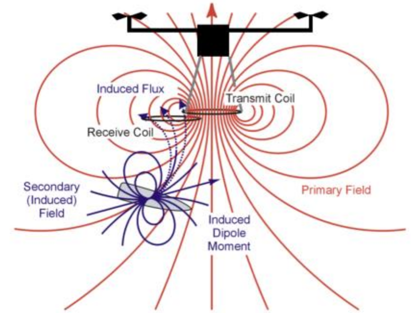


Weiss et al., Sandia National Laboratories

COTS GPR and EM Induction Sensors

https://www.sensoft.ca/

Prototype UAV packages

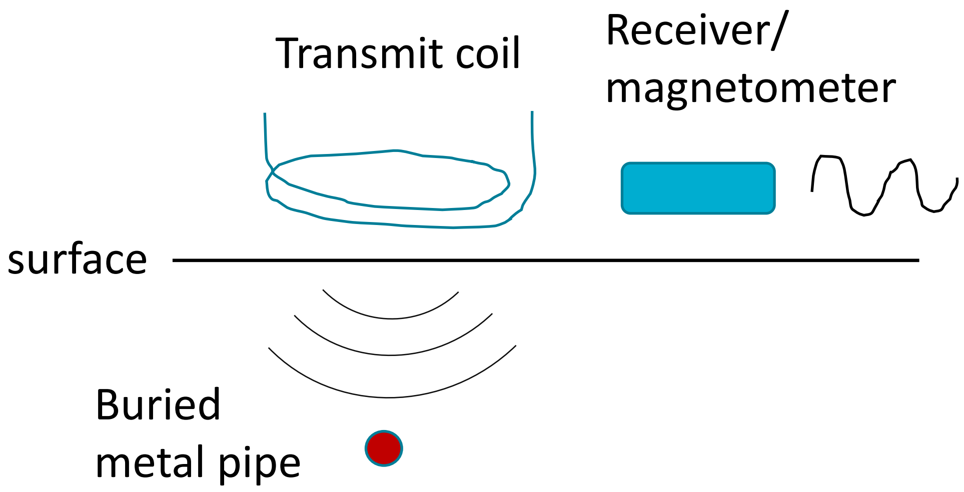


Barrowes et al. (2019), ERDC/CCREL-19-DRAFT

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)



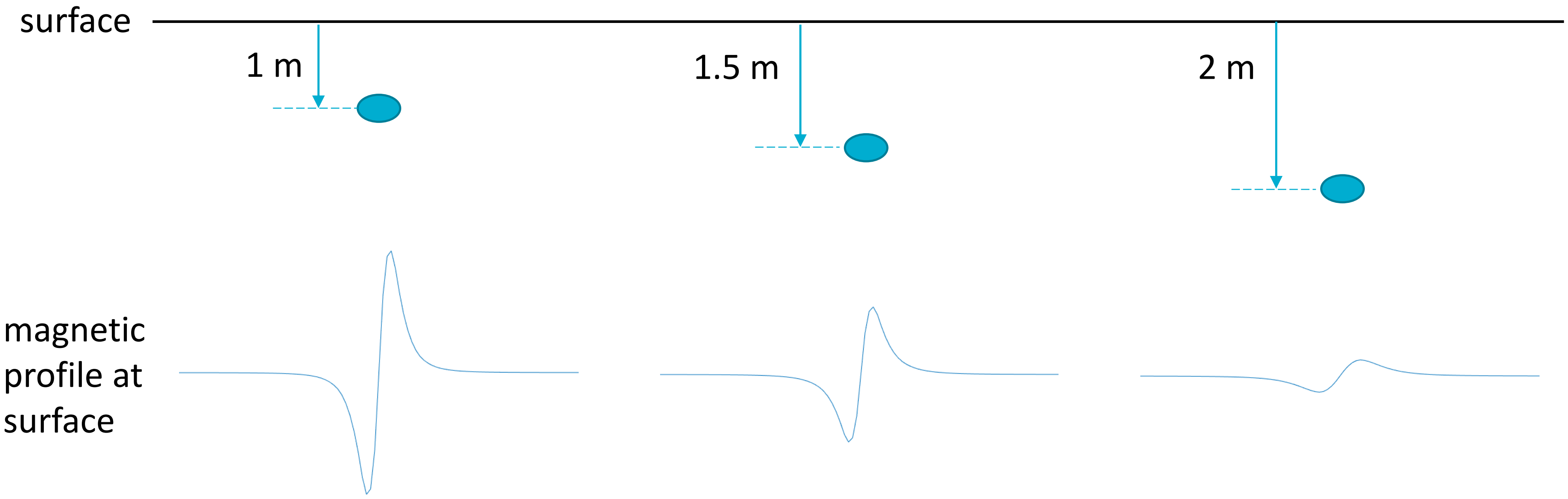
Faraday's Law

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

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

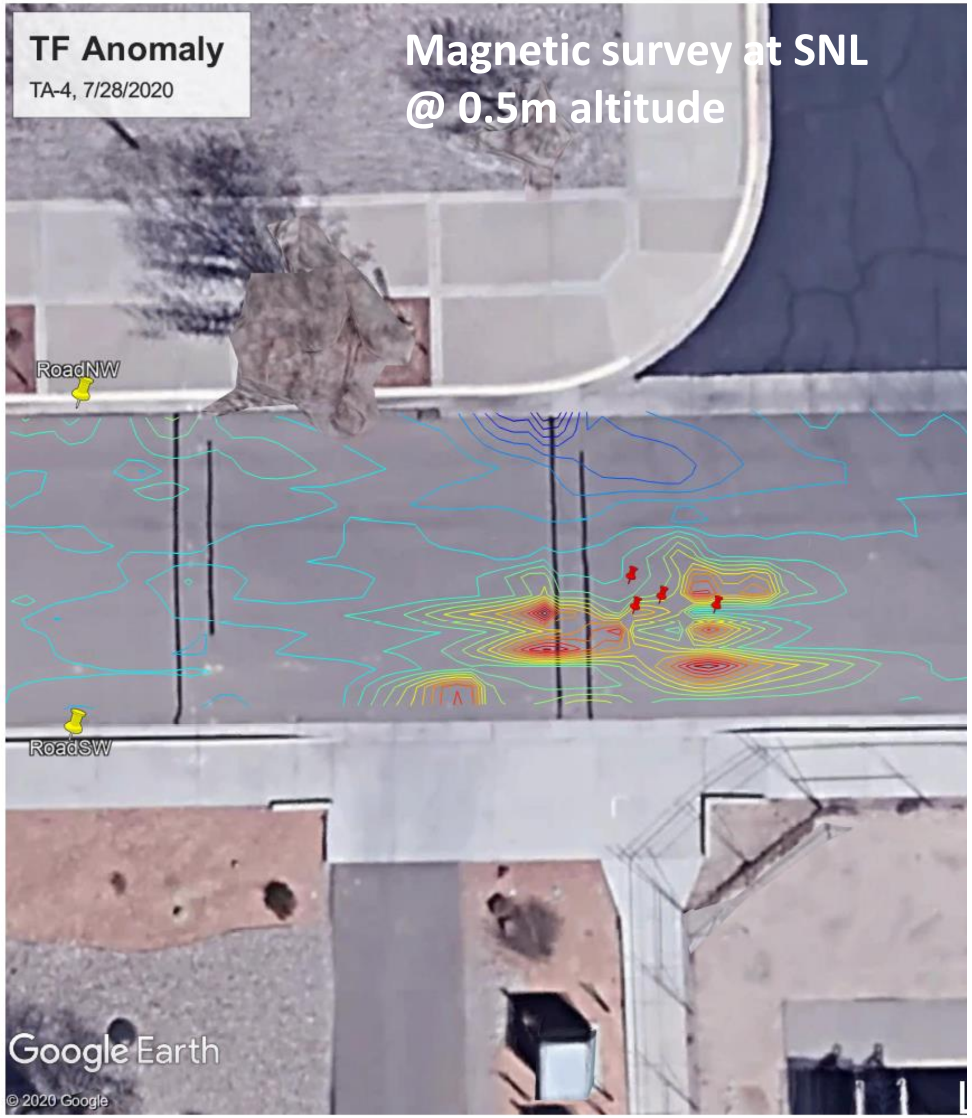
- EMI = active technique to detect conductors by inducing current in buried object via Faraday's Law.
  - Time and frequency domain methods
- Advantage: works for all metals, ferrous or non-ferrous (aluminum, copper, etc.)
- Disadvantage: Range and detection swath are limited by physics of transmission 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

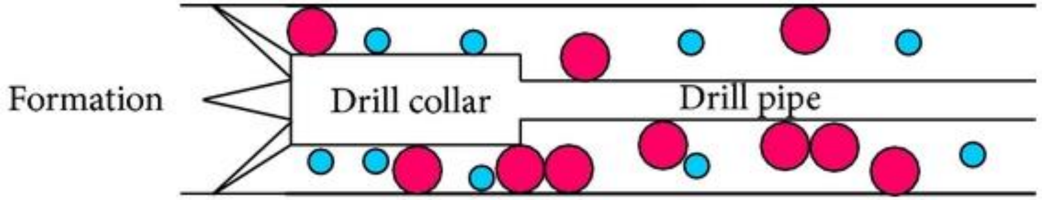


- Passive magnetic sensing relies on magnetism of the buried object
- Advantage: Greater detection depth
  - $1/R^3$ range dependence of signal for dipole source
  - No loss from soil attenuation
- Disadvantages:
  - Only works for iron-containing (ferrous) metals
  - Signal can be confused by nearby 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



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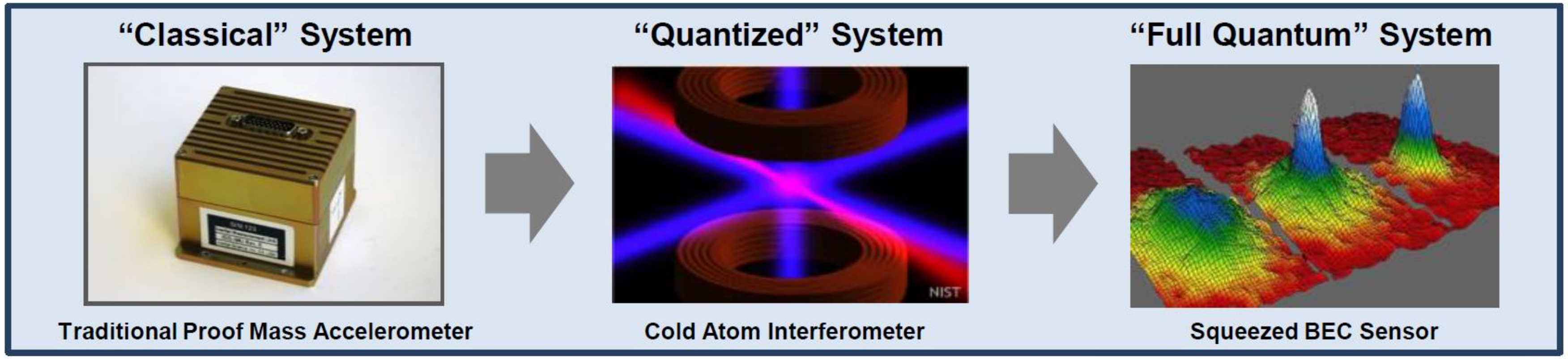
- Topside sensors can have higher SWaP and lower TRL
- Data collection includes GPS position
- Facilitates mapping

- 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

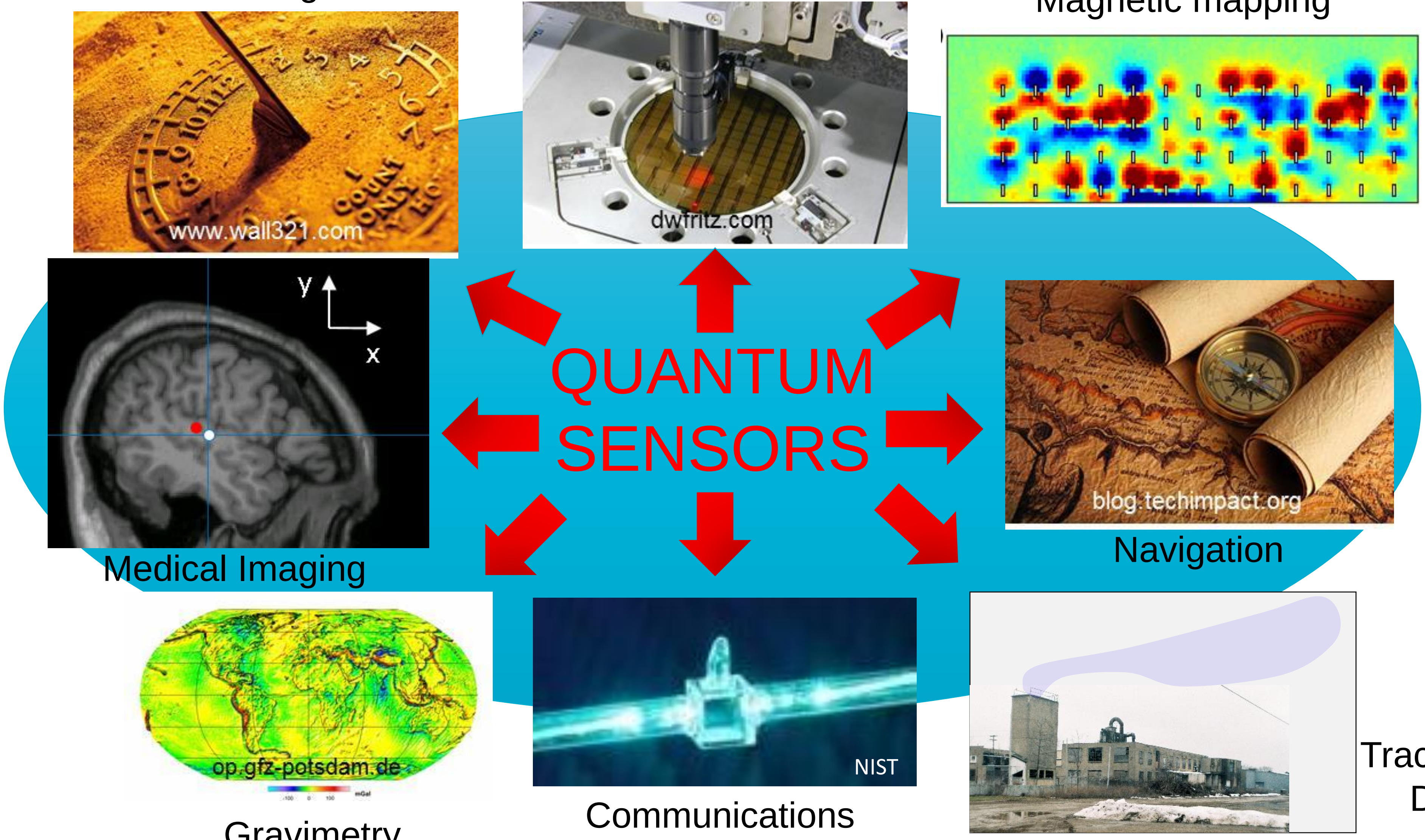


Quantum 1.0

Quantum 2.0

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

Potential application impact



Timing

Non Destructive Evaluation

Magnetic mapping

QUANTUM SENSORS

Medical Imaging

Navigation

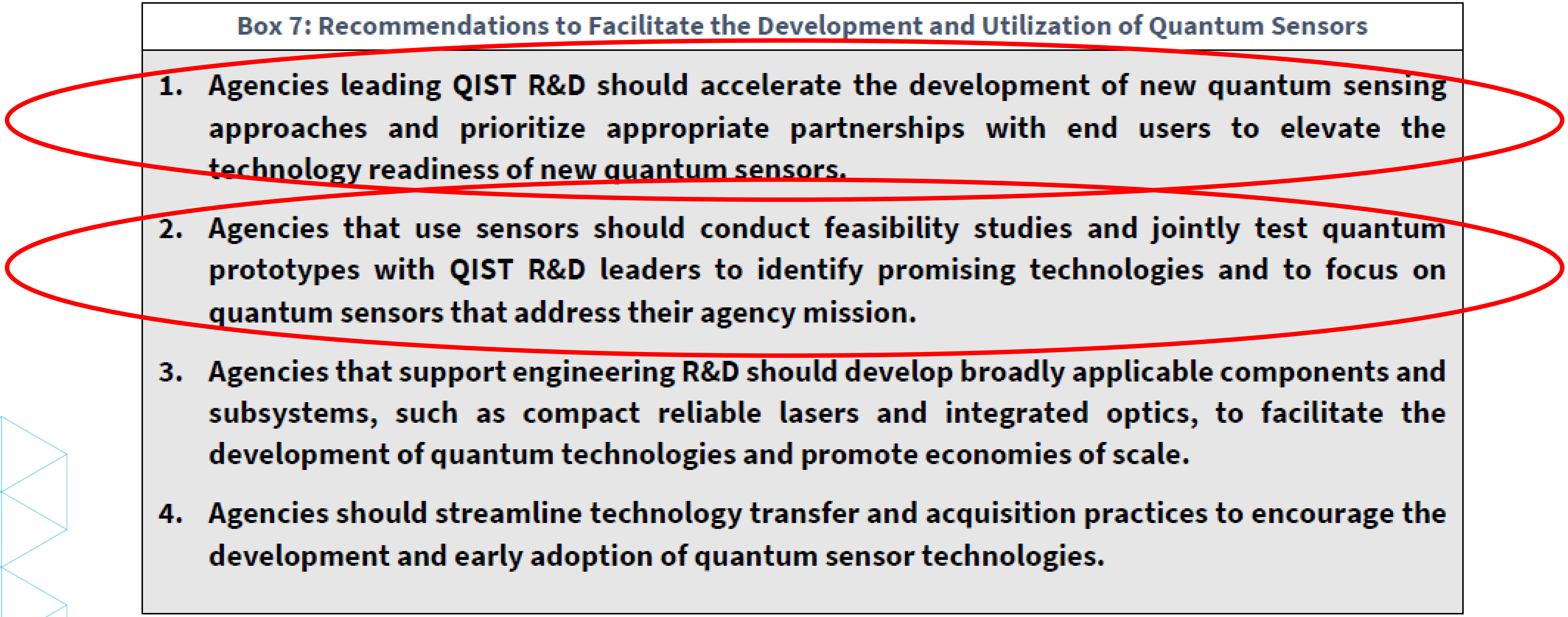
Gravimetry

Communications

Trace Chemical Detection

White House Office of Science and Technology Policy

- March 2022 report: Bringing Quantum Sensors to Fruition



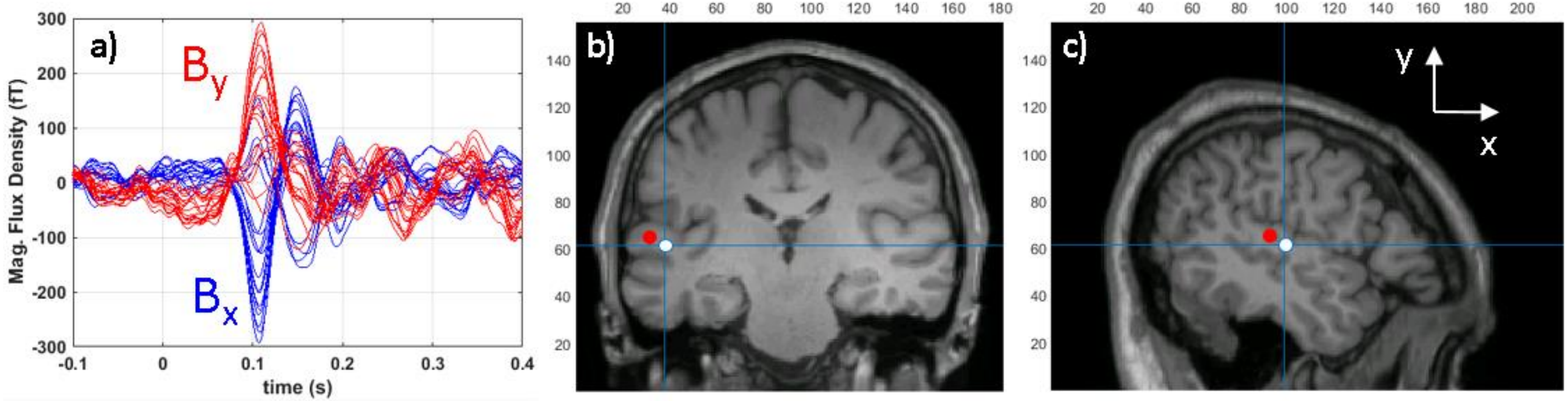
Box 7: Recommendations to Facilitate the Development and Utilization of Quantum Sensors

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
- Development of a OPM gradiometer
  - DARPA: Atomic Magnetometer for Biological Imaging In Earth's Native Terrain (AMBIIENT)
- Nitrogen-vacancy centers in diamond
  - Internally funded: LDRD
  - High spatial resolution magnetometry
    - Electrical circuit failure analysis

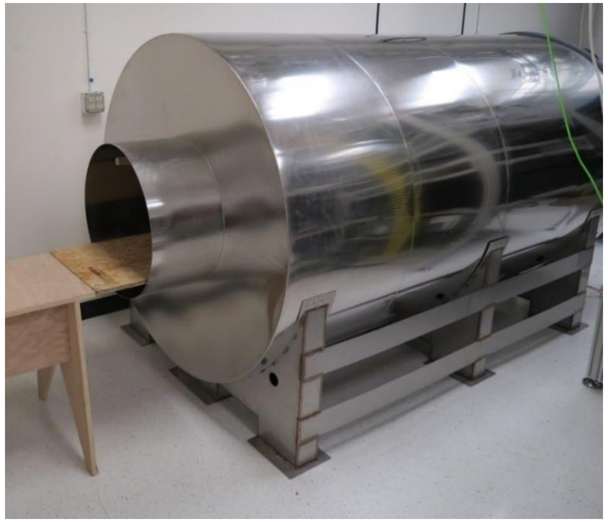
Magnetoencephalography (MEG): localize auditory activity



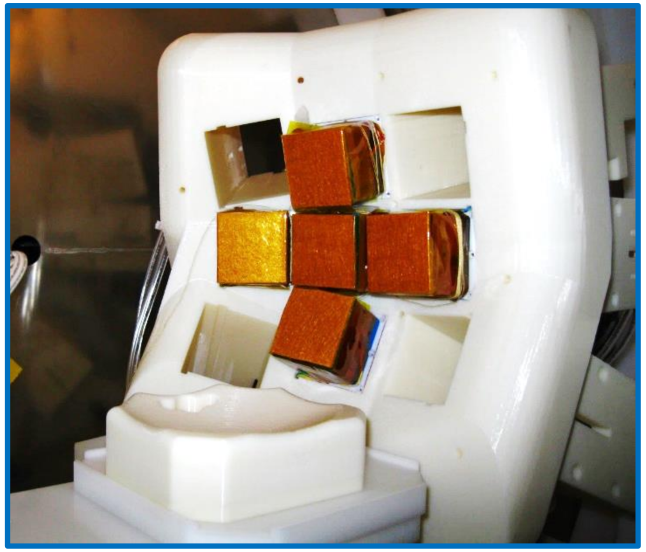
- Auditory stimulation
  - 1000 Hz tone, every 1 to 1.5 s
  - 456 trials
- White dot: OPM location
- Red dot: SQUID MEG location

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

Magnetic Shield

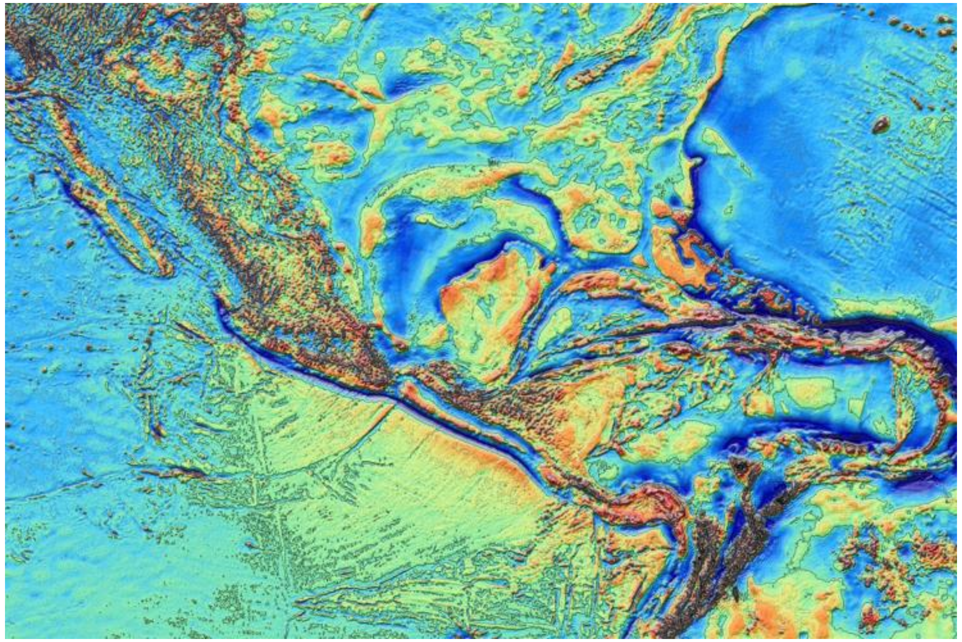


5-sensor, 20-channel array

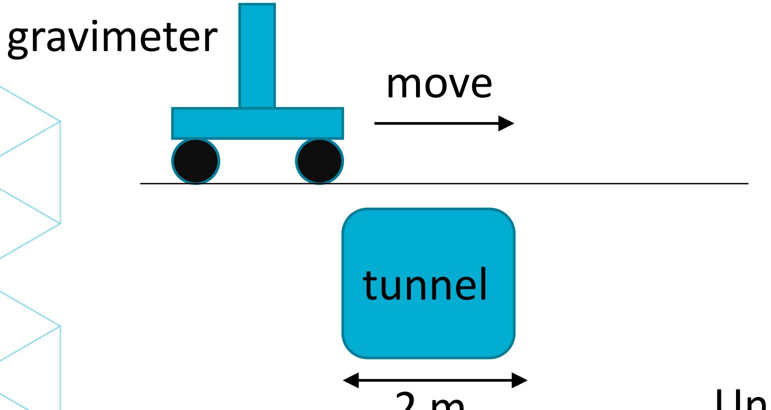


Gravity anomaly mapping with quantum gravimeter

Combined Gravity Anomaly (North America)



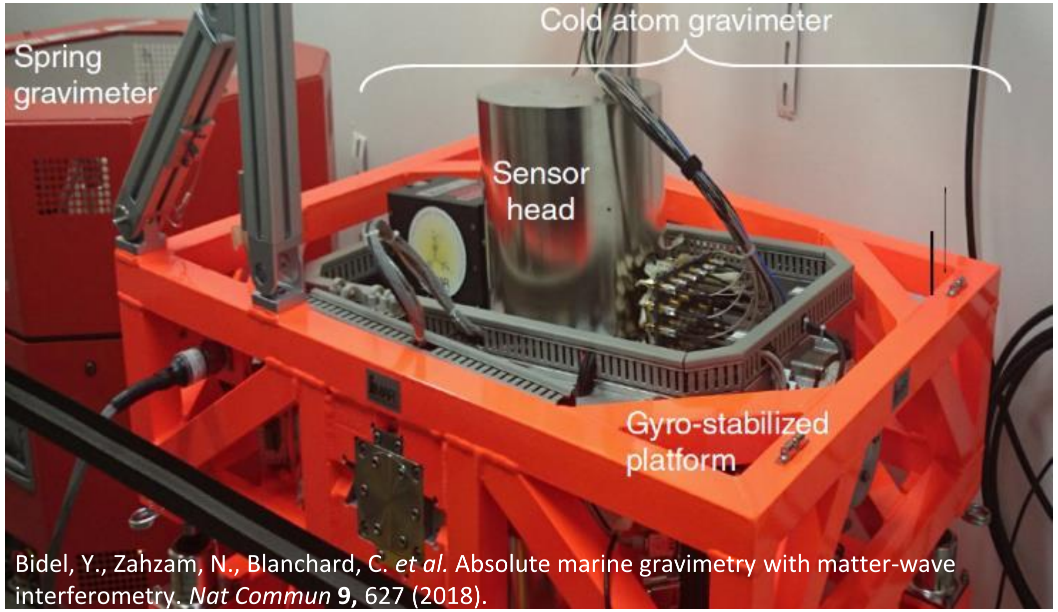
Sandwell et al., Science, 346, 6205 (2014).



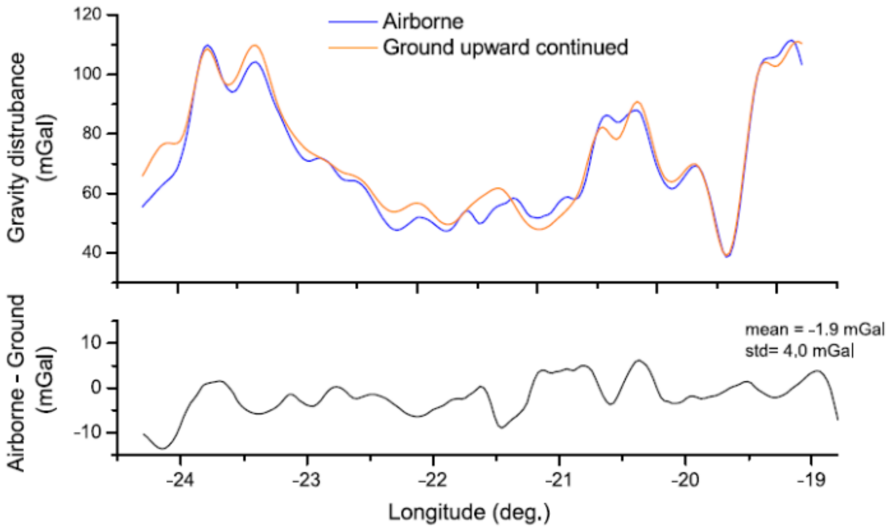
- Gravity anomalies due to mass variations underground can be detected by sensitive gravimeter (accelerometer)
  - Cannot be shielded
  - Less sensitive to clutter than mag
- Techniques pioneered by oil & gas industry for large scale resource exploration
- Current quantum gravimeters are large
  - 7 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



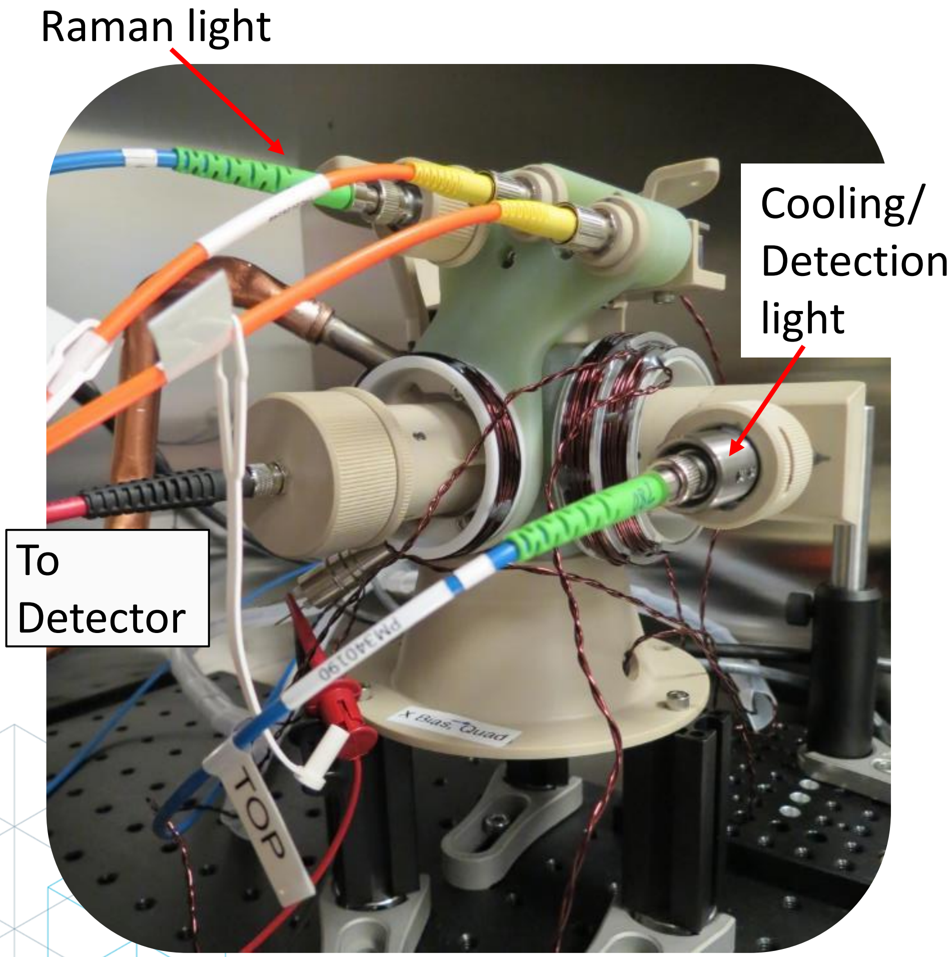
Bidel, Y., Zahzam, N., Blanchard, C. *et al.* Absolute marine gravimetry with matter-wave interferometry. *Nat Commun* **9,** 627 (2018).



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

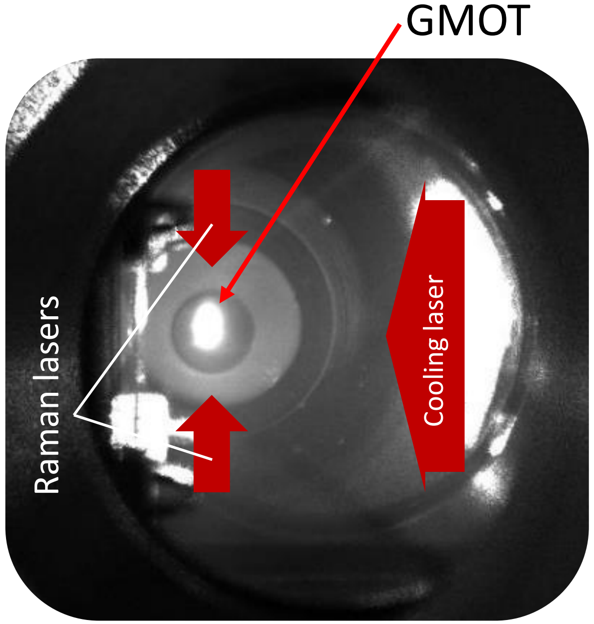
Ship: Bidel, Y., Zahzam, N., Blanchard, C. *et al.* Absolute marine gravimetry with matter-wave interferometry. *Nat Commun* **9,** 627 (2018).

Sandia compact atom interferometer sensor head

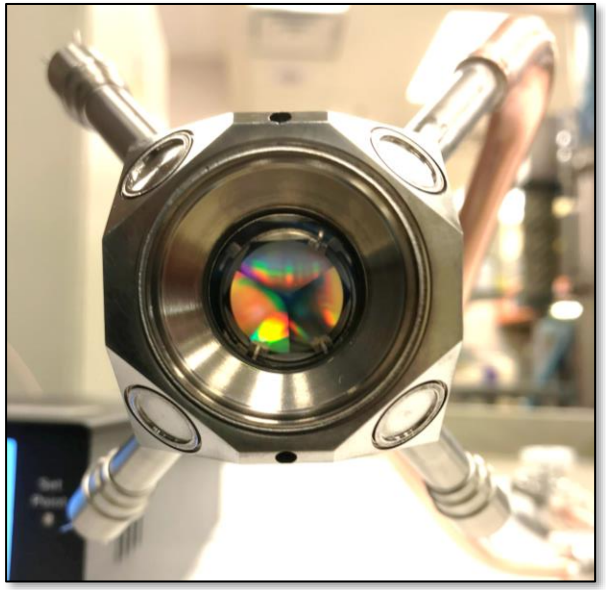


Same Raman configuration used in McGuinness, et al., APL (2012)

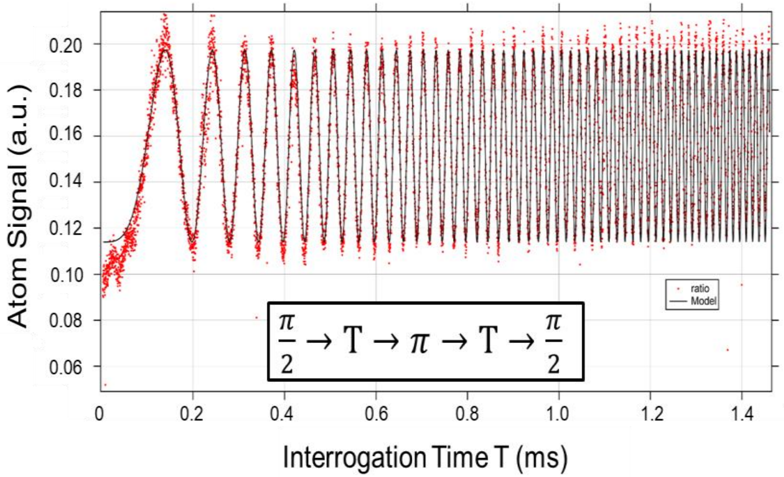
- Grating magneto optical trap (GMOT)
- Grating replaces one window of vacuum package
- Vacuum maintained by ion pump, fused silica windows
- Atom number: 10^7 laser cooled to 18 μK.



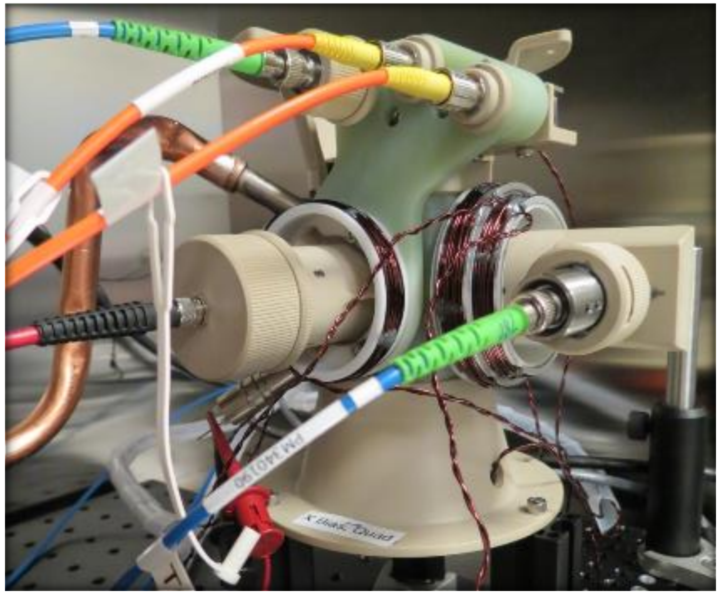
Ti Vacuum Package with Grating



Gravimeter Signal



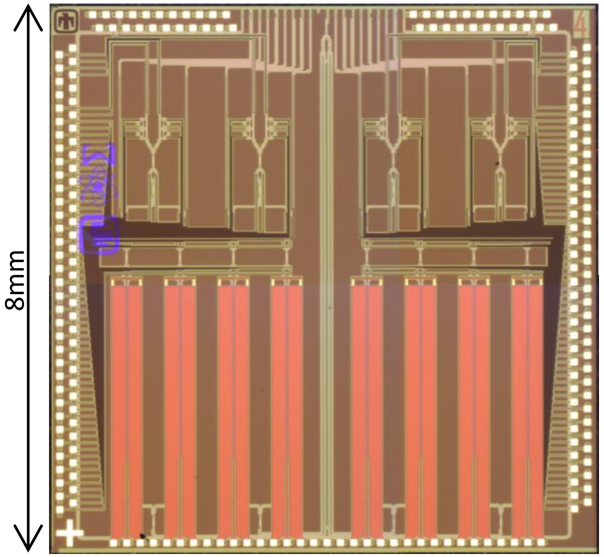
Inertial sensing with atom interferometry



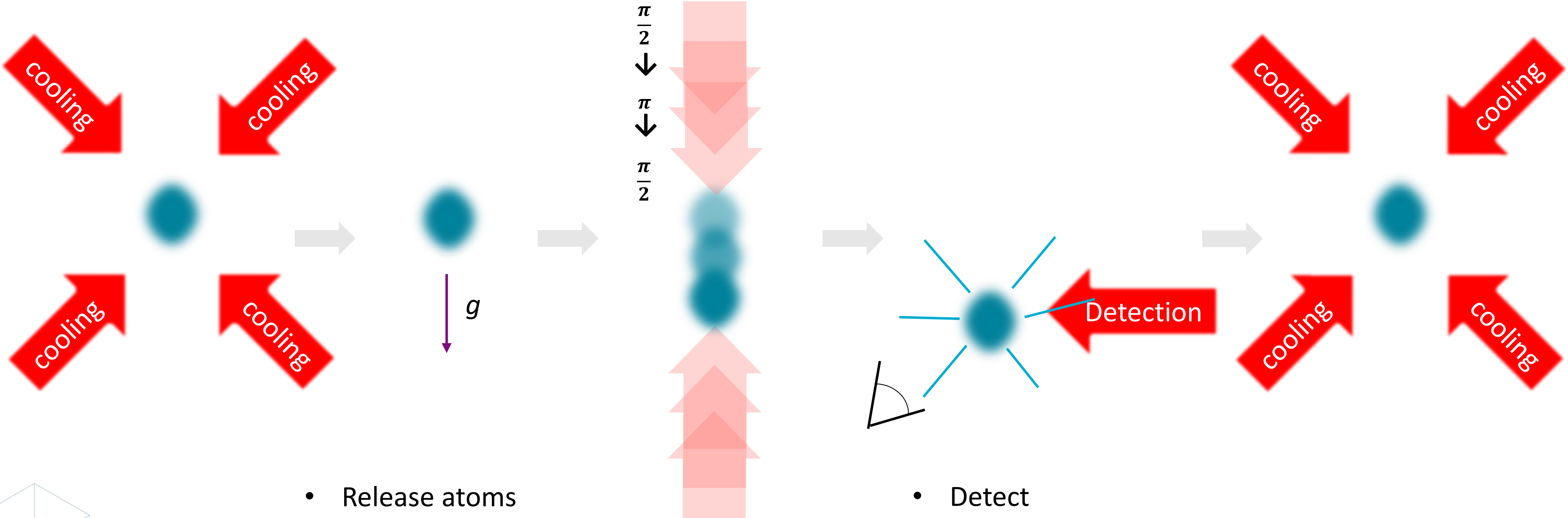
- Strategic-grade accelerometer: 0.25 μg
- 50 Hz data rate
- Targeting a fieldable sensor
- Developing chip-scale laser system (PIC) for extreme miniaturization

GMOT Grating

Photonic Integrated Circuits



High data rate atom interferometry



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