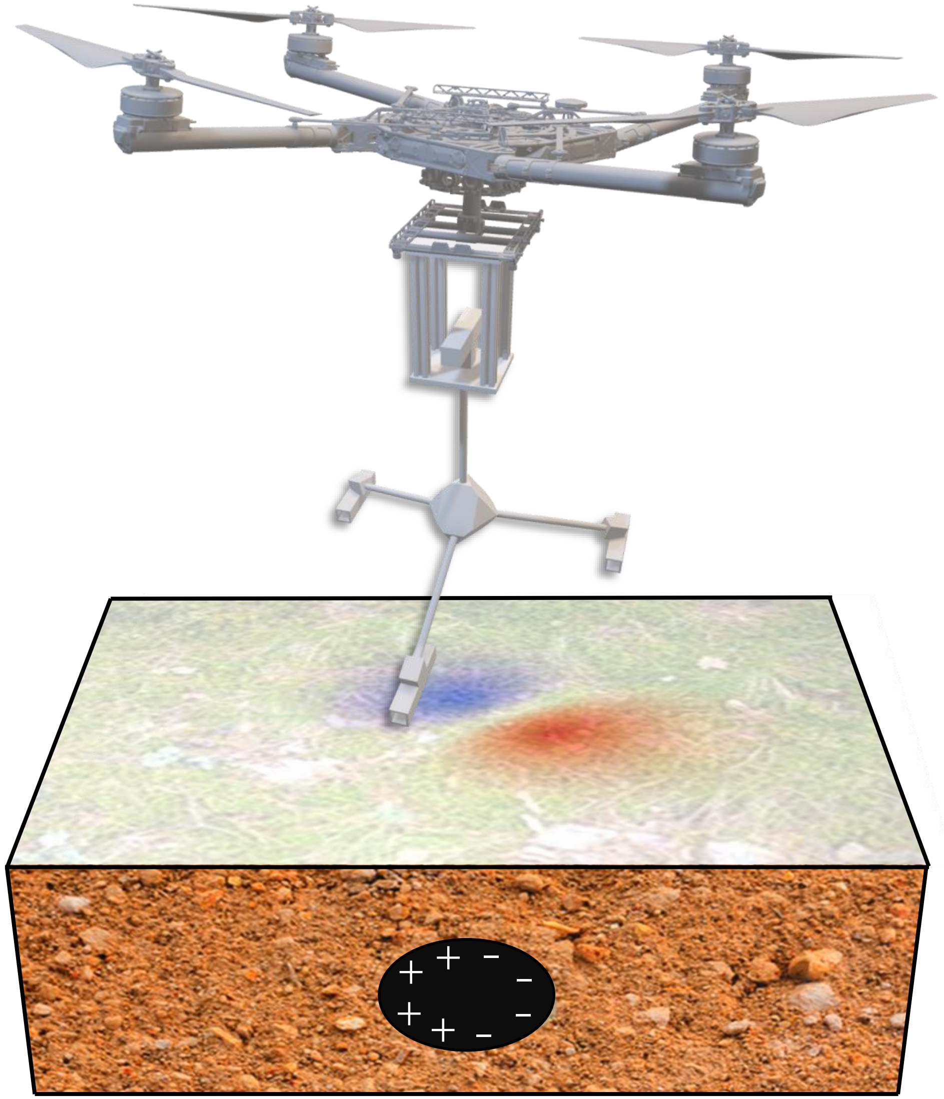


Toward Multi-Modal, UAV-Based UXO and Landmine Detection: Development of a Tetrahedral Magnetic Gradiometer

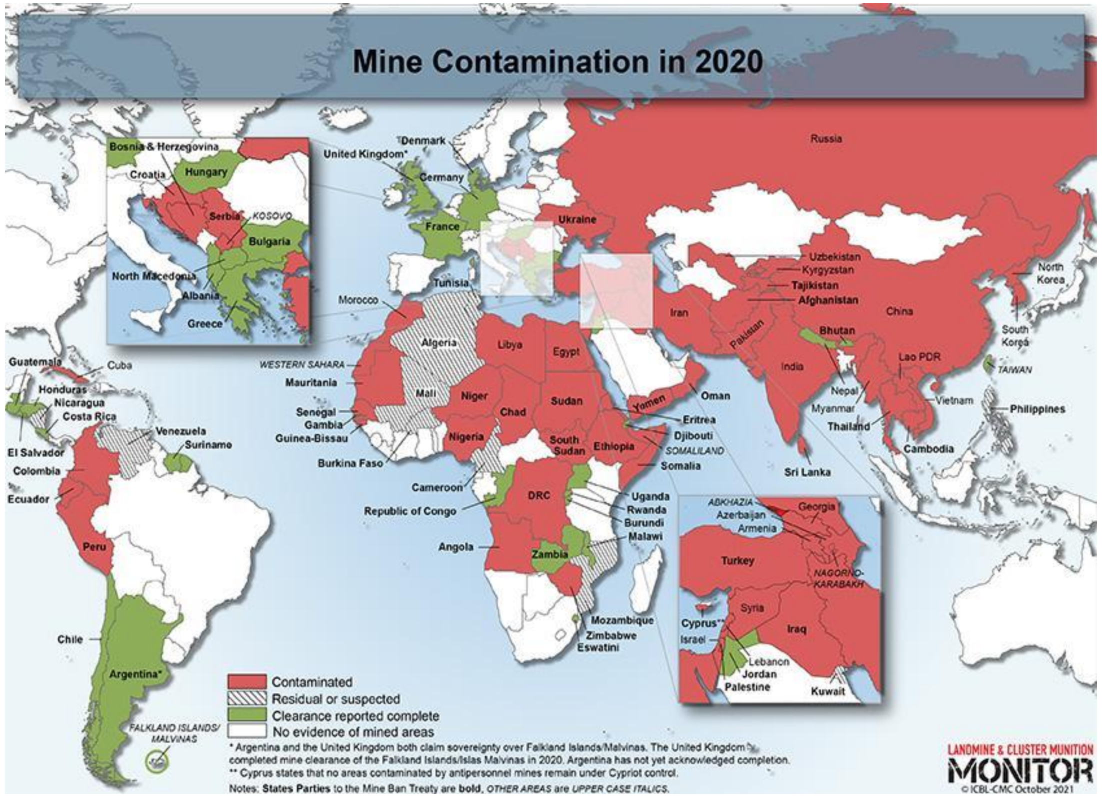
SAGEEP Conference
5 April 2023

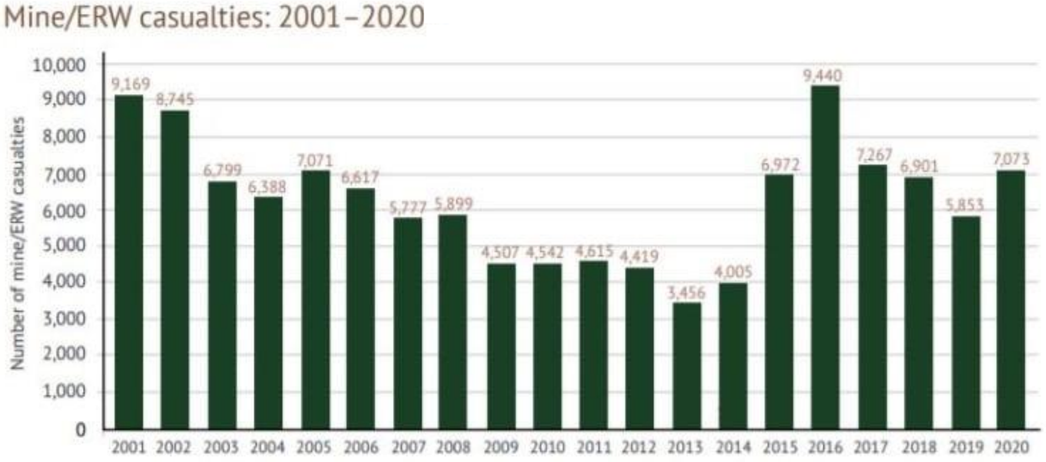
Heidi Myers
Daniel Lathrop
Vedran Lekić

NSF PFI-RP 2044611

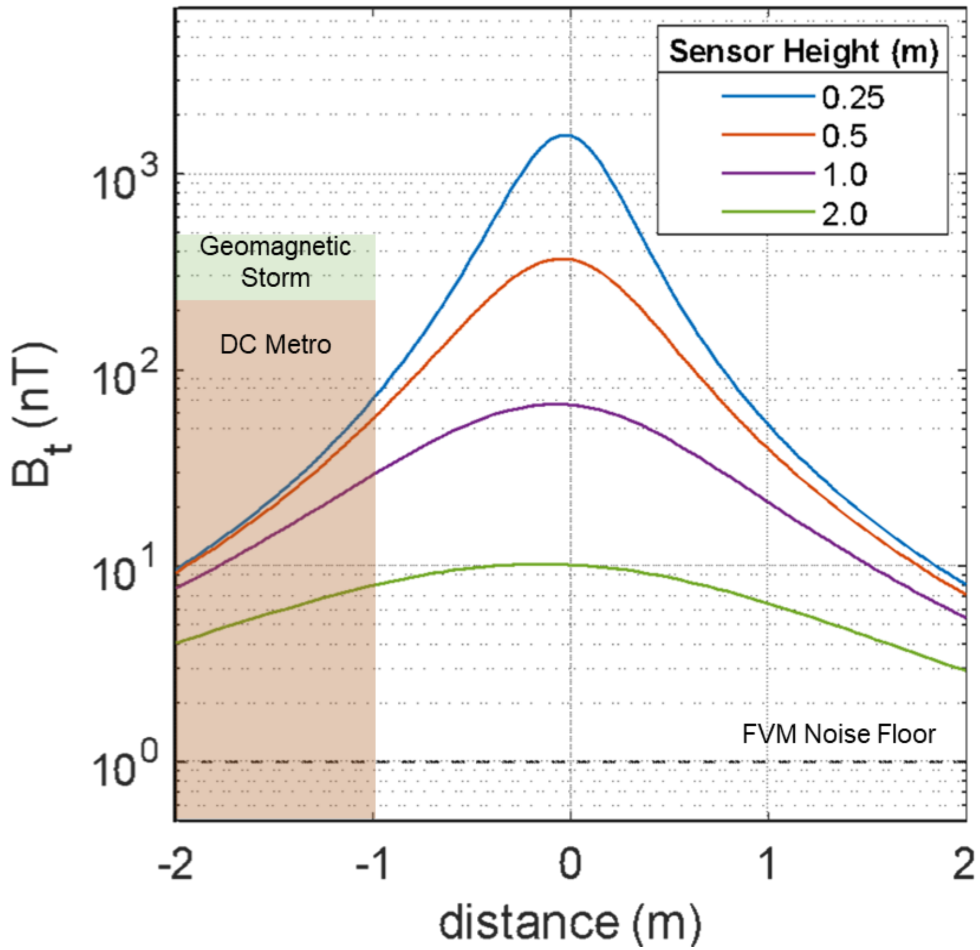
MOTIVATION

- >110 million landmines, unexploded ordnance (UXO), and other explosive remnants of war (ERW) buried worldwide
  - 5x increase in casualties with recent conflicts
- New burial outpacing detection/removal efforts
- 1 de-miner killed, 2 injured for every 5000 located mines





PROBLEMS WITH SINGLE MAGNETOMETERS



SCALAR MAGNETOMETERS

- High sensitivity, not impacted by orientation

BUT:

- Limited information content
- Sensitive to space weather and cultural noise sources
  - Temporal variations map to spatial variations when moving
- Signal amplitude depends on sensor height
  - As height increases, small amplitude signals obfuscated → false negatives

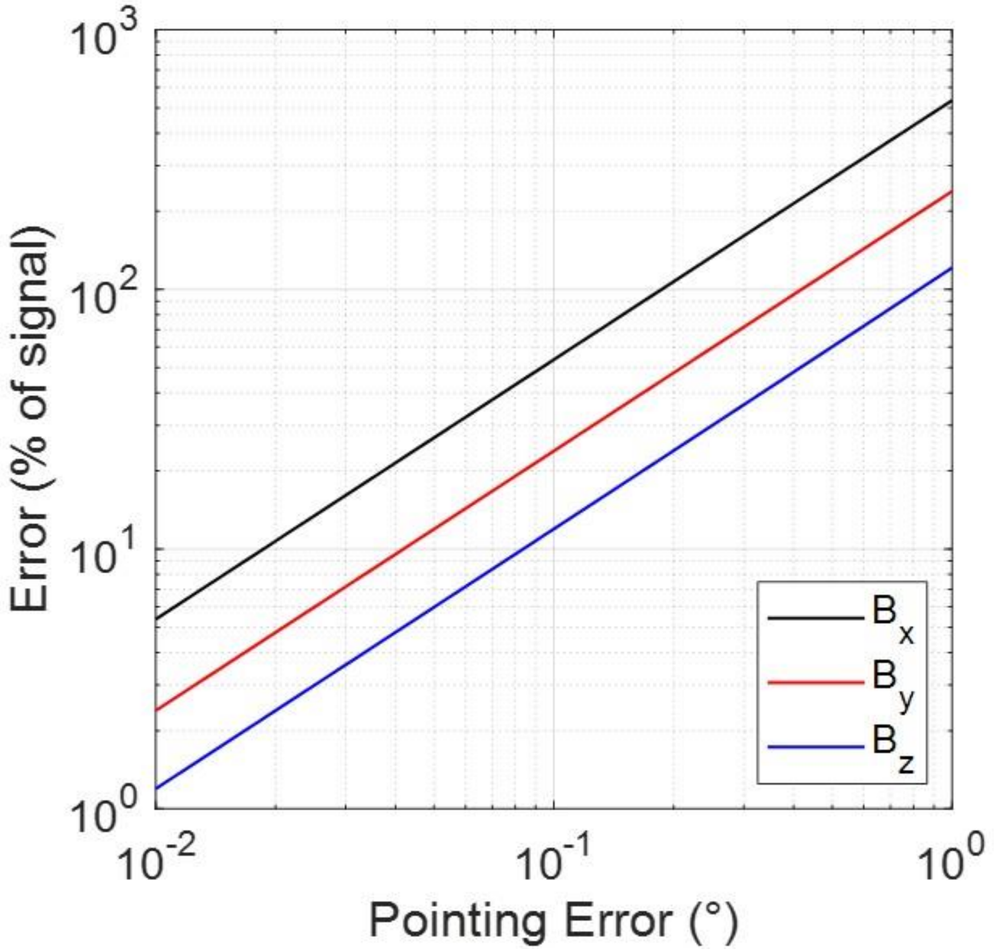
PROBLEMS WITH SINGLE MAGNETOMETERS

VECTOR MAGNETOMETERS

- High sensitivity and more information (vector components)

BUT:

- Sensitive to space weather and cultural noise sources
  - Temporal variations map to spatial variations when moving
- Signal amplitude depends on sensor height
- Extreme sensitivity to heading error
  - Very small pointing errors comparable to signals of interest
    → false flags



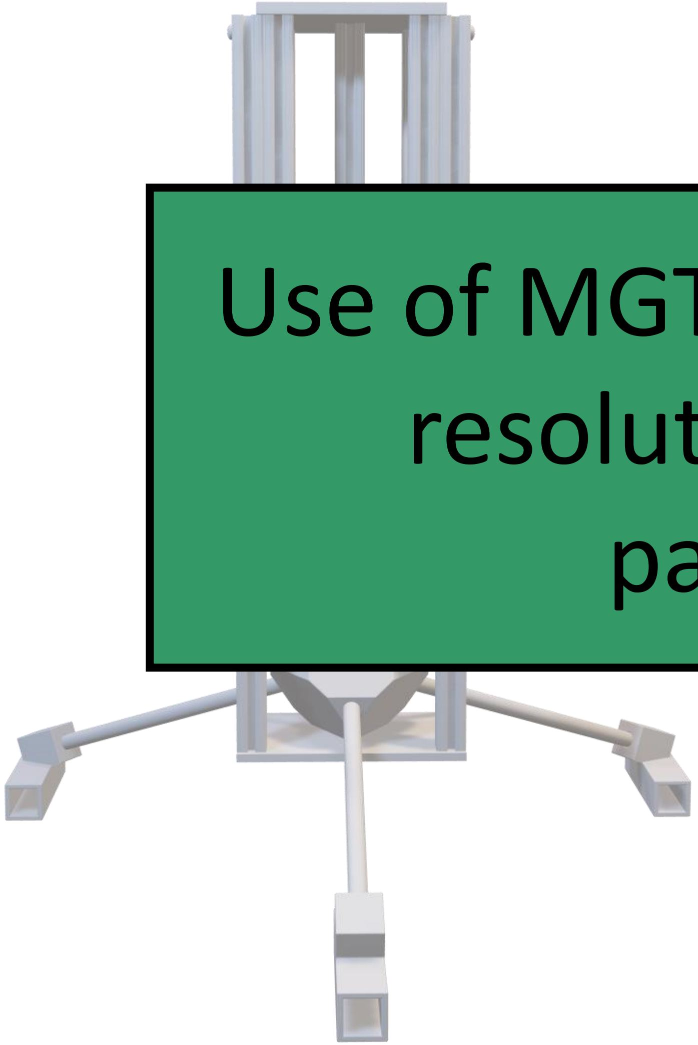
Signal error as the percentage of expected magnetic anomaly for a metal AT mine buried at 15 cm depth, measured from 0.5 m height, as a function of the pointing (heading) error of the sensor.

SOLUTION: MAGNETIC GRADIOMETRY

TetraMag

- Gradiometers sensitive to nearby changes, insensitive to distant changes
  - Solves temporal-to-spatial mapping of cultural and space weather noise
- Directly sample full magnetic gradient (finite difference) tensor
  - Higher resolving power than the analytic signal
- Redundancy of tensor components
  - Inherent error correction and noise estimates
- Rigid structure allows for control of individual heading errors
  - Orientation errors dramatically reduced but not eliminated

SOLUTION: MAGNETIC GRADIOMETRY



Use of MGT invariants can help improve resolution and allow for source parameter estimation

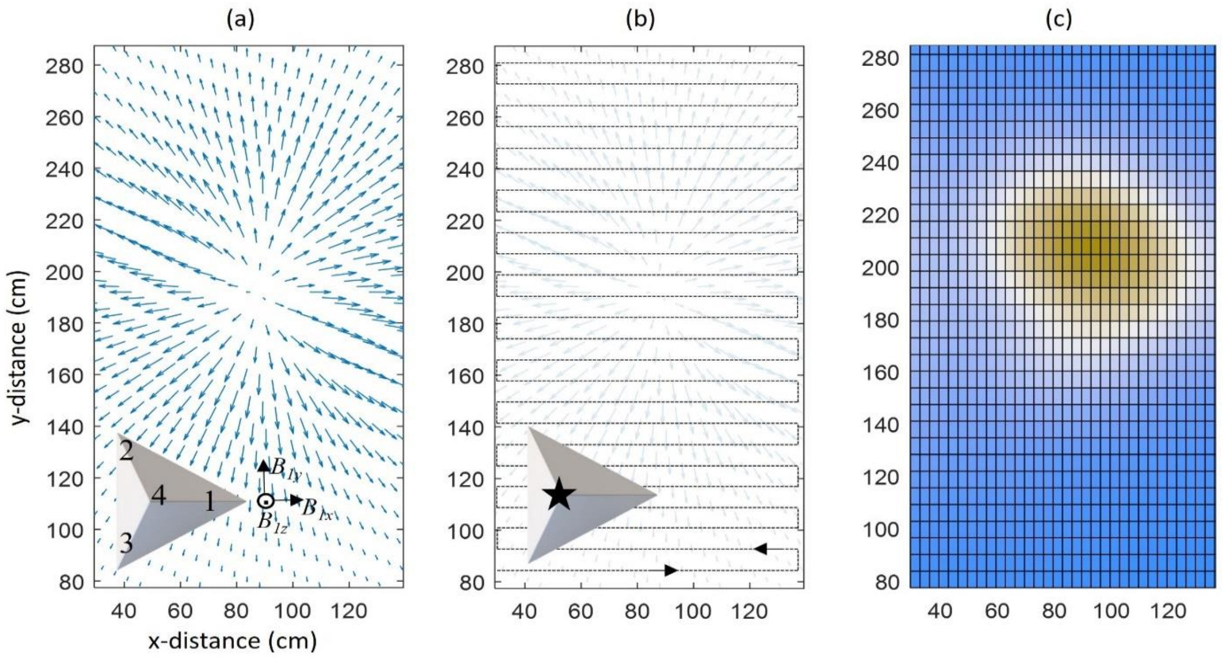
TetraMag

- Gradiometers sensitive to nearby
  nges
  apping
  noise
  lient
  ne
  ts
  - Inherent error correction and noise estimates
- Rigid structure allows for control of individual heading errors
  - Orientation errors dramatically reduced but not eliminated

GRADIENT TENSOR INVARIANTS

SYNTHETICS

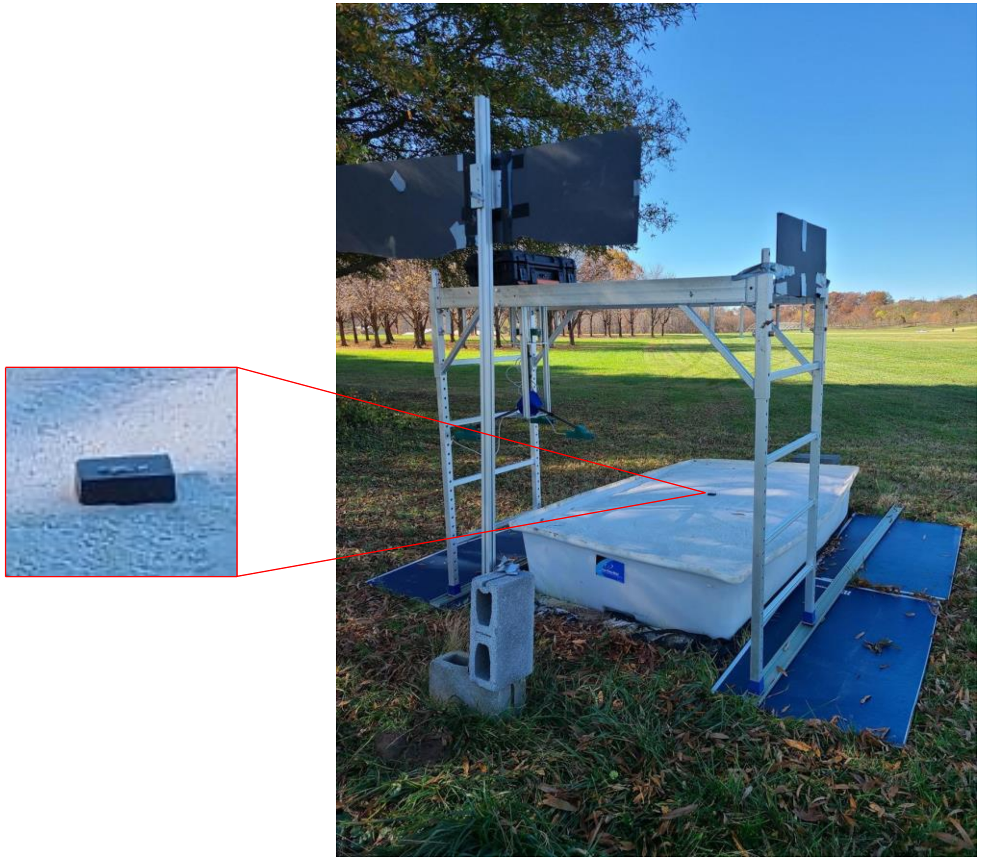
- Derived from forward model using TetraMag geometry



TetraMag survey methodology and map view of FDMGT invariants

FIELD DATA

- Measured using TetraMag on UAV-simulating scaffold in controlled test bed



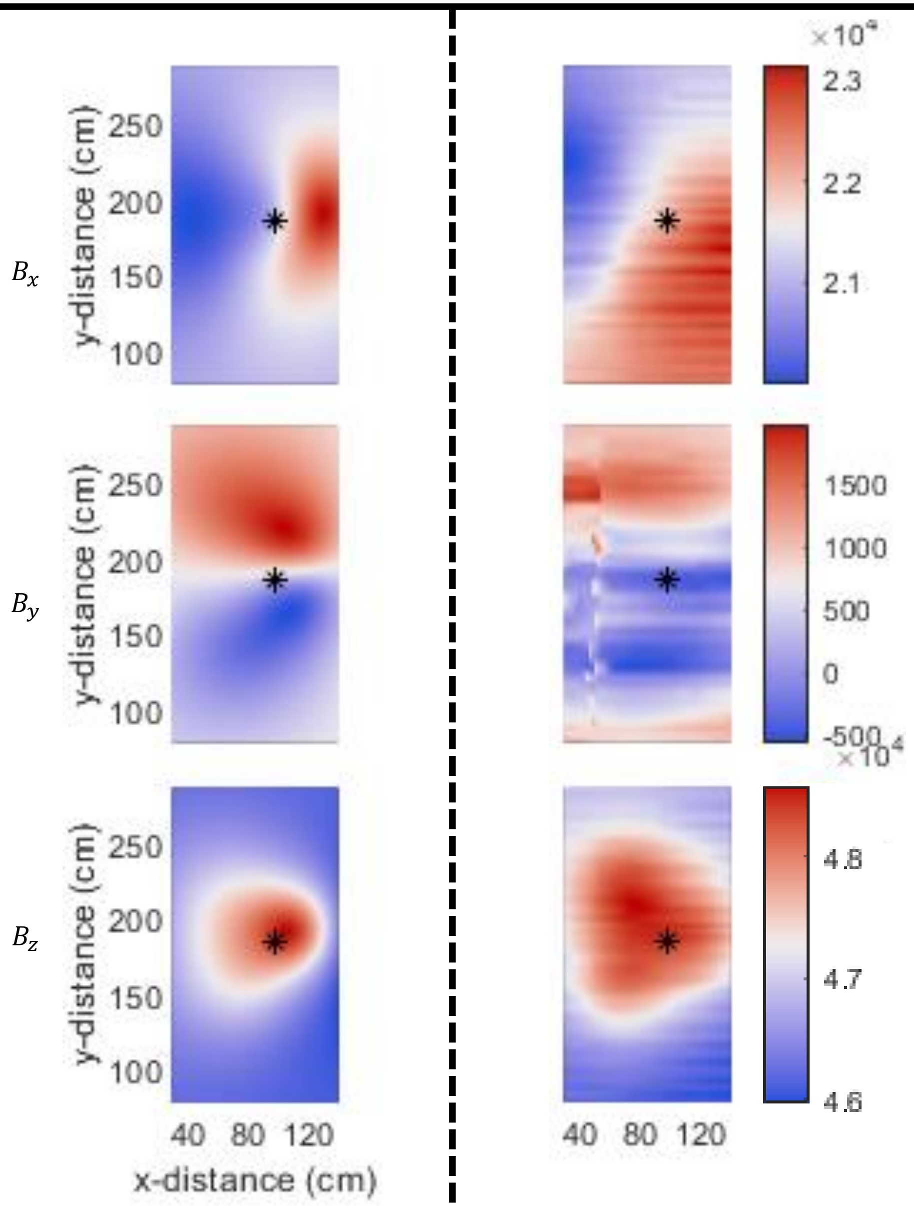
TetraMag field setup

GRADIENT TENSOR INVARIANTS

$$G_f = G_S + G_A$$

SYNTHETICS

- Average B_x, B_y, and B_z (nT) computed at 0.5 m height, buried 15 cm
- Black star indicates dipole-like target



$$G_S = \frac{G_f + G_f^T}{2}$$

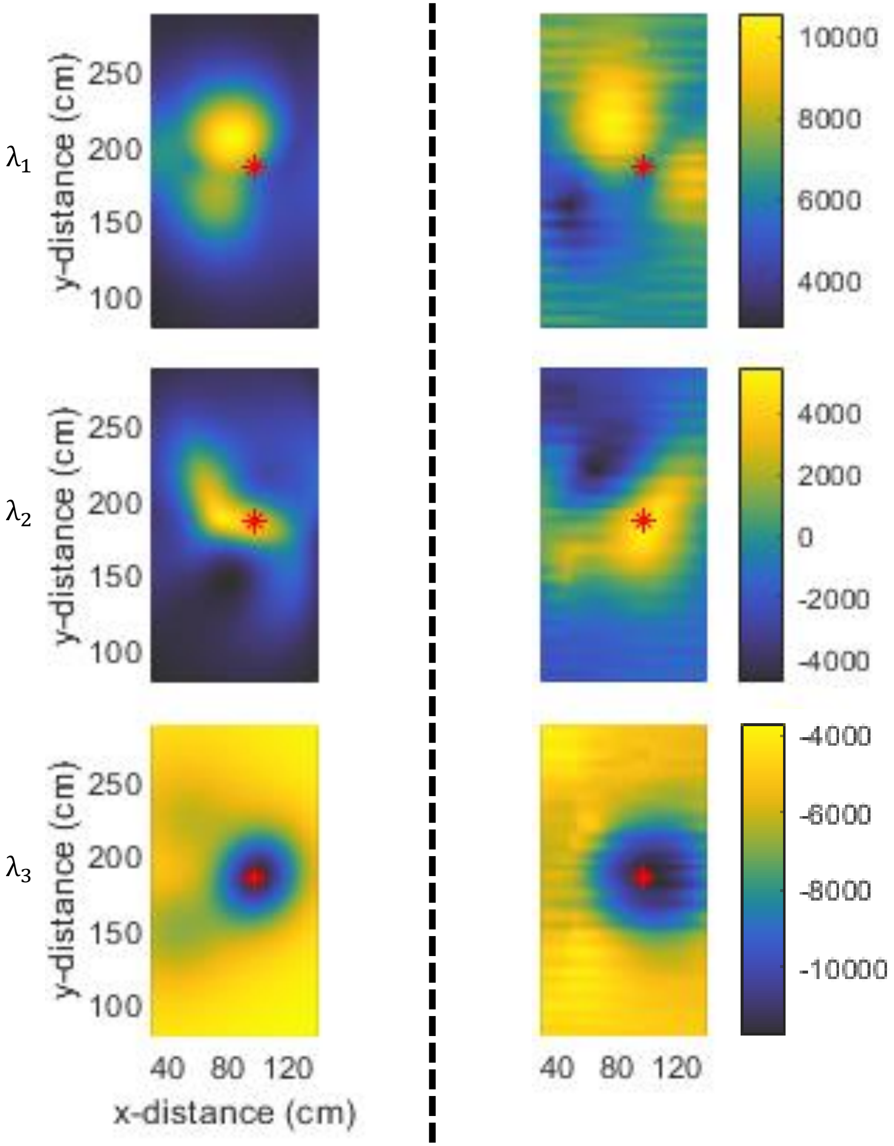
$$G_A = \frac{G_f - G_f^T}{2}$$

FIELD DATA

- Average B_x, B_y, and B_z anomalies (nT) measured at 0.5 m height, buried 15 cm
- Black star indicates dipole-like target
- Noise from scaffold holding TetraMag piecewise removed from B_y

GRADIENT TENSOR INVARIANTS

$$G_f = v^T \begin{bmatrix} \lambda_1 & & \\ & \lambda_2 & \\ & & \lambda_3 \end{bmatrix} v$$



SYNTHETICS

- Red star indicates dipole-like target
- Target localized by edge of λ_1 positive anomaly, center of λ_2 positive anomaly, center of λ_3 negative anomaly

FIELD DATA

- Horizontal shift in field data λ_1
- λ_2 and λ_3 localization match synthetic data well
- λ_1, λ_2, and λ_3 field data more diffuse than synthetic

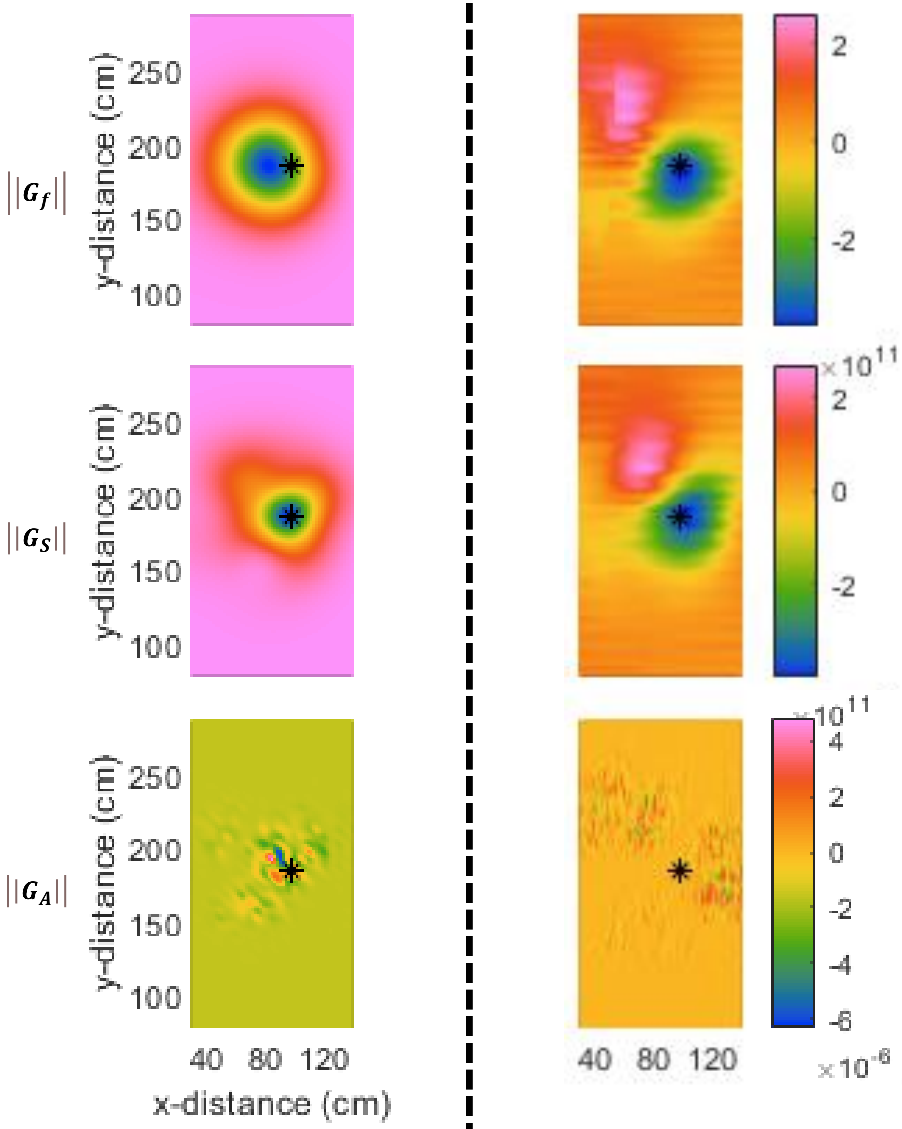
GRADIENT TENSOR INVARIANTS

$$||G_S|| = \left\|\frac{G_f + G_f^T}{2}\right\|$$

$$||G_A|| = \left\|\frac{G_f - G_f^T}{2}\right\|$$

SYNTHETICS

- Black star indicates dipole-like target
- $||G_A||$ produced by FDMGT, leads to off-center $||G_f||$
- $||G_S||$ produces negative anomaly with target localized at center



FIELD DATA

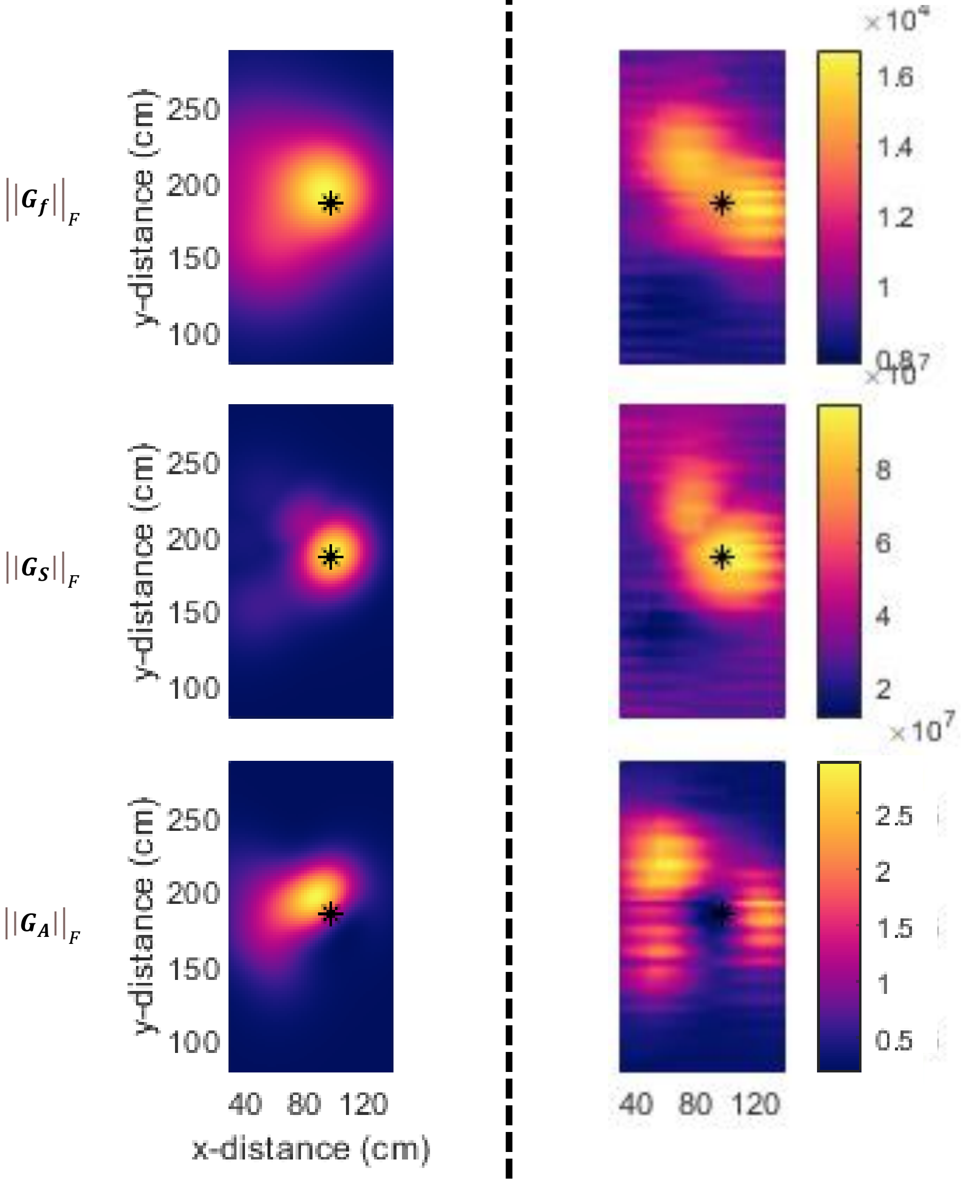
- Good agreement between synthetic and field $||G_f||$, $||G_A||$, and $||G_S||$ patterns
- Additional positive anomaly in field data not seen in synthetics

GRADIENT TENSOR INVARIANTS

$$\left\|\boldsymbol{G_f}\right\|_F = \sqrt{\sum_{i=1}^{3}\sum_{j=1}^{3}\left|g_{\mathrm{f},ij}\right|^2}$$

SYNTHETICS

- Black star indicates dipole target
- $\left\|\boldsymbol{G_A}\right\|_F$ produced by FDMGT
- Target localized at center of positive anomaly
- $\left\|\boldsymbol{G_S}\right\|_F$ localizes target with higher resolution



FIELD DATA

- Target localized well for synthetic and field data
- Positive anomaly elongated
- Additional positive anomalies in field data not seen in synthetics

GRADIENT TENSOR INVARIANTS

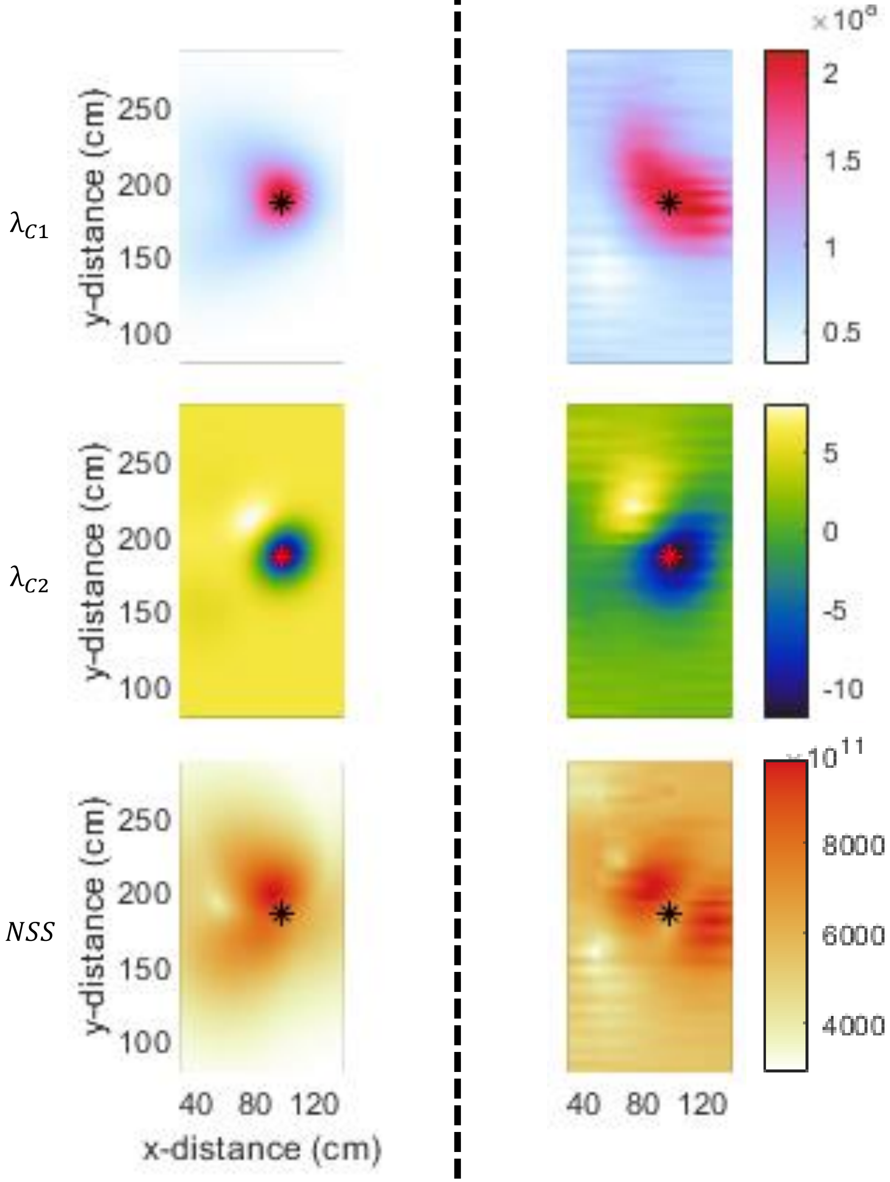
$$\lambda_{C1} = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$$

$$\lambda_{C2} = \lambda_1^3 + \lambda_2^3 + \lambda_3^3$$

$$\text{NSS} = \sqrt{-\lambda_2^2 - \lambda_1\lambda_3}$$

SYNTHETICS

- Black star indicates dipole target
- Target localized at center of positive anomaly for $\boldsymbol{\lambda_{C1}}$, negative anomaly for $\boldsymbol{\lambda_{C2}}$, edge of NSS
- Burial depth proportional to diameter of $\boldsymbol{\lambda_{C2}}$ anomaly



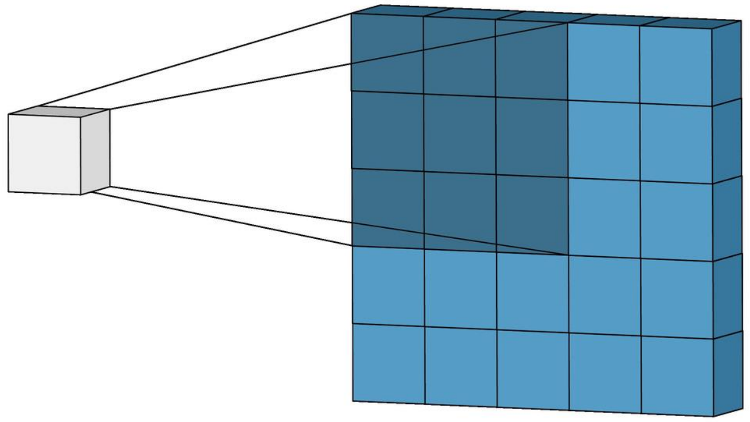
FIELD DATA

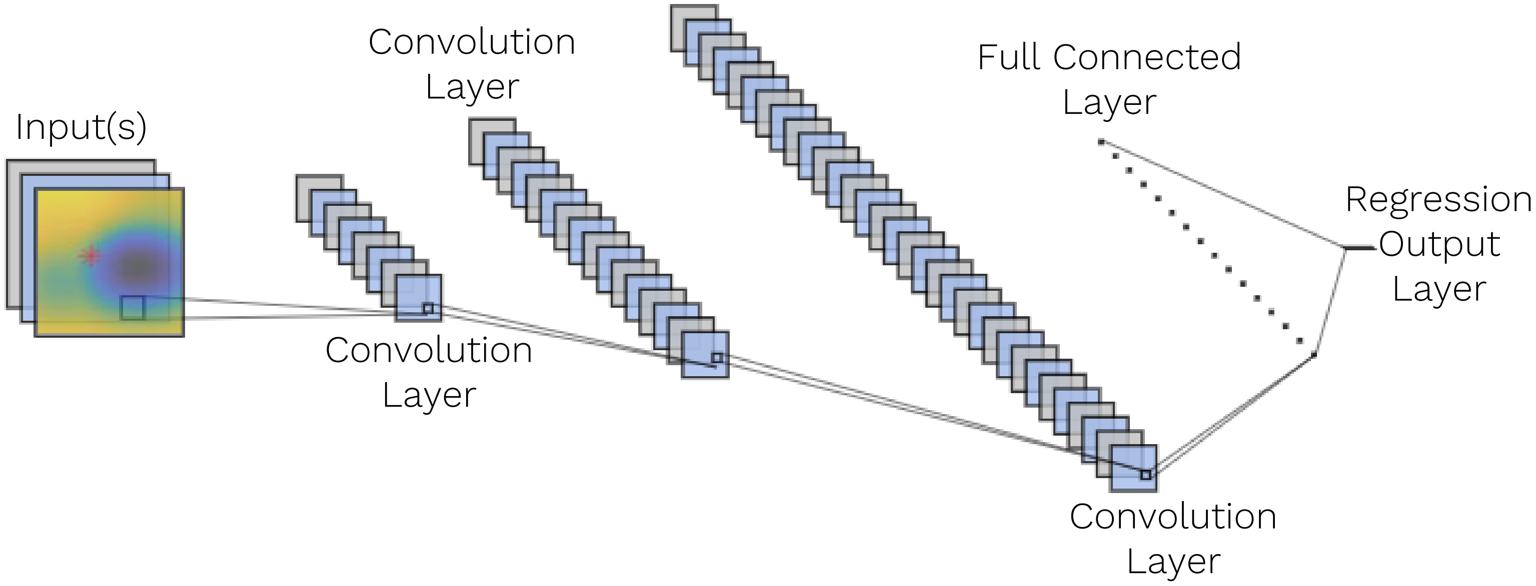
- Target localized well for synthetic and field data
- $\boldsymbol{\lambda_{C1}}$ anomaly elongated
- Additional positive anomaly in NSS not seen in synthetics

ML-ASSISTED PARAMETER ESTIMATION

CONVOLUTIONAL NEURAL NETWORK (CNN)

- Captures temporal and spatial dependencies in data via convolution with learned filters
- Efficient at summarizing low-level and high-level features
- Regression layer at end of architecture enables parameter estimation

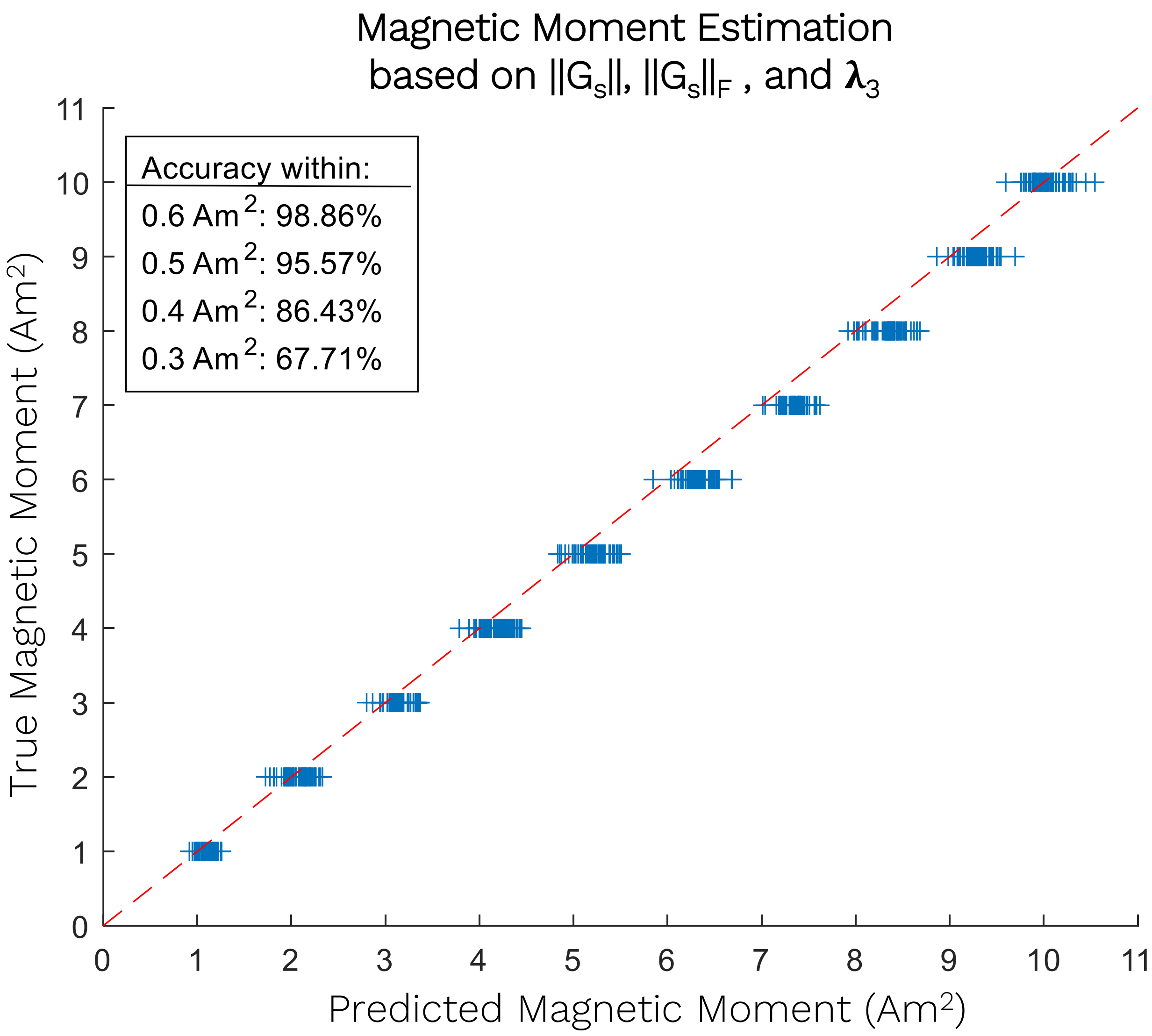




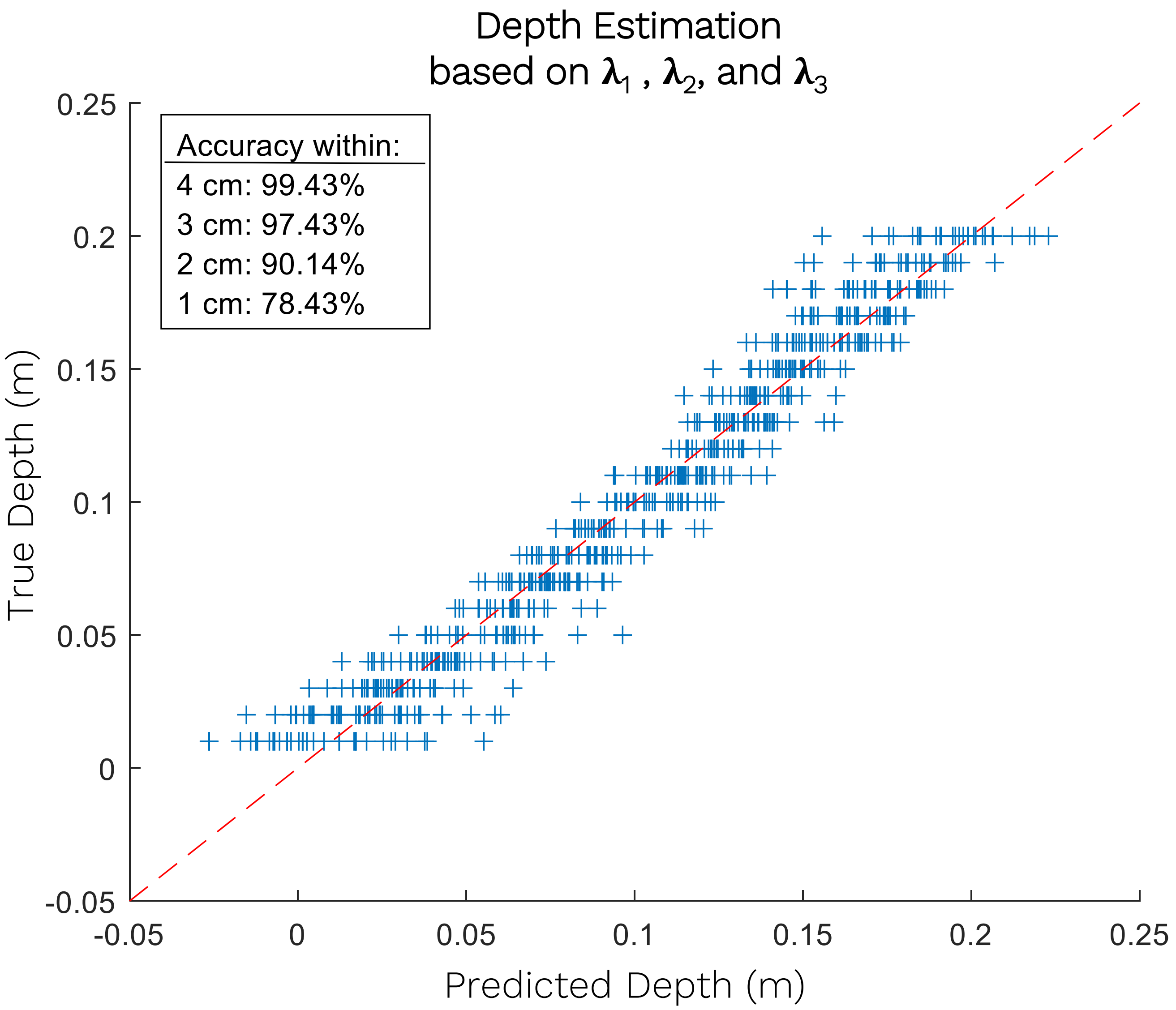
ML-ASSISTED PARAMETER ESTIMATION

MAGNETIC MOMENT

- Inputting spatial patterns of $||G_s||$, $||G_s||_F$, and λ_3 to infer magnetic moment using CNN
- Able to estimate magnetic moment within 0.6 Am^2
  - Order of magnitude improvement on current methods
    - Wang, Chen, et al. (2016)
    - Yang, Zhicheng, et al. (2019)



ML-ASSISTED PARAMETER ESTIMATION



BURIAL DEPTH ESTIMATION

- Inputting spatial patterns of λ_1 , λ_2, and λ_3 to infer burial depth using CNN
- Able to estimate depth at cm scale
  - Nearly an order of magnitude improvement on current depth estimation techniques

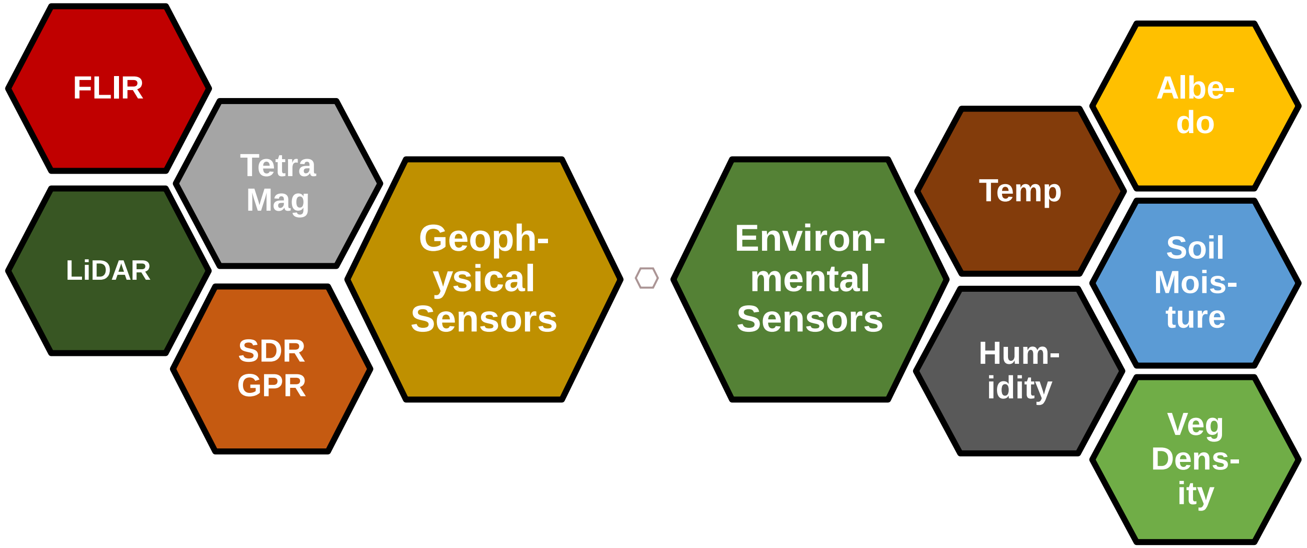
CONCLUSIONS AND NEXT STEPS

Conclusions

- Magnetic gradiometry overcomes limitations of single scalar or vector component magnetometry
  - TetraMag samples FDMGT
  - Invariants from FDMGT enables localization of targets and provides information about orientation, magnetic moment, and burial depth
- CNNs extract useful features from MGT invariants to estimate source parameters
  - Improvement on current analytical techniques

Next Steps

- Continue refining gradiometer target search algorithms
- Continue scaffold field tests (UXO sandbox test bed)
- Integrate with other sensors and UAV flight tests



THANKS!

hpm@umd.edu

NSF PFI-RP 2044611