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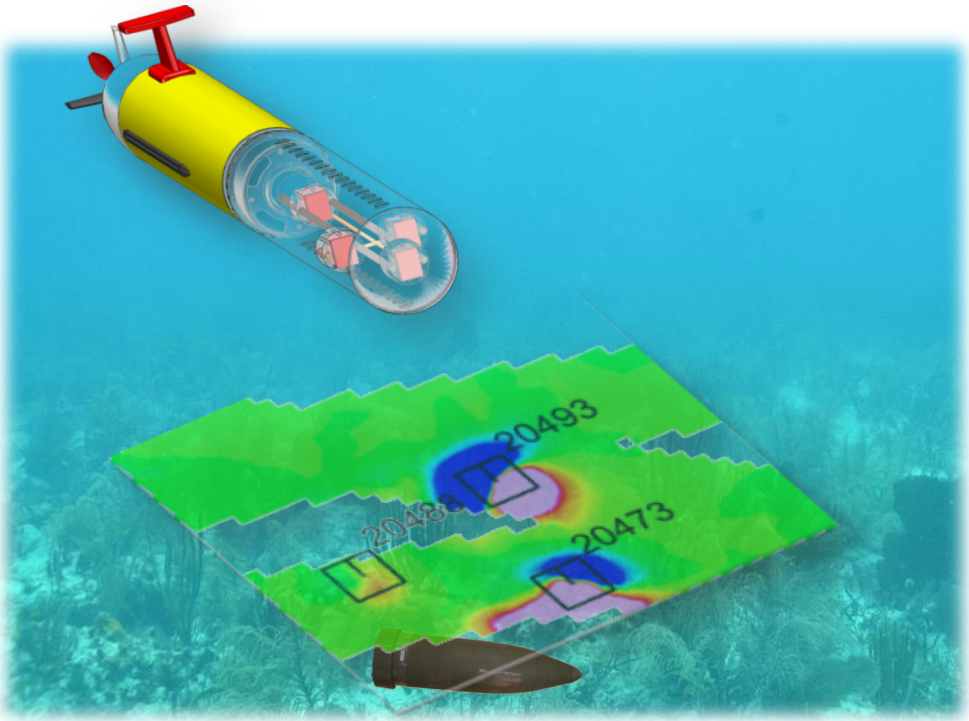
Underwater Magnetics:
Current and Emerging Technologies for UXO

Greg Schultz

SERDP • ESTCP
SYMPOSIUM
2018 | Enhancing DoD's Mission Effectiveness

Overview

1. Background
   - Magnetics for Underwater UXO
   - MAG Physics & Sensors
2. New Sensor Developments
3. Arrays and Gradiometers
4. Platforms & Deployment Challenges
5. Summary Outlook



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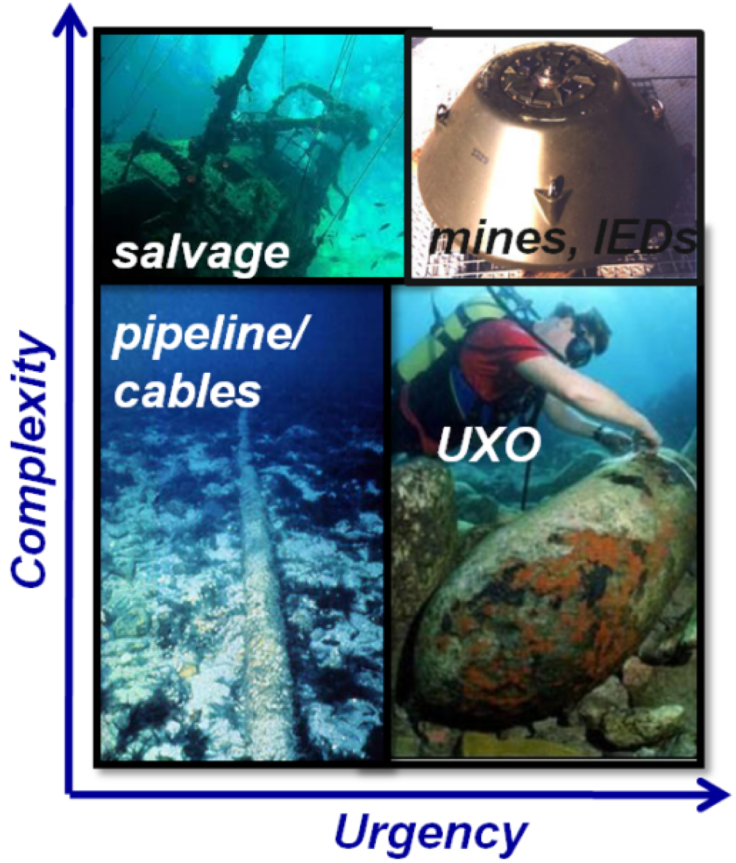
Magnetometers for Underwater UXO



Background

- Simple to use, passive, widely deployed
- Well established in naval operations
- Sensitive to ferrous materials (only)
- Can detect relatively deep targets ($1/r^3$)
- Somewhat sensitivity to metallic clutter, infrastructure, and geologic noise
- Lack spatial/temporal character to resolve unique features of targets (size, shape, etc.)

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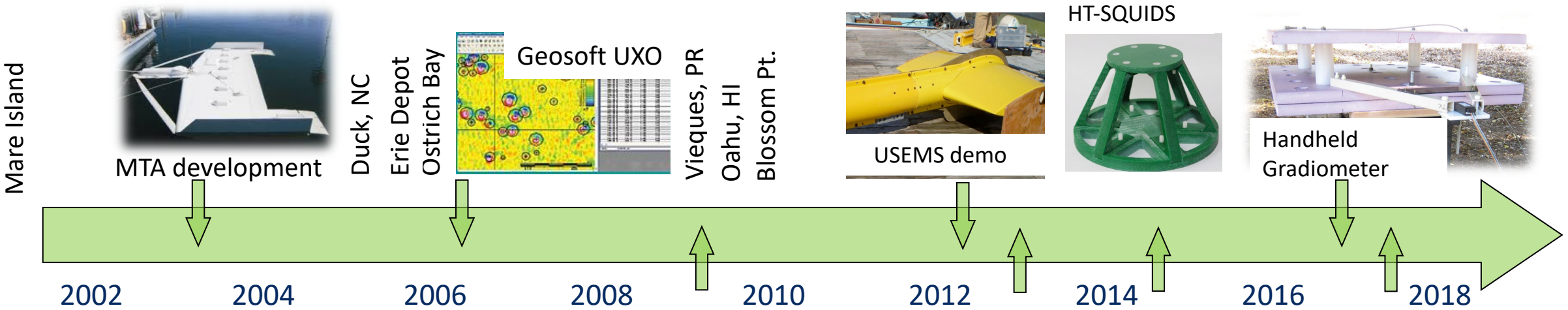
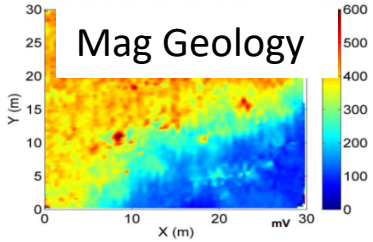
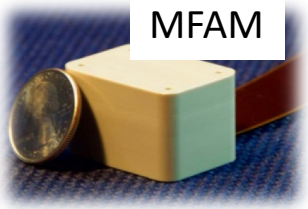
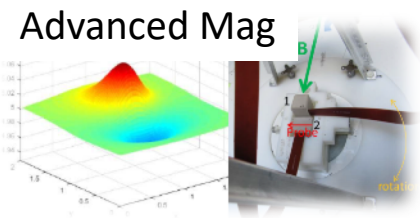
Magnetic Sensing for UXO (2002-2018)









- Underwater UXO Needs (1322)
- Marine UXO Detection (MTA) (200324)
- Deep Water Detection (200739)
- USEMS (200733)
- Wide Area Marine UXO Assessment (200808)

- Micro-Fab'ed Atomic Magnetometer (1512, 1568)
- AUV Detection (201002)
- High Temp SQUIDS (1661)
- UXO via AUVs (1631)
- Underwater Geolocation (1719)

- Underwater E-&B-field Sensing (1714)
- Real-time Localization ATR (201612)
- Real-time Handheld Array (2104)
- Advanced Magnetometer System (2646)

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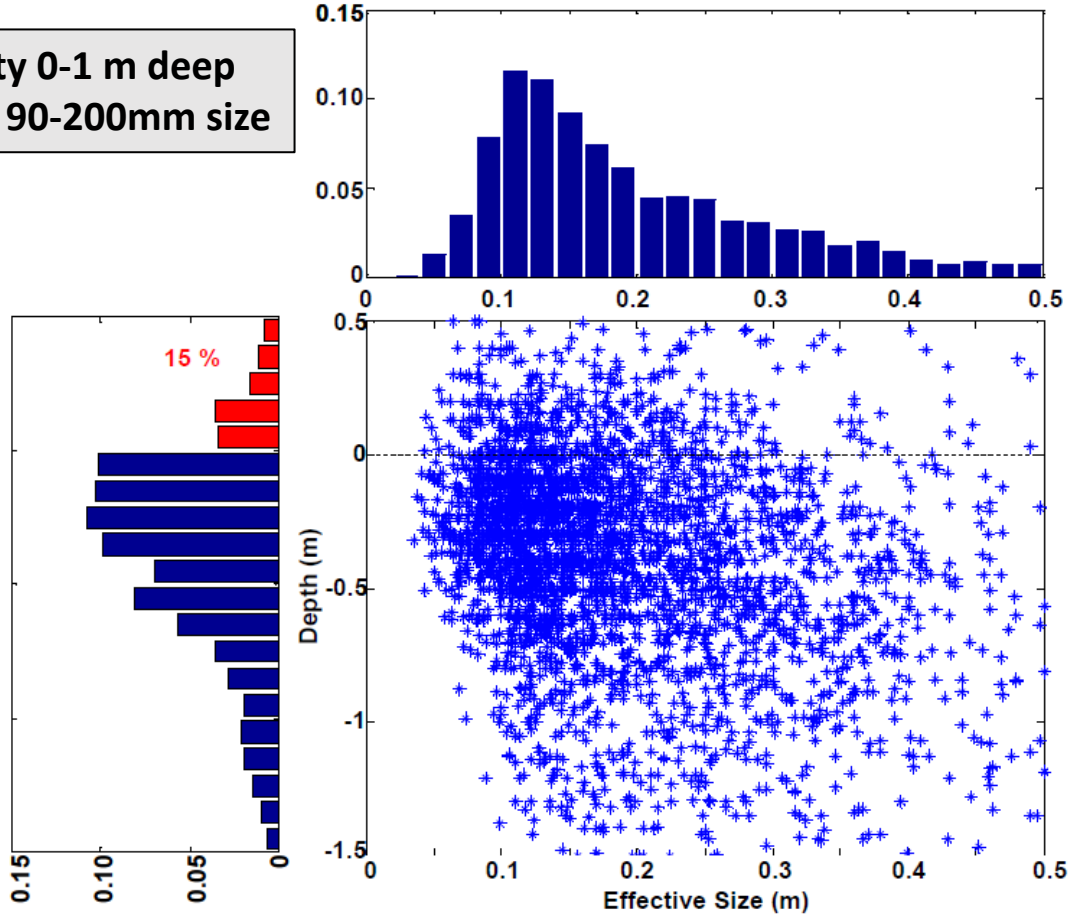
Magnetometers for Underwater UXO

Target Observations Over Multiple Underwater Magnetometer Array Deployments: 2004-2008 (from SERDP MM-0739 by SAIC)

Site	Depth (m)	Targets	Year
Duck, NC	1-3	432	2005
Ostrich Bay	1-12	648	2006
Lake Erie	1-10	779	2006
Vieques, PR	1-10	603	2007
Oahu	1-10	253	2007
Blossom Pt.	1-10	619	2008
TOTALS	1-12	3334	2005-'08

Majority 0-1 m deep
Mostly 90-200mm size



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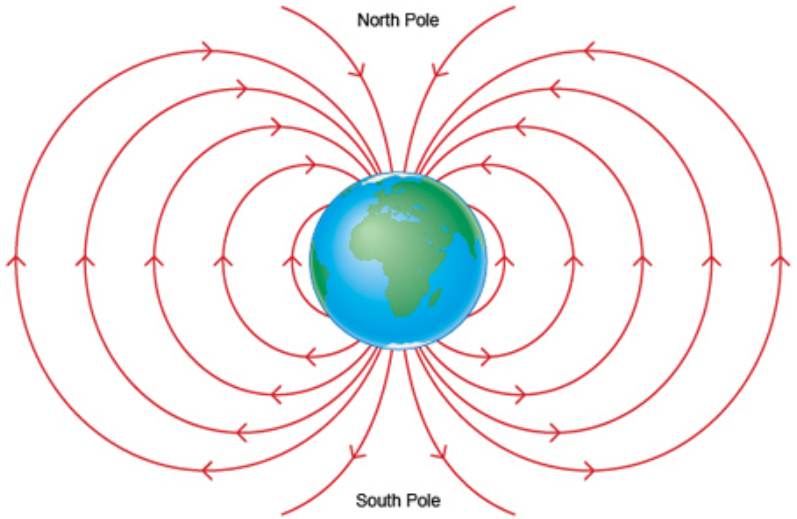
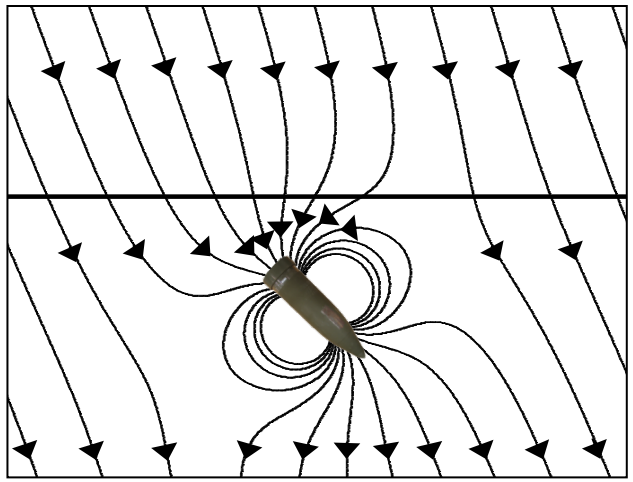
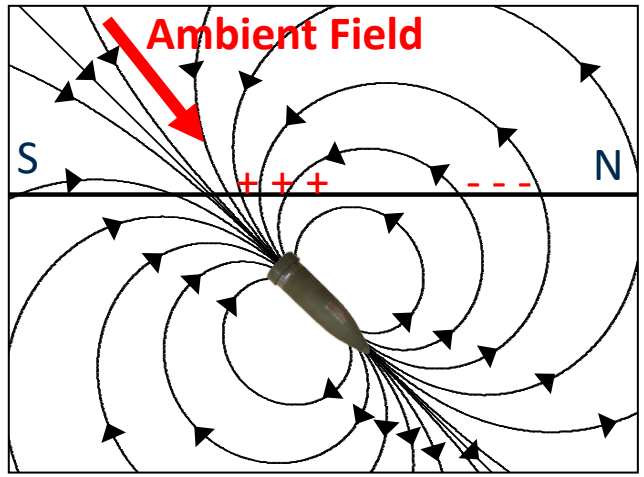
Magnetics: Physics







- Earth's field provides "transmitter"
- B_{Earth} locally uniform but directional
- Temporal variation generally slow

- Ambient field perturbed (flux concentrated)
- Anomalous field is projection of $B_{ambient}$ onto the effective dipole moment of object
- At ***range >> D_{object}*** objects look like a dipole, acts like a dipole

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What Could Go Wrong?

Platform Noise

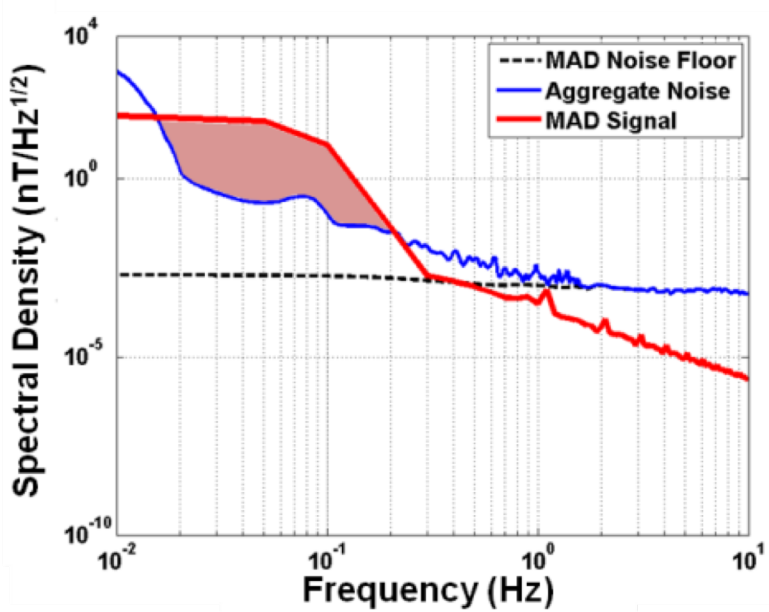
- Metal bits (ferrous)
- Actuation, circuitry

Motion Noise

- Moving through Earth's magnetic field
- "Compensation"

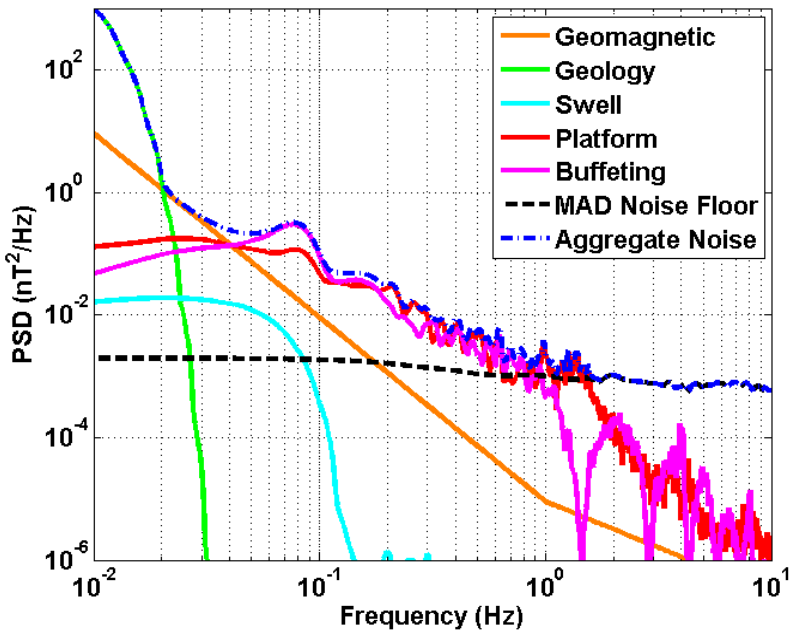
Environmental Noise

- Geology, clutter
- Geomagentics (weather)



SNR → Does the signal exceed the noise? At what frequencies? To what range?

Noise sources conspire to limit the effective bandwidth



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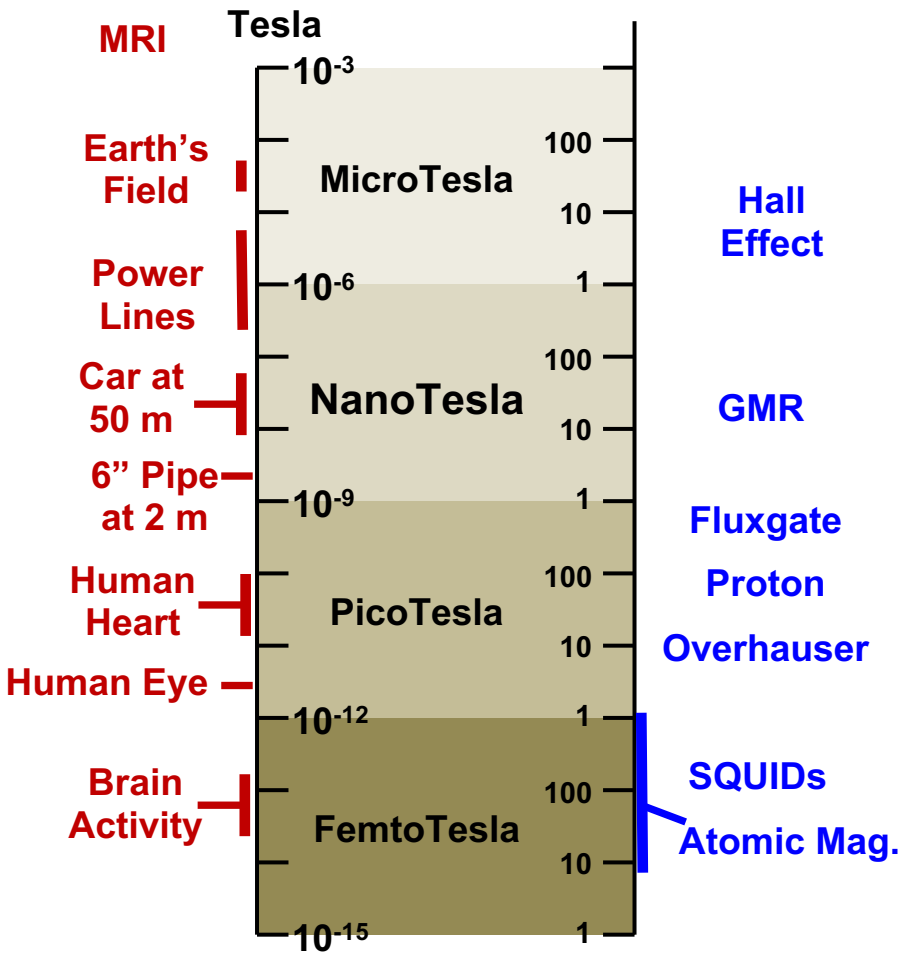
Modern Magnetometers
(What's a nanoTesla?)

- Survey magnetometers are primarily scalar
- Most sensitive are SQUIDS and atomic magnetometers
- Sensor noise constrained by:
  - Thermal stability
  - Electronic noise
  - Processing / control
  - Slew rate / gradients
  - Motion errors (heading errors and dead zones)



adapted from Romalis et al.

Vector *Scalar*

DC (quasi-static): <100 Hz

AC: >100 Hz

Responsive to all sources of magnetic induction

Larmor Precession

$$\omega = \gamma B$$

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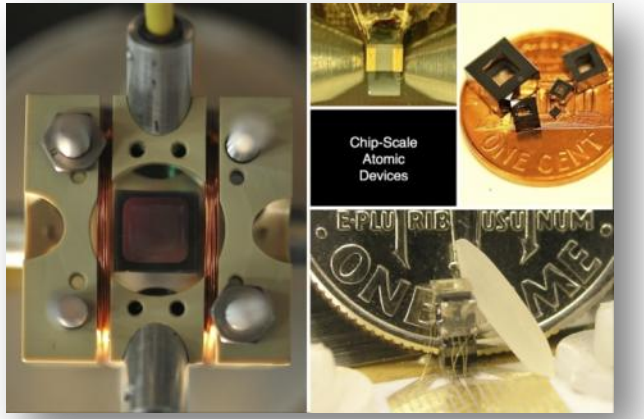
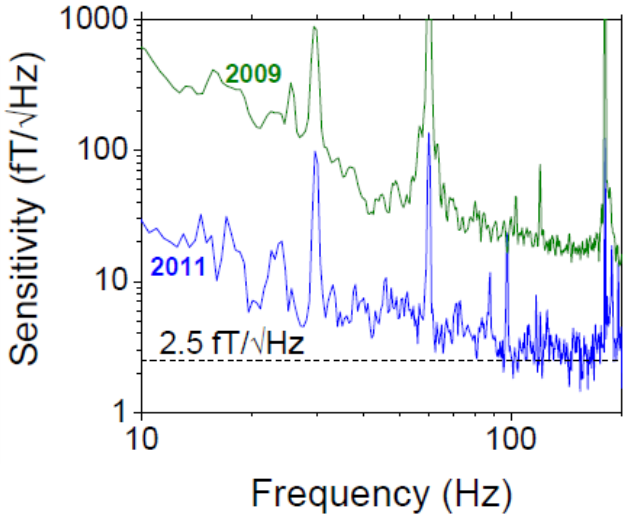
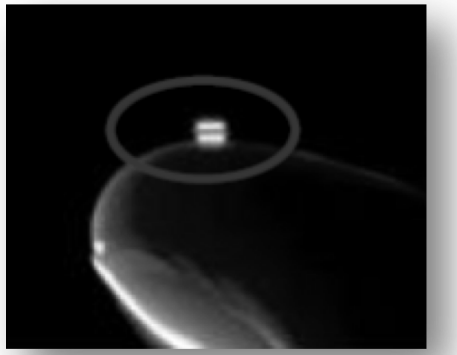
Miniaturized Atomic Magnetometers

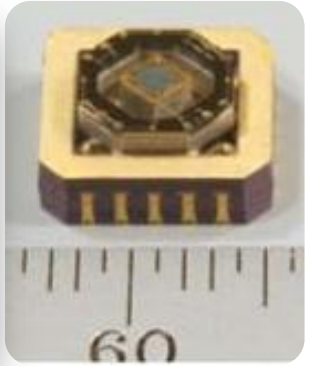
- Leap-frog advances from congruence of MEMS techniques (micro-optics, VCSELs, anodic wafers, micro-bonding)
- Applications by NIST, DARPA, and Universities pushed miniaturization of atomic devices
  - Atomic clocks, Gyros, Magnetometers
- Significant improvements in size, weight, power, cost, and sensitivity
  - Sensitivity increased 2 orders magnitude
  - 2-10 $pT/Hz^{0.5}$ → 10-100 $fT/Hz^{0.5}$
  - Miniaturization → New configurations

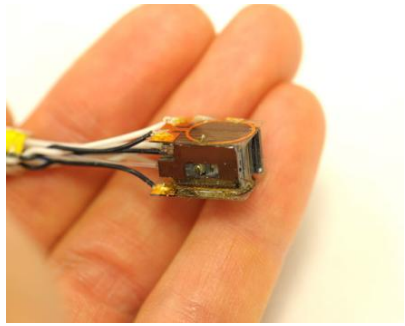


from NIST Atomic Devices Group (Kitching et al.)









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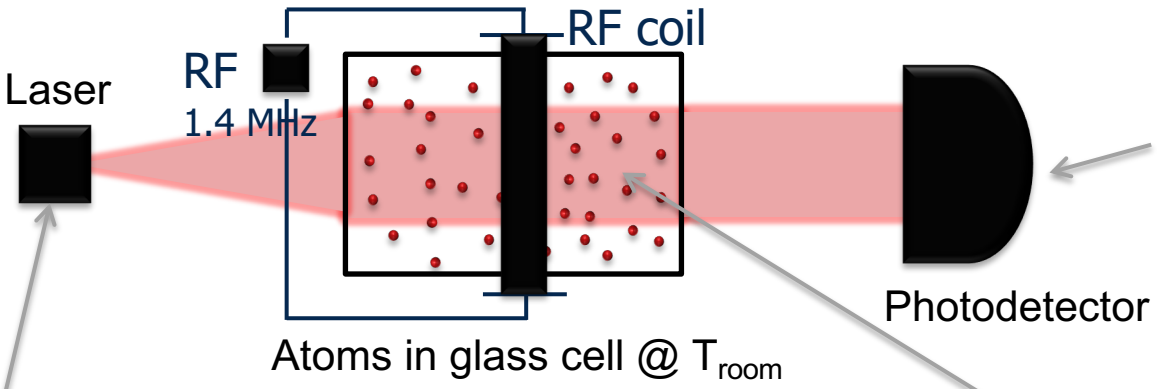
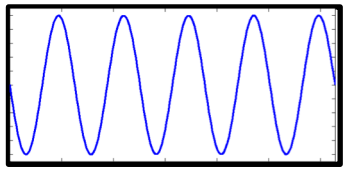
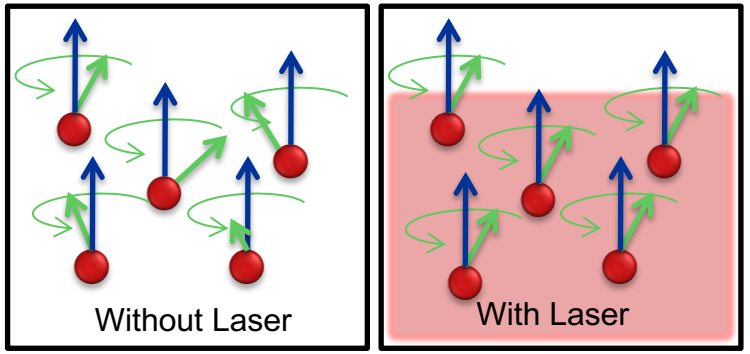
Miniaturized Atomic Magnetometers

from Neil Claussen, NSWC-PCD



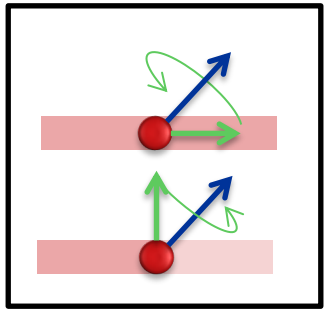


The oscillation frequency is proportional to the magnetic field magnitude.



Laser aligns the atoms' magnetic moments.

With RF on, laser absorption depends on the magnetic moment orientation.



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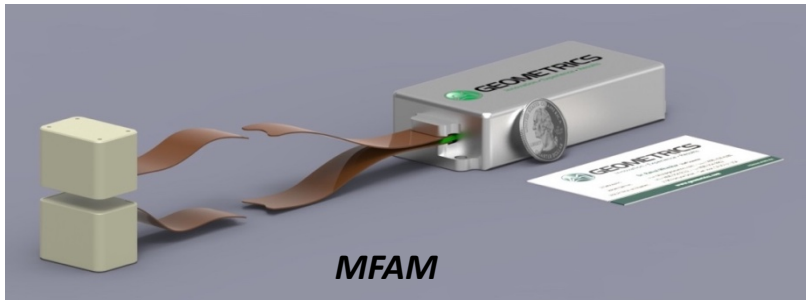
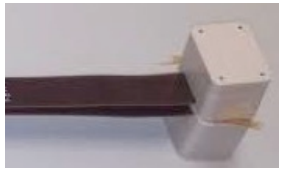
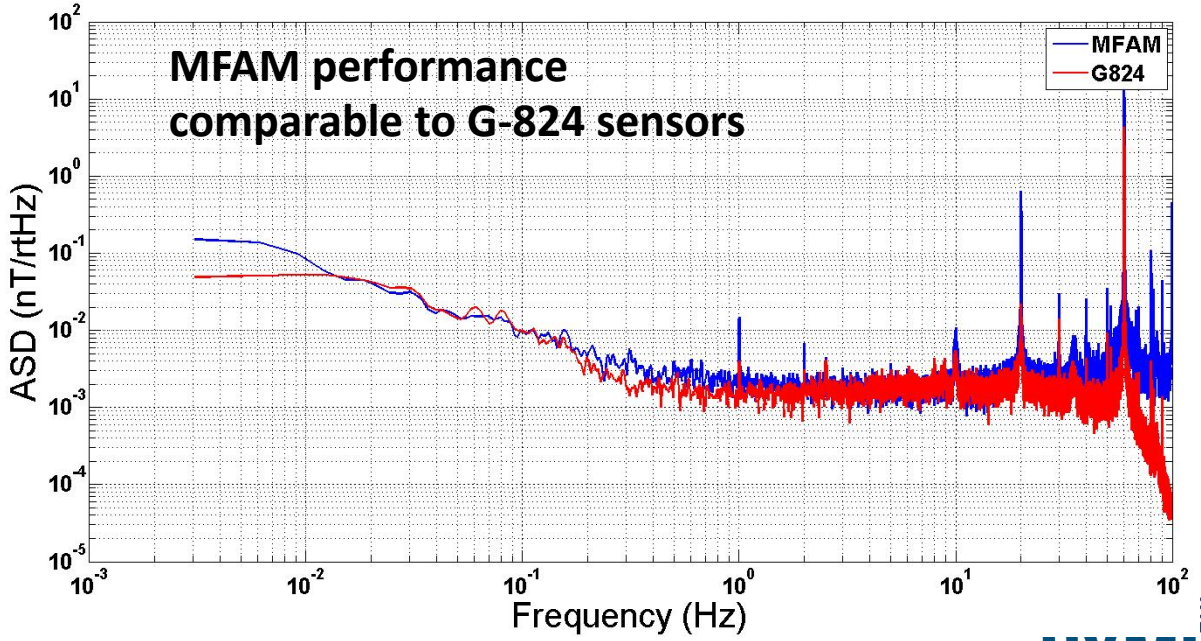
Miniaturized Atomic Magnetometers





Geometrics compact, low power sensors for UXO = MFAM's

- **MM-1512 – Basic sensor development**
- **MR-1568 – Exploring high performance regimes**
- **MR-2104 – Miniature electronics and real-time array**



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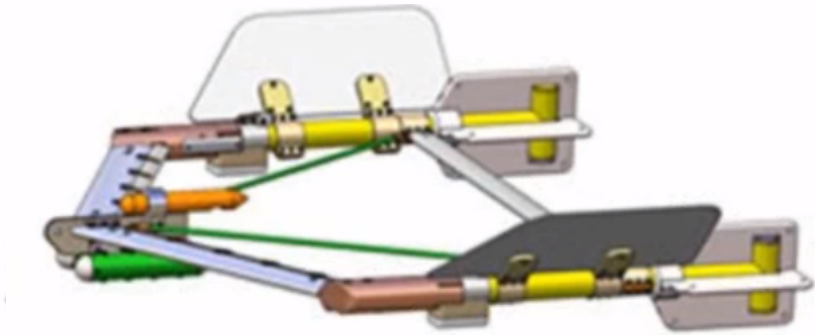
Deployment Methods: Arrays



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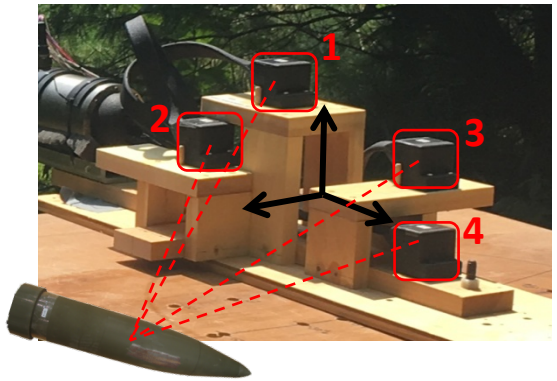
Magnetic Gradiometers

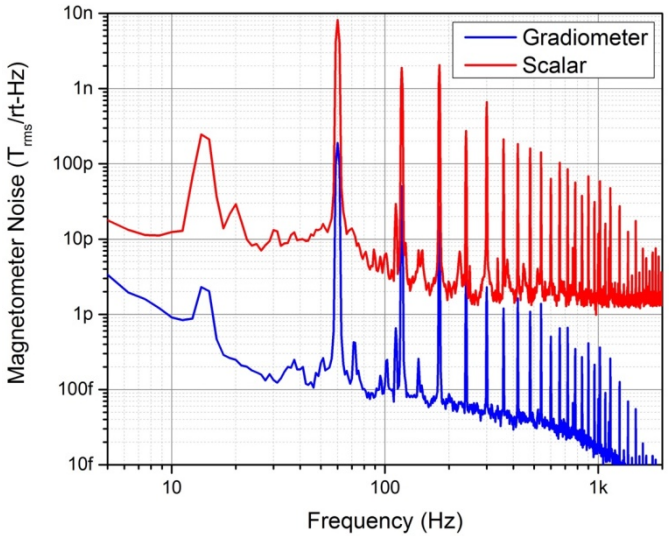


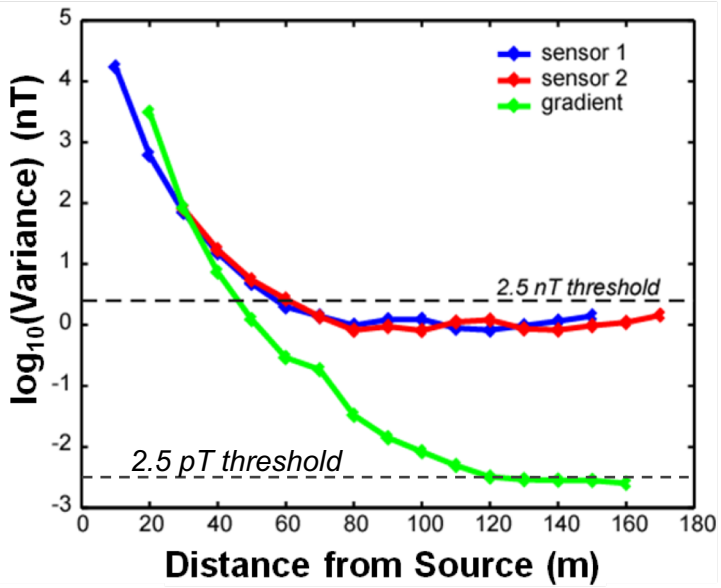
Gradient Noise Rejection

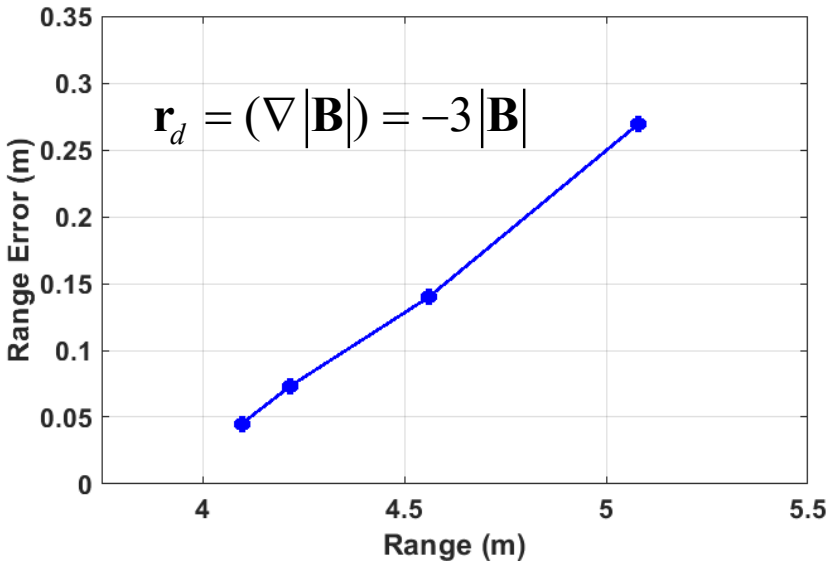
- Common mode noise suppression
- Coherent (gain *N*) and incoherent (gain $\sqrt{N}$) noise cancellation

Target Localization

- Lateral gradients used to accurately geo-locate contacts
- Bearing and range more accurately defined with gradient array







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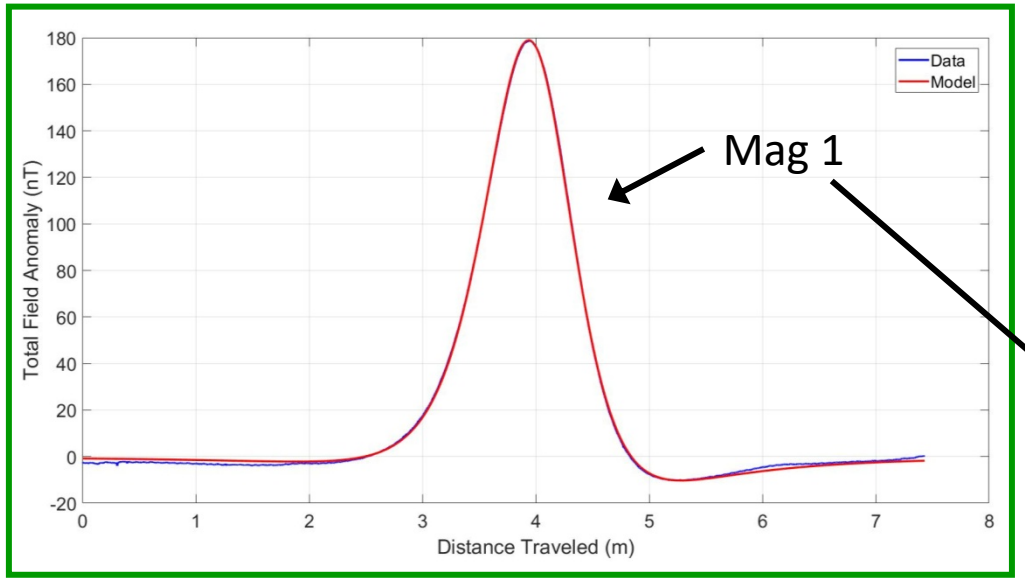
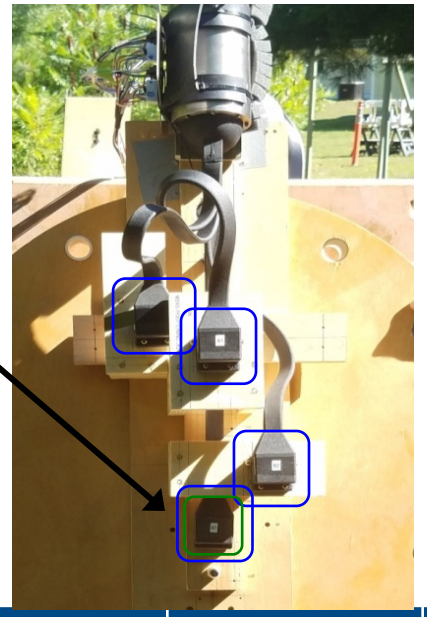
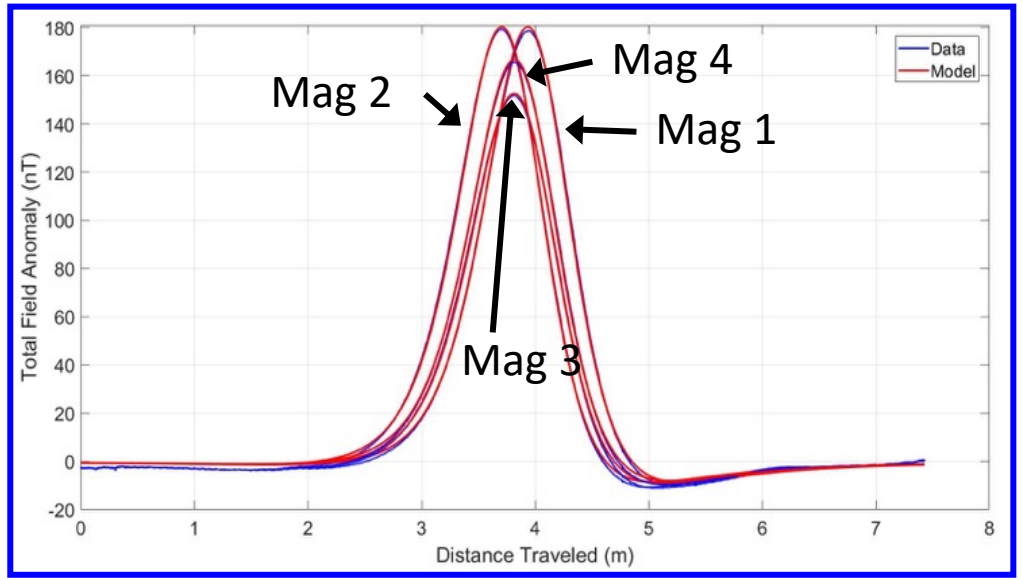
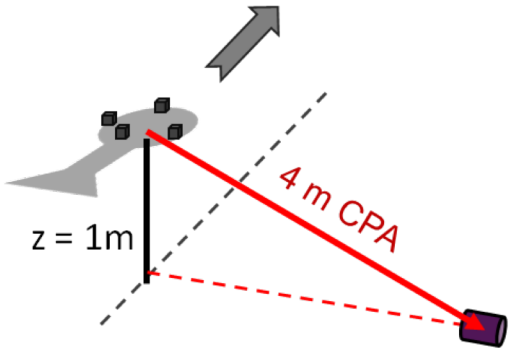
Gradiometer Localization Example









	Across Track (m)	Along Track (m)	Depth (m)	Location Error	Moment (Am^2)	Moment Error
Measured	0.00	4.04	-0.87		0.61	
1 MAG Estimate	0.00	4.01	-0.89	4.2 cm	1.15	89%
4 MAG Estimate	0.00	4.01	-0.89	2.4 cm	0.61	<1%

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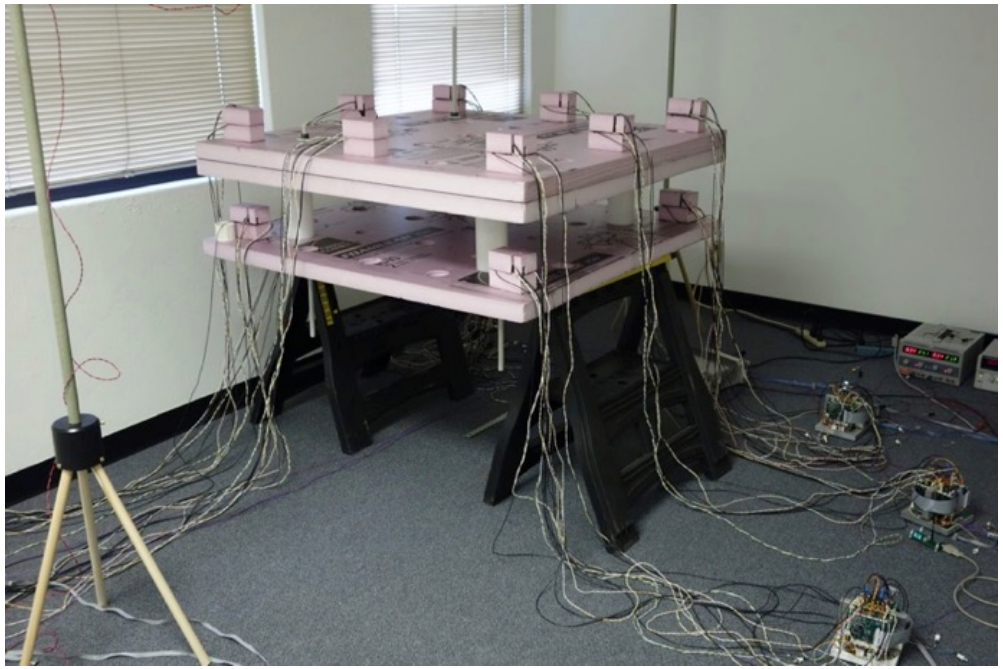
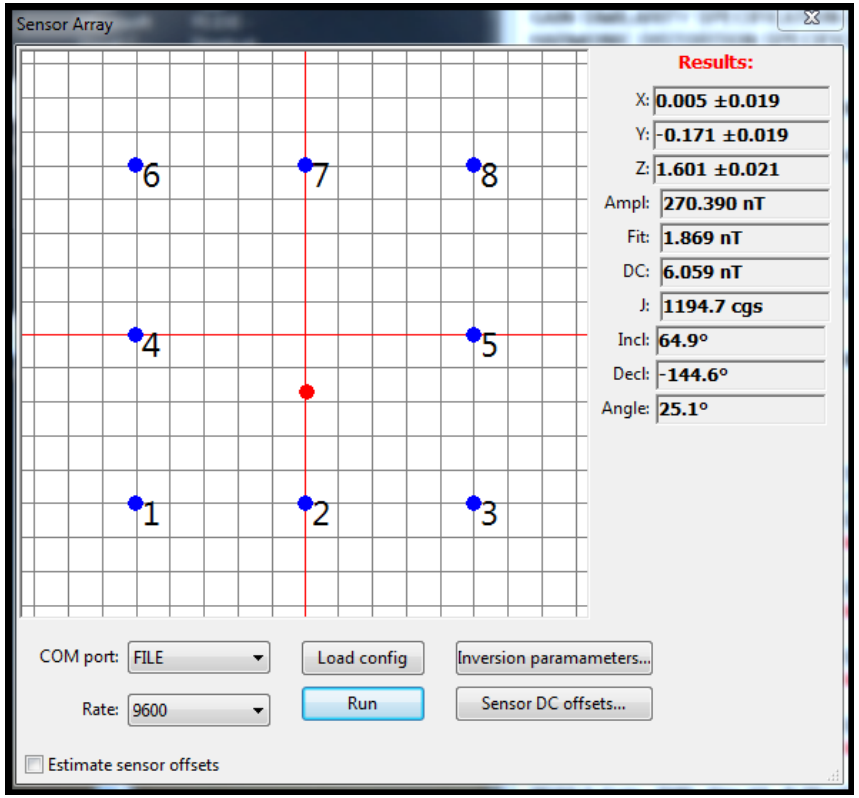
Gradiometer Localization Example
SERDP MR-2104 (Geometrics)

Underwater Array Prototype





Gradiometer data acquired & analyzed at 10Hz

3D location, target size/orientation displayed

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Gradiometer Arrays on UUV Platforms
(MR-201612, NSWC-PCD)

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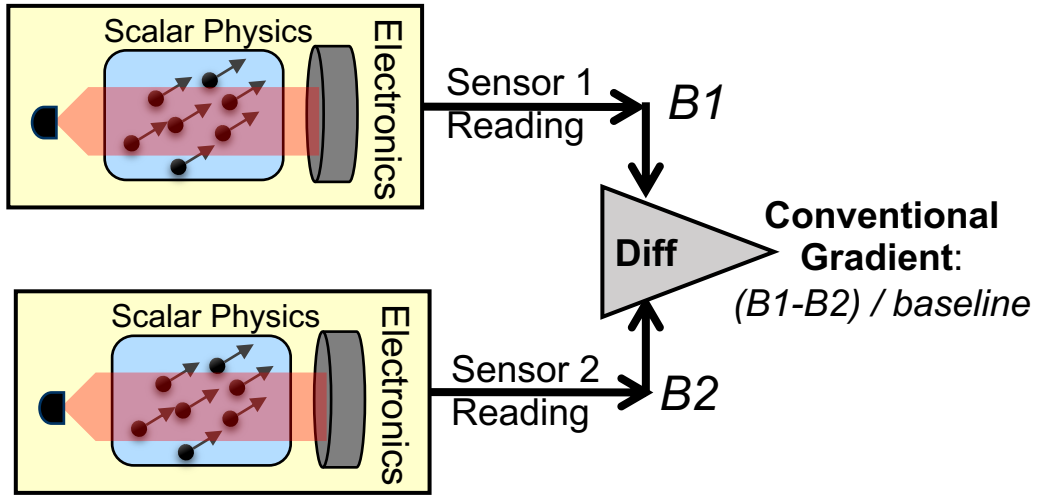
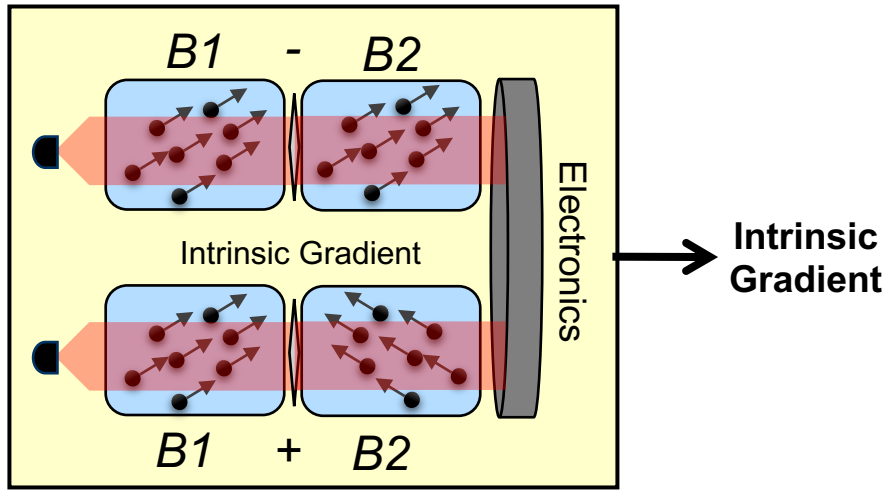
New Intrinsic Gradiometers

Traditional Gradiometer Configuration



- Requires independent measurements
- Requires physically separate sensing modules
- Baseline limits noise rejection

"Intrinsic" Gradiometer Configuration



- Gradient physics matched within sensor
- Potentially very short baseline (mm?)
- Significant increase in common mode cancellation
- Aggressively pursued under DARPA & ONR

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Miniaturization = More Deployment Modes

Seabotix LBV ROV w/ Magnetometer Array

Multi-rotor Drone w/ Geometrics MagArrow

Raytheon Coyote Fixed-wing UAV w/ Magnetometer Nose Payload

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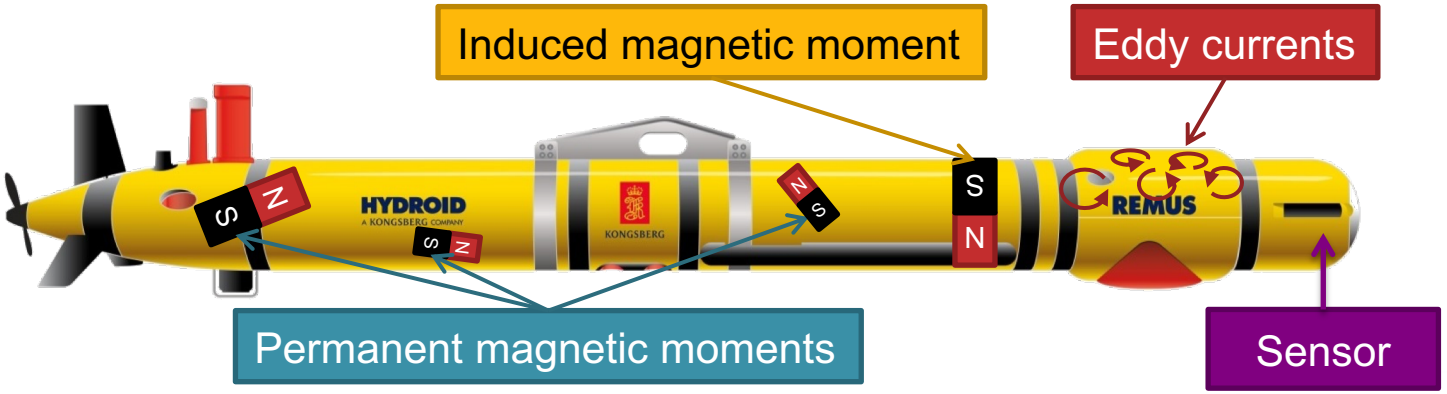
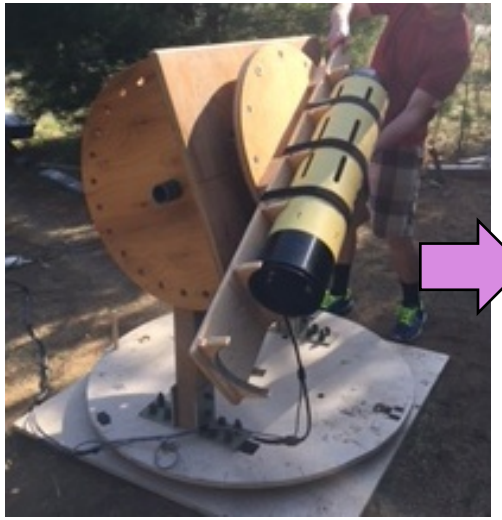
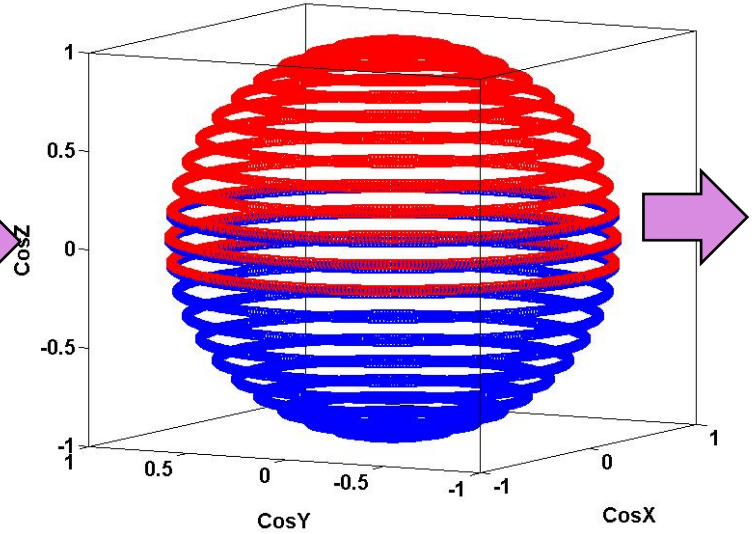
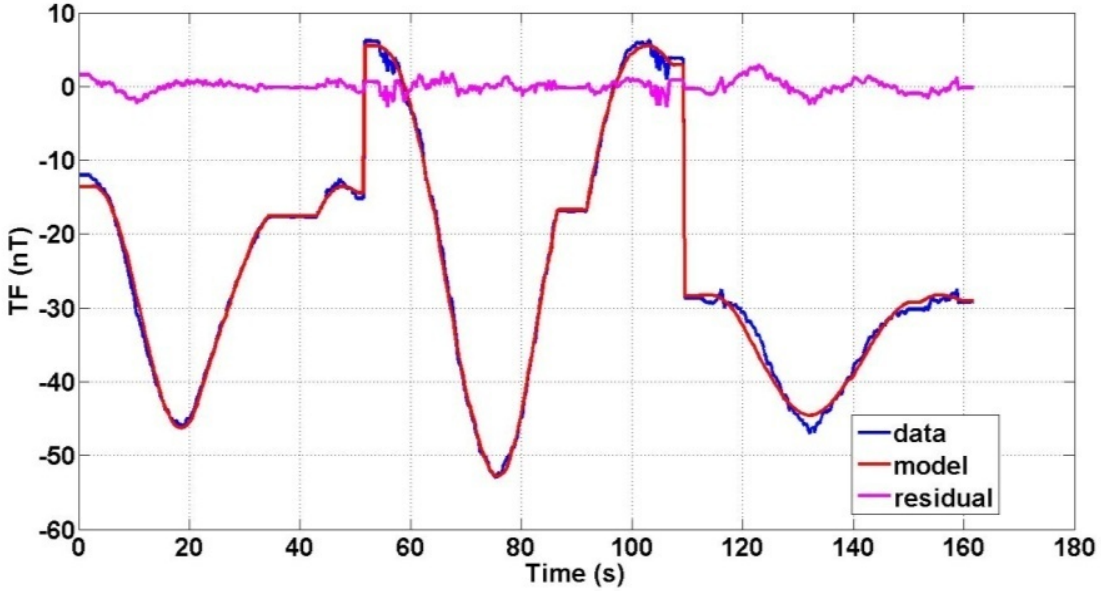
Platform Motion Compensation



Vehicle motion results in a changing magnetic field near the sensors, without any magnetic targets.







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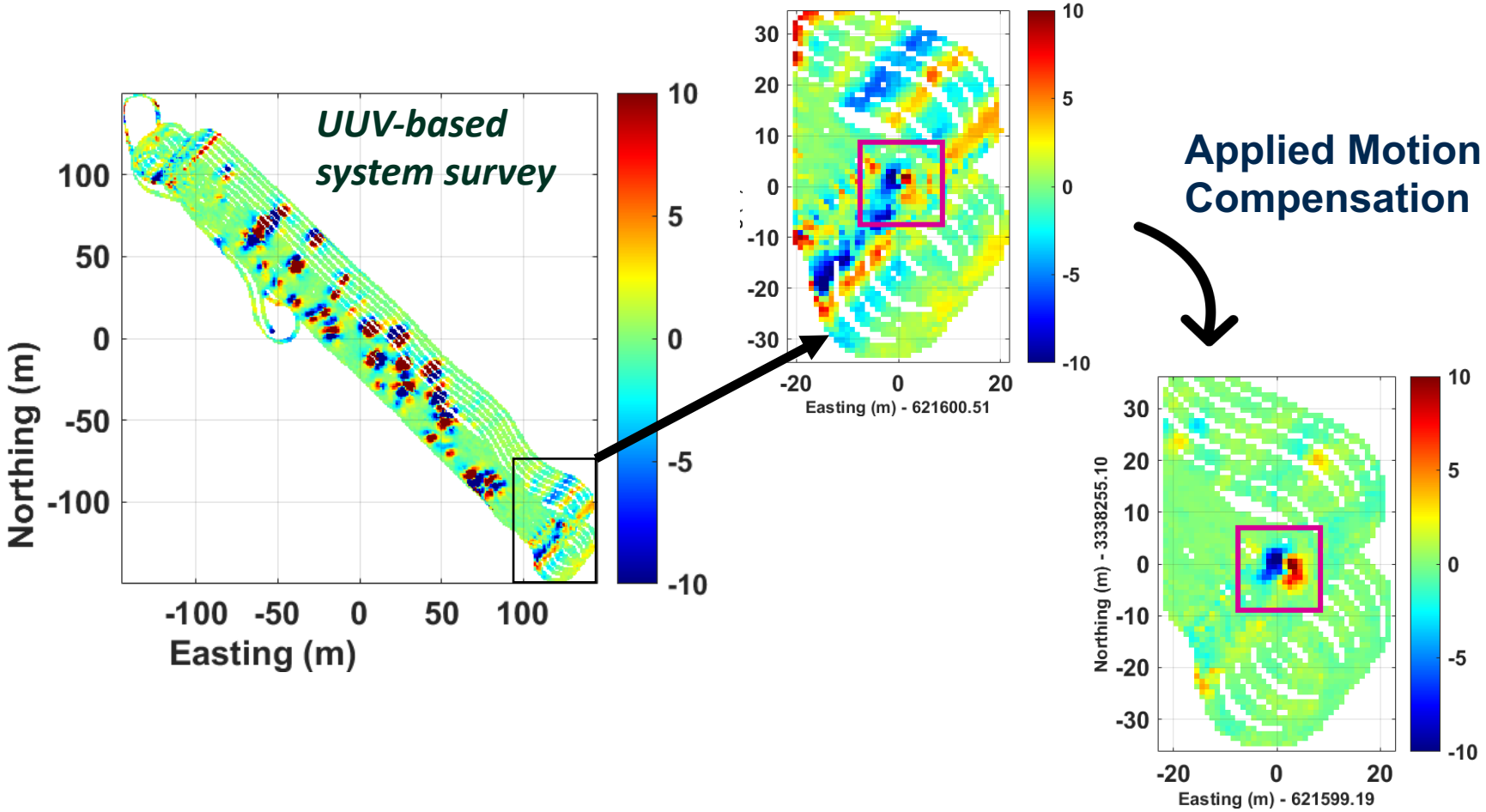
Platform Motion Compensation



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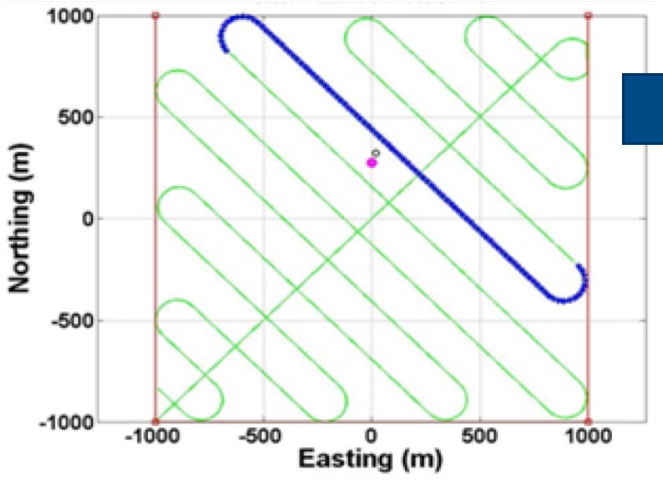
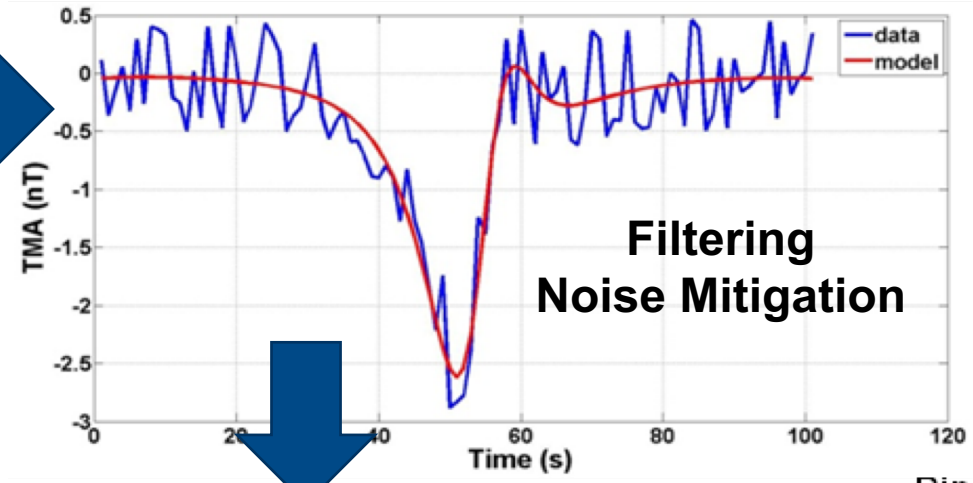
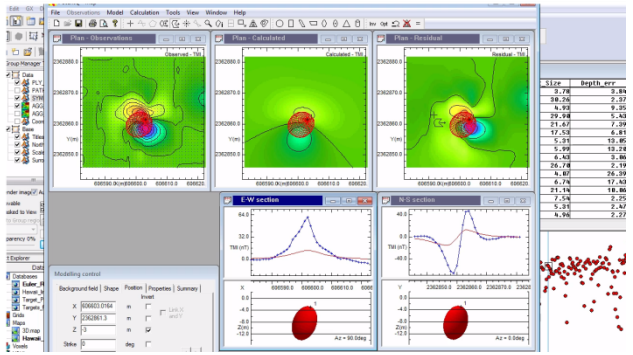
UXO Data Processing



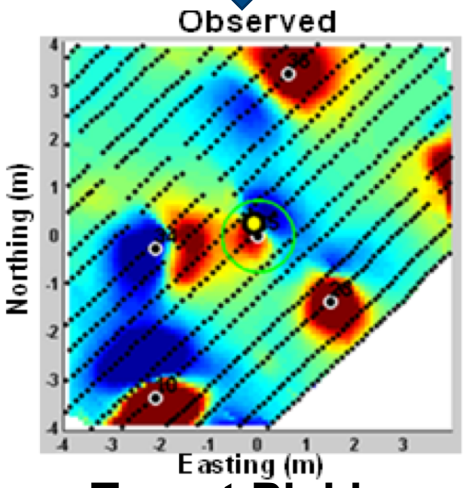


Filtering
Noise Mitigation

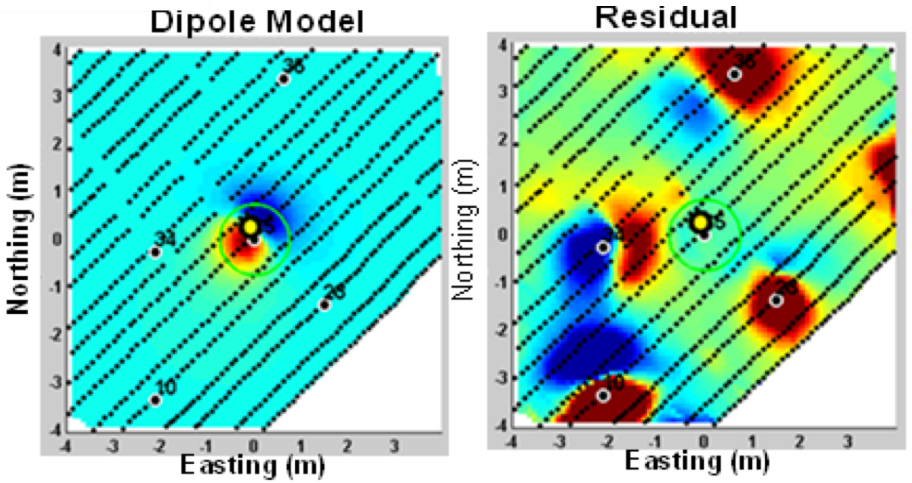
GeoSoft UXO Marine Workflow



Data Preparation
NAV Merge
Data QA / Corrections



Target Picking



Inversion

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Summary Outlook

- Continued improvements in atomic sensor sensitivities (pT → fT)
- Quantum initiatives → new magnetic sensing modalities (NV-diamond)
- Further miniaturization → array deployment opportunities
- Lightweight/compact/low cost → new platform deployments, new noise challenges
- Gradiometer configurations for noise suppression & localization
- Enhanced operating envelopes (e.g., bandwidth, sample rate)

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- Dr. Tom Bell, Liedos

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