# Selecting Optimal Models for Inverting EMI Data

**Project Number (MM-1637)**

**Len Pasion**
**University of British Columbia**
**and Sky Research Inc.**

**Brief To The Scientific Advisory Board**

**Sept 11, 2007**

# Performers

## Dr. Len Pasion (PI)

- University of British Columbia and Sky Research Inc.
- Specialist in the Interpretation of Geophysical data for the detection of UXO

## Dr. Nicolas Lhomme

- University of British Columbia and Sky Research Inc.
- Specialist in Geophysical Data processing and Climate Modeling

## Prof. Douglas W. Oldenburg

- University of British Columbia
- Specialist in Inverse Theory applied to Geophysical Data

## Dr. Lin-Ping Song

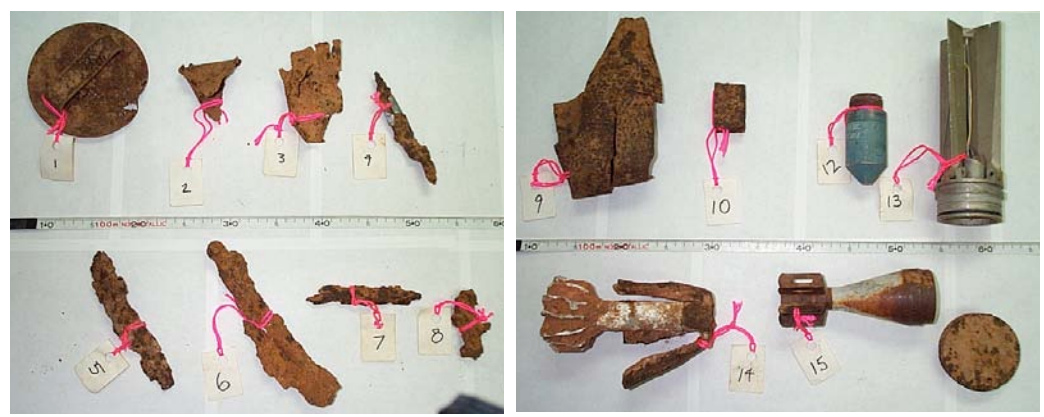
- University of British Columbia
- Specialist in Electromagnetic Modeling and UXO data processing

# Problem Statement

- Practical and cost-effective strategies for remediation require reliable algorithms for discrimination
- Discrimination depends upon the ability to estimate parameters. The success of this procedure requires:
  1. A careful choice of the forward modeling, and
  2. An understanding of how data quality impacts parameter estimates of the chosen forward model.

**UXO**

**Scrap**



# Technical Objective

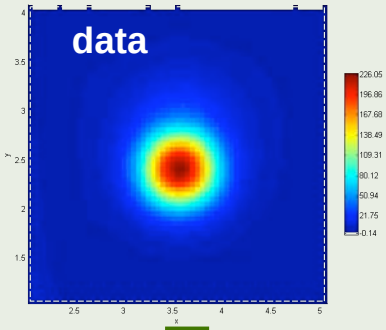
- The goal of this research is to delineate the circumstances for which a particular type of forward model should be chosen.
- Methodologies will be developed that would allow a user to more efficiently extract meaningful parameters from data.
- Specific objectives:
    1. Determine the conditions for which the Surface Magnetic Charge Model might yield superior information compared to dipole models
    2. Determine which parameterizations of the dipole model are most useful for discrimination
    3. Develop practical diagnostic procedures to assess which data anomalies are of high enough quality to warrant inversion and which inversion procedure should be used

# Technical Background

- The standard processing stream for detection and discrimination of UXO using geophysical data:

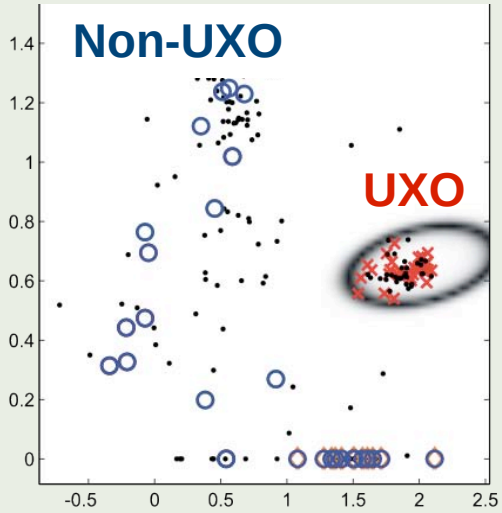
**1. Data Collection**

**2. Parameter Estimation**




*feature vector*

**3. Discrimination**

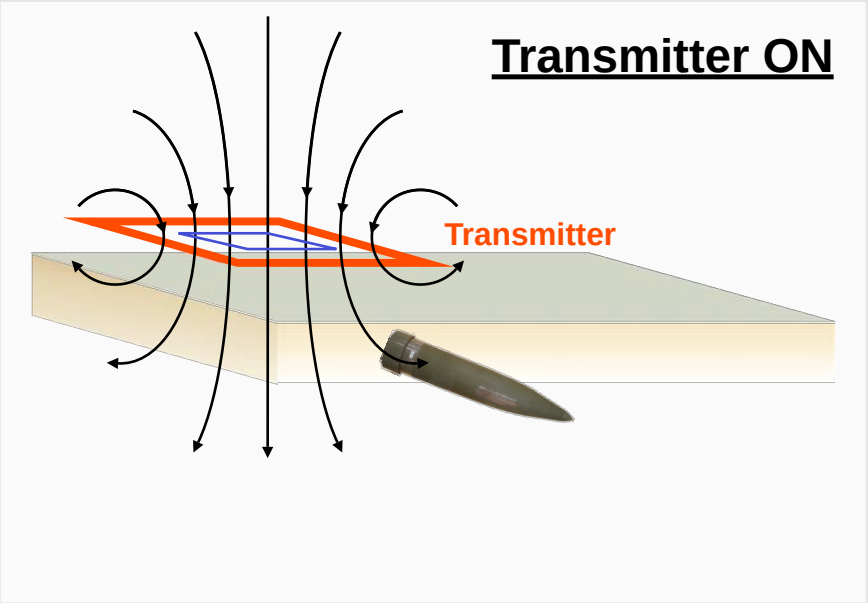


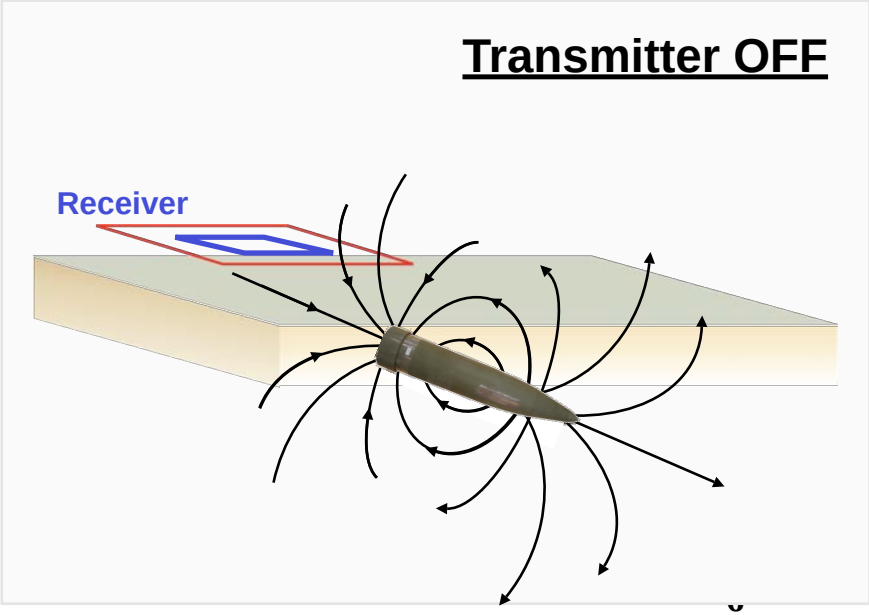
# Technical Background

Data Collection → Parameter Estimation → Discrimination

## Electromagnetic Induction

- Subsurface illuminated by a time varying field
- Measures eddy currents induced in nearby conductive material



# Technical Background

Data Collection → **Parameter Estimation** → Discrimination

**Data based features:**

- Amplitude
- Spatial extent

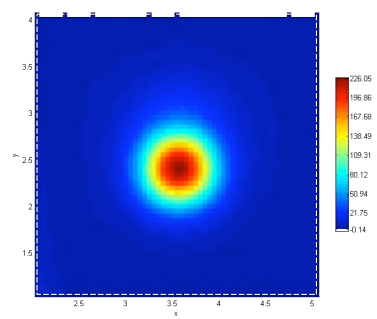
**Model based features:**

- Inversion of data for parameters of a physics-based model
- These parameters reflect the size, shape, and material properties of the target

***Forward Operator***

$$d = F[m]$$

***Sensor data:*** $d$



***Model Parameters:*** $m$

$$m = F^{-1}[d]$$

***Inverse Operator***

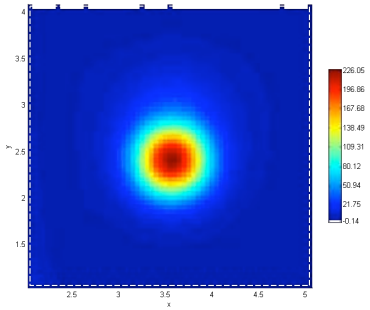
# Technical Background

Data Collection → **Parameter Estimation** → Discrimination

***Forward Operator***

$$d = F[m]$$

***Sensor data:*** $d$



***Model Parameters:*** $m$

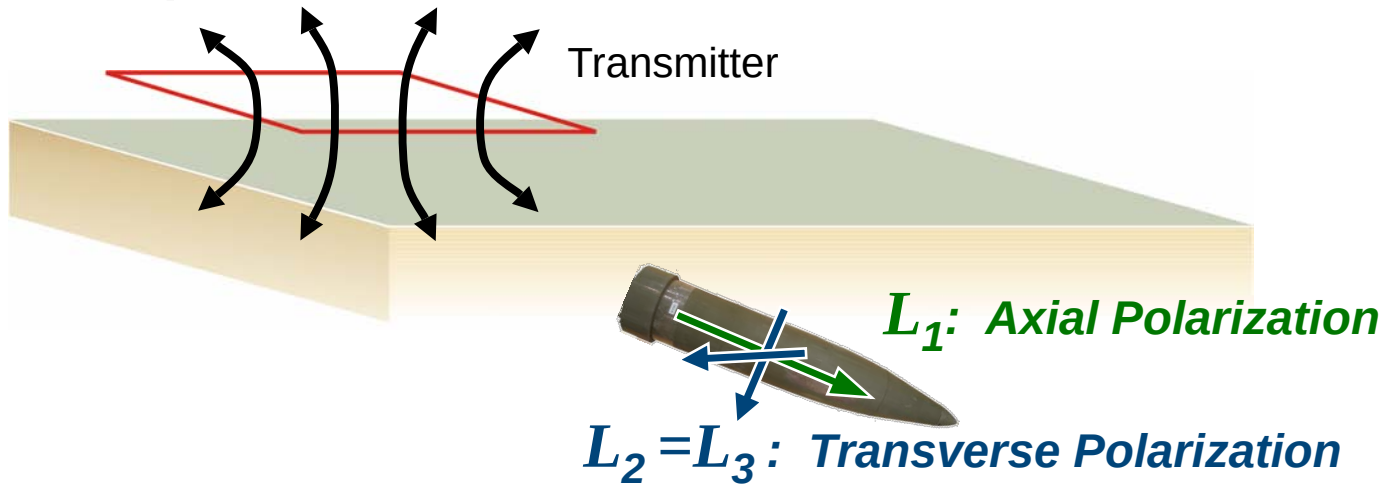
$$m = F^{-1}[d]$$

***Inverse Operator***

- Effective inversion depends on
  1. Choice of forward model
     - Accuracy, Complexity, and Computational Efficiency
  2. Quality of the data
     - Signal-to-Noise Ratio, Spatial Coverage, etc.

# Technical Background

## The Point Dipole Model




- Most commonly used forward model for UXO processing

$$\mathbf{B}(t) = \frac{\mu_o}{4\pi r^3}\mathbf{m}(t)\times\left(3\hat{\mathbf{r}}\hat{\mathbf{r}} - \overline{\overline{\mathbf{I}}}\right)$$

with

$$\mathbf{m}(t) = \frac{1}{\mu_o}\overline{\overline{\mathbf{M}}}(t)\times\mathbf{B}_o$$

and

$$\overline{\overline{\mathbf{M}}}(t) = \begin{bmatrix} L_x(t) & 0 & 0 \\ 0 & L_y(t) & 0 \\ 0 & 0 & L_z(t) \end{bmatrix}$$

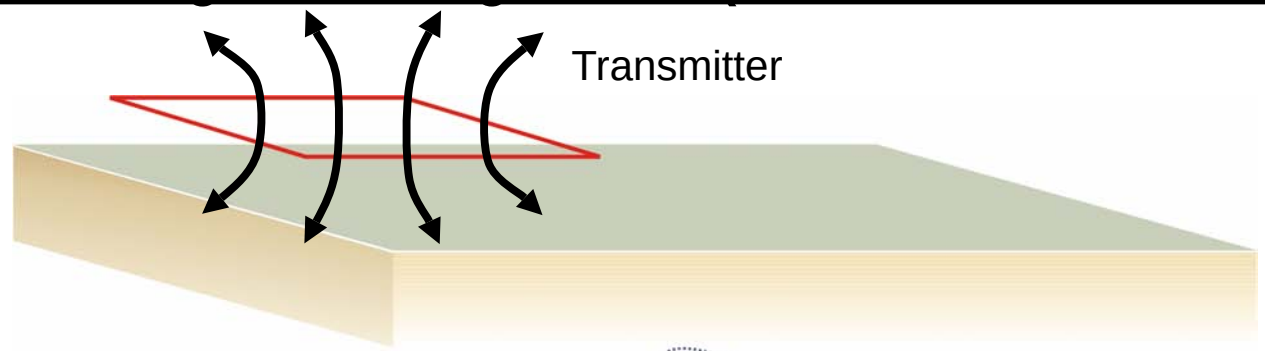
- The forward operator can then be written:

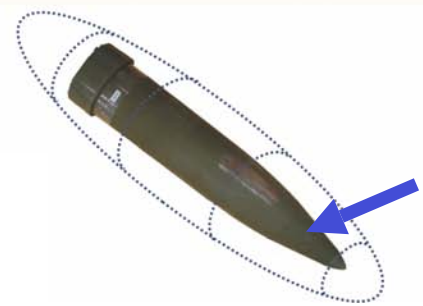
$$\mathbf{d} = F[\mathbf{m}] = F^t\left[\mathbf{r}, \phi, \theta, \mathbf{p}^t\right]$$

$\mathbf{r}$: target location
$\phi, \theta$ : orientation
$\mathbf{p}$: polarization parameters

# Technical Background

## The Surface Magnetic Charge Model (Shubitidze et al. 2005)



**Surface charge Distribution $\sigma_m$**

$$\mathbf{H}^{sc}(\mathbf{r},\xi) = \frac{1}{4\pi\mu_o}\int_S \sigma_m(\mathbf{r}',\xi)\,\frac{\mathbf{r}-\mathbf{r}'}{|\mathbf{r}-\mathbf{r}'|^3}\,dS'$$

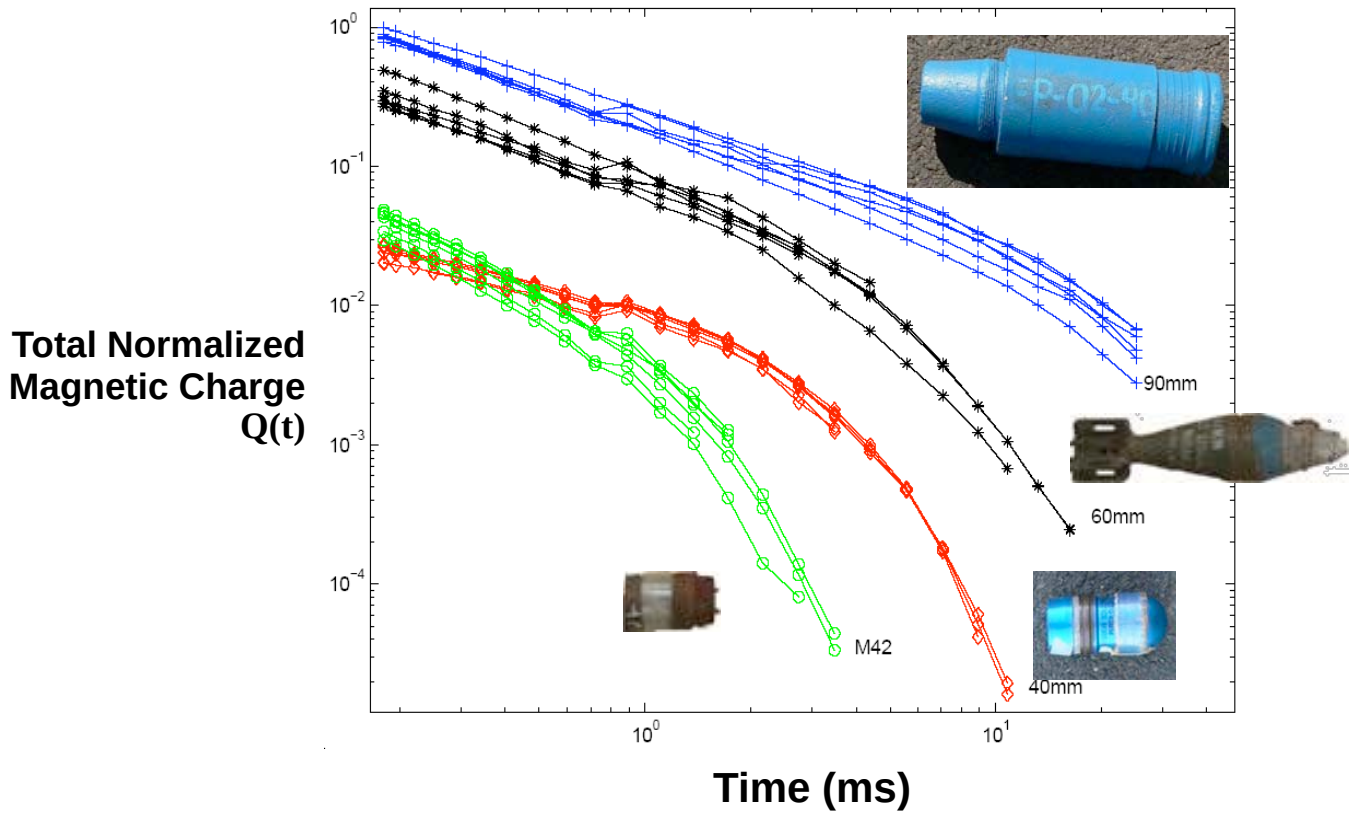
- Define surface charges $\sigma_m(r')$ on **spheroid** around ordnance:
- Define charges ***q(r')*** by normalization with normal component of primary field
- Define **Total Normalized Magnetic Charge (TNMC)** *Q:*

$$Q(\xi) \equiv \int_S q_m(\mathbf{r}',\xi)\,dS'$$

# Technical Background

Example: ERDC Test stand data inverted for the Total Normalized Magnetic Charge

- SERDP SEED MM-1446
- Time Domain TNMC determined using Geonics EM63 data.
- High level of non-uniqueness required a regularized solution

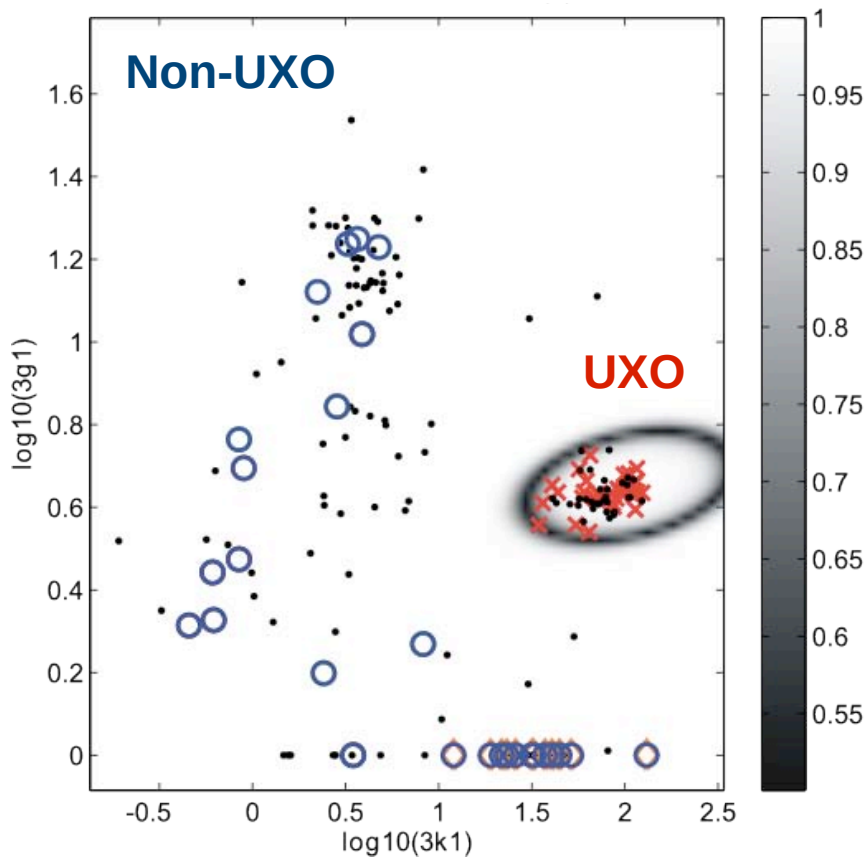


# Technical Background

Data Collection → Parameter Estimation → **Discrimination**

Example: Inversion of Geonics EM63 Data at Camp Sibert

- ESTCP Discrimination Pilot Study



UXO

partial UXO

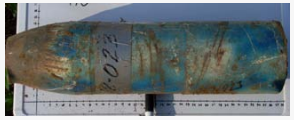
NonUXO
- Base Plate
- Frag
- Scrap Metal
- Rock

Unlabelled

# Technical Background

Data Collection → Parameter Estimation → **Discrimination**

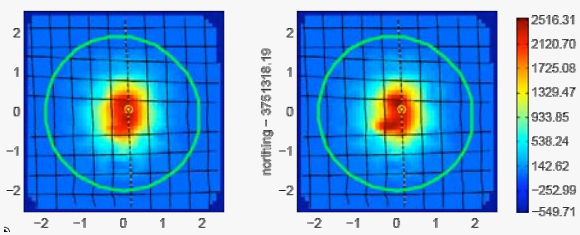
Example: Inversion of MTADS data collected at Camp Sibert



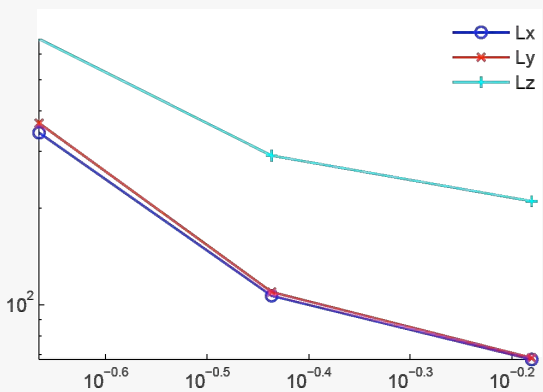
## UXO: 4.2 in. Mortar

### Depth = 0.18 m

**Observed Data** **Predicted Data**

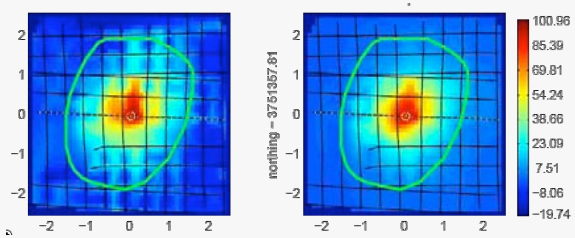



**Recovered Polarizations**

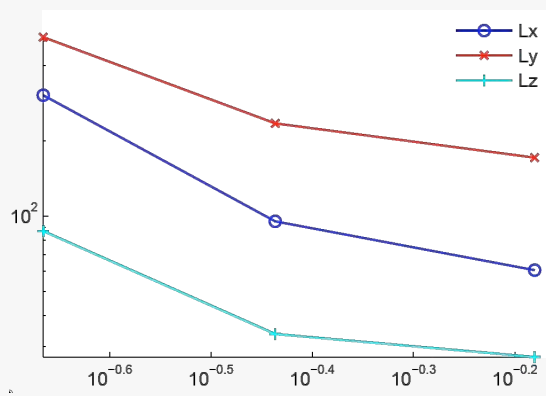



### Depth = 1.06 m

**Observed Data** **Predicted Data**



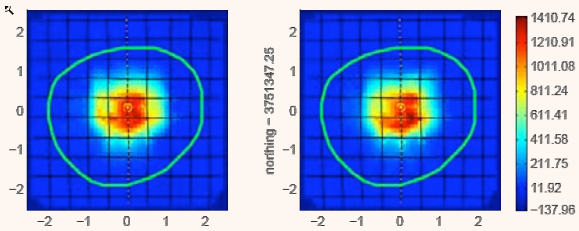

**Recovered Polarizations**



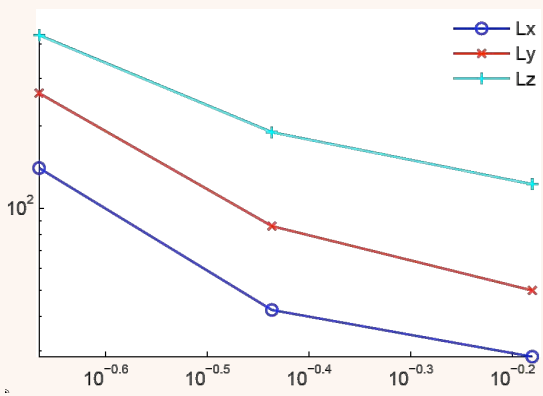

## Scrap: Partial 4.2 in Mortar

### Depth = 0.11 cm

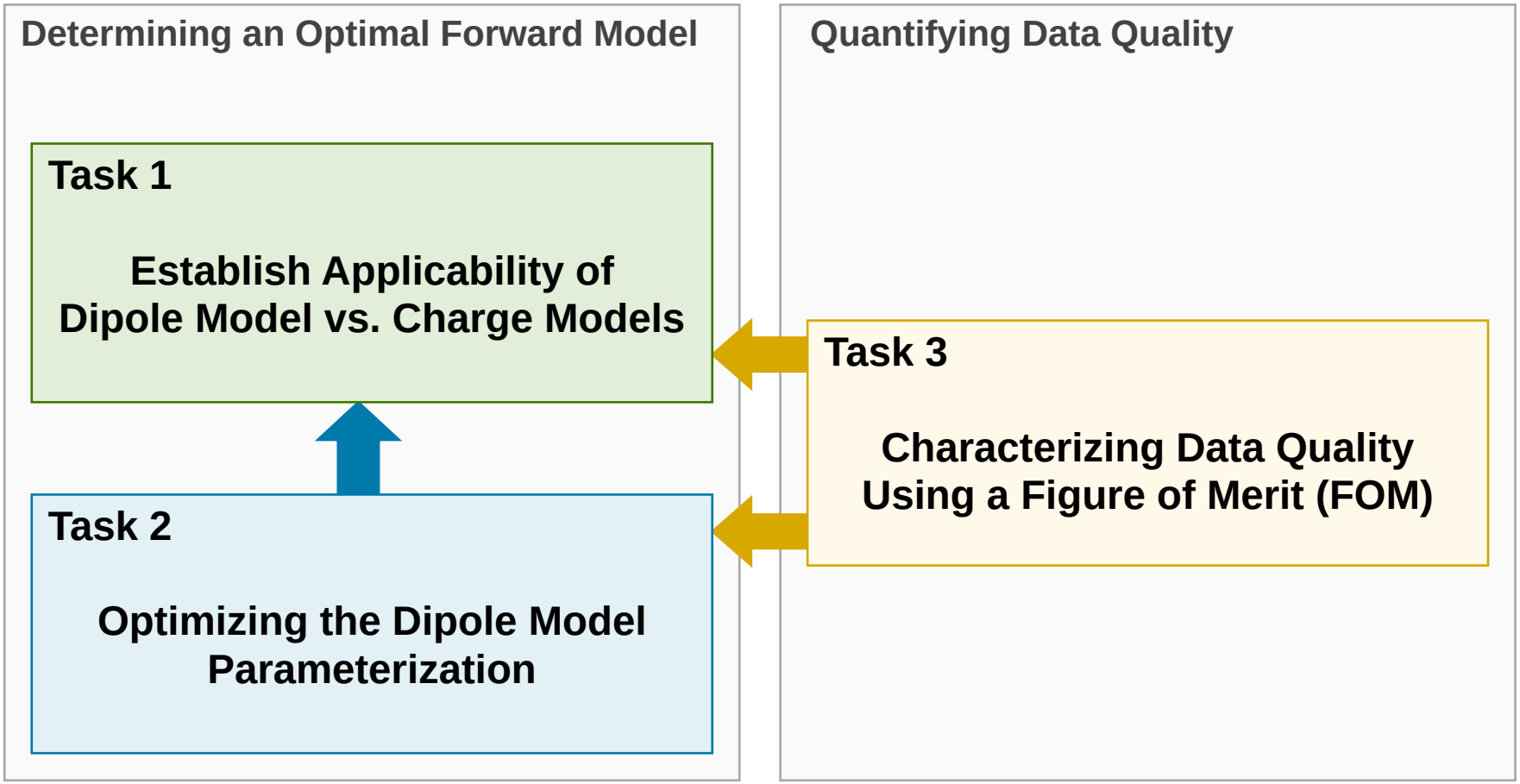
**Observed Data** **Predicted Data**




**Recovered Polarizations**



# Technical Approach



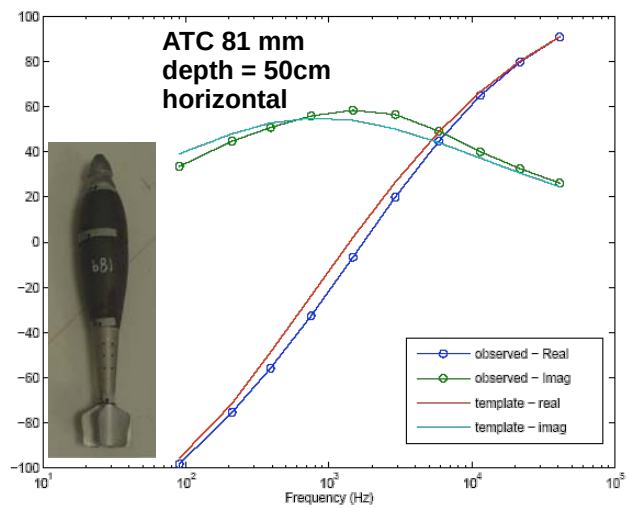
# Technical Approach

Task 1: **Establish Applicability of Dipole model vs. Charge Models**

1. Analyze the variance of recovered dipole and charge model parameters
   - Simulated data generated using the Standard Excitation Approach (SEA) and test stand data (USACE ERDC, Vicksburg)
2. Data from the SEA models will be fit with dipole models to determine the extent to which non-dipolar components bias the dipole parameters
3. For cases where the dipole model produces large class cluster variances, we will invert for the SMC model and compare the class cluster variance to that of the dipole model

Geonics EM63 on the ERDC Test Stand

**Data fit using SEA Model**




From SERDP SEED MM-1446

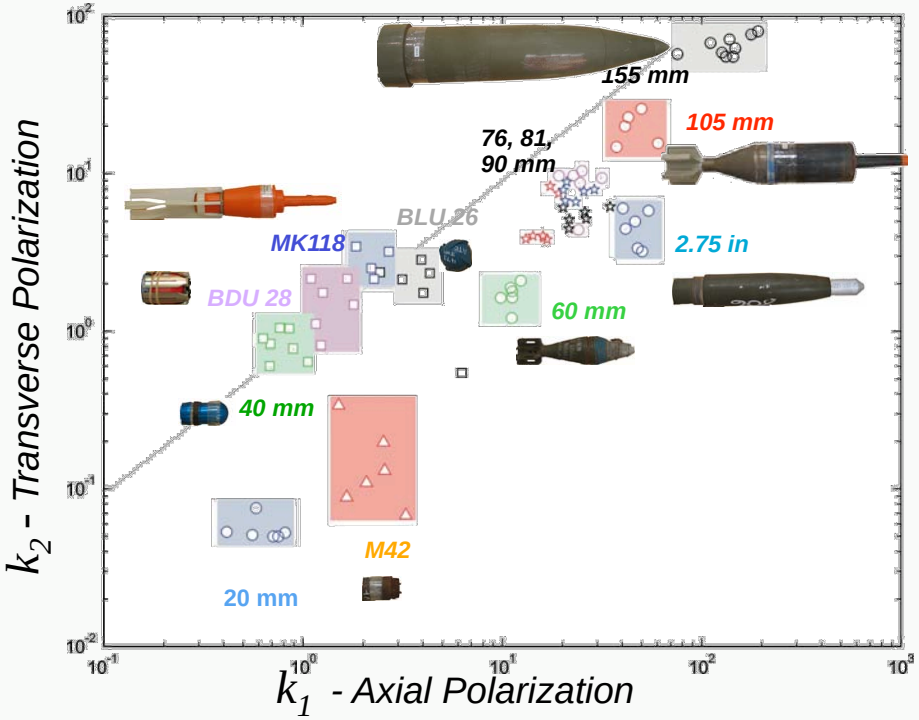
# Technical Approach

Task 1: **Establish Applicability of Dipole model vs. Charge Models**

Example: ERDC Test stand Geonics EM63 data

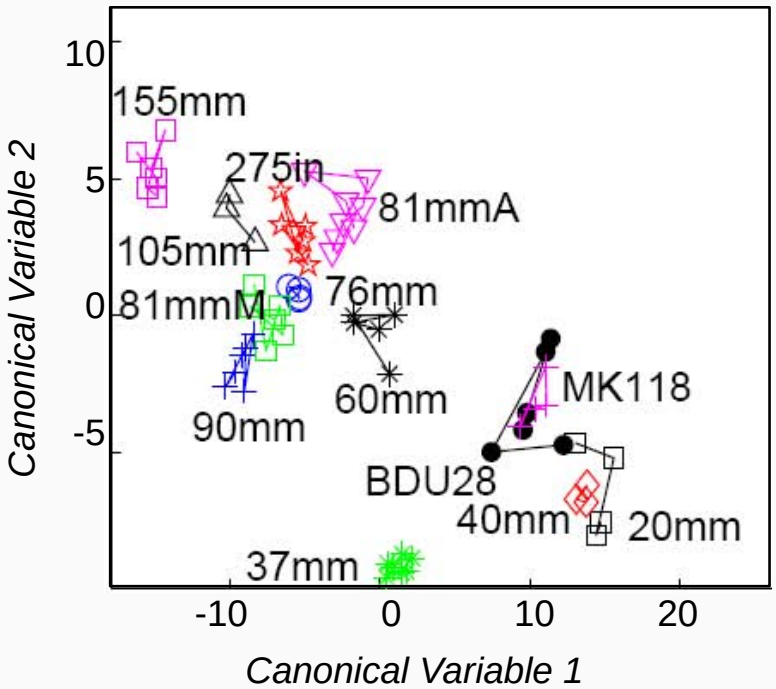
## Dipole Model:

Polarization Amplitude




## Surface Magnetic Charge Model:

Total Normalized Charge



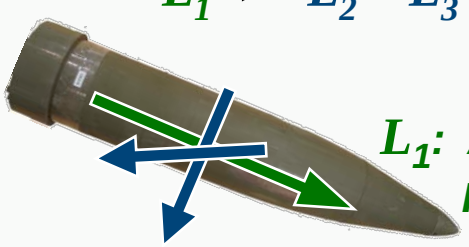
# Technical Approach

## Task 2: **Optimizing the dipole model parameterization**

- We will examine the data quality required to constrain:
  - The two-transverse polarizations for UXO targets, and
  - 3 unique polarizations for non-axial symmetric targets.
- We will develop strategies for determining the number of independent polarizations:
  1. *A priori* statistical analysis of the Eigenstructure of the data covariance matrix
  2. Posterior statistical tests of inversion results.
- We will investigate how estimated variances can be used for discrimination.
- We will investigate different parameterizations of the time and frequency domain polarization tensor

Axi-symmetric (UXO-like)

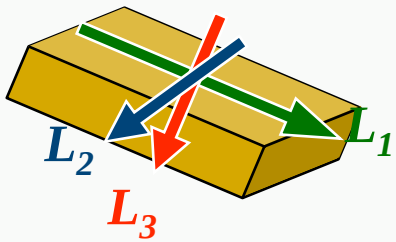
$L_1 > L_2 = L_3$



$L_1$: ***Axial Polarization***

$L_2 = L_3$ : ***Transverse Polarization***

No Axial Symmetry (e.g. scrap) $L_1 \neq L_2 \neq L_3$

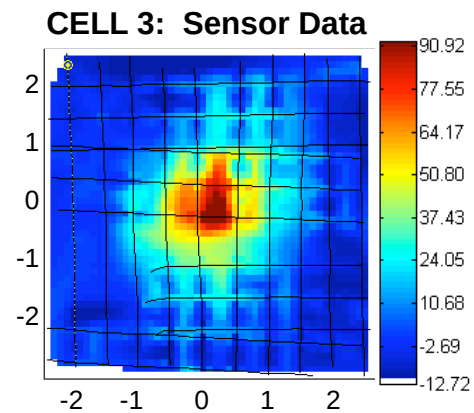


# Technical Approach

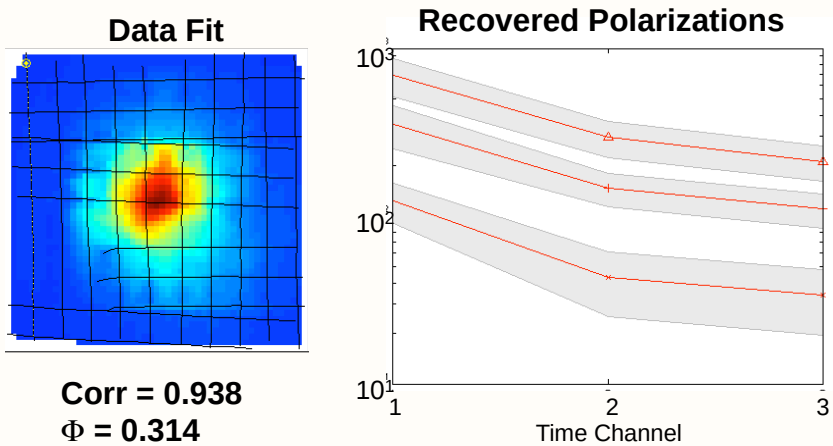
## Task 2: **Optimizing the dipole model parameterization**

Example: Inversion of MTADS data collected at Camp Sibert

- 4.2 inch mortar, depth = 1.06 m
- Data fit is ***nearly identical*** for 2 or 3 polarization model
- Recovered 3 polarization parameters have a ***larger variance*** than the 2 polarization parameters

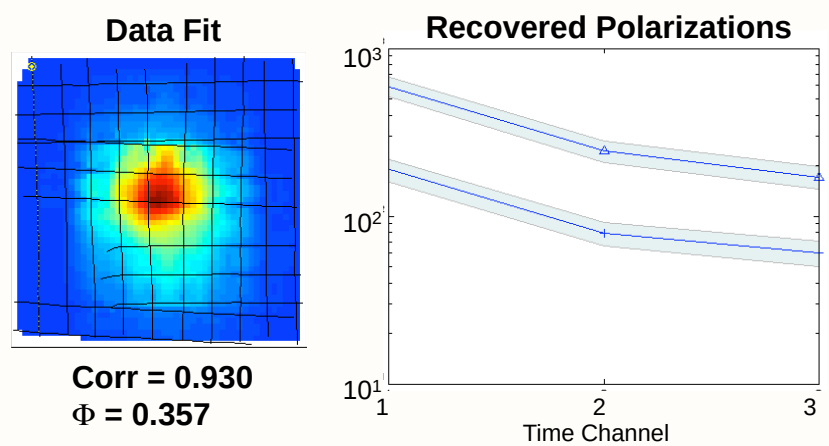



**Three** Polarizations




**Corr = 0.938**
**Φ = 0.314**

**Two** Polarizations




**Corr = 0.930**
**Φ = 0.357**

# Technical Approach

Task 3: **Characterizing data quality using a Figure of Merit (FOM)**

- Define a FOM for multi-channel EMI data. This procedure will require numerous data simulations and inversions.
- Test protocol on test stand data. Adjust definition of FOM if necessary.
- Apply and validate FOM on field data for which inversion, classification and ground truth are available so that FOM can be used as diagnostic.
- Incorporate FOM analysis in UXOLab software.

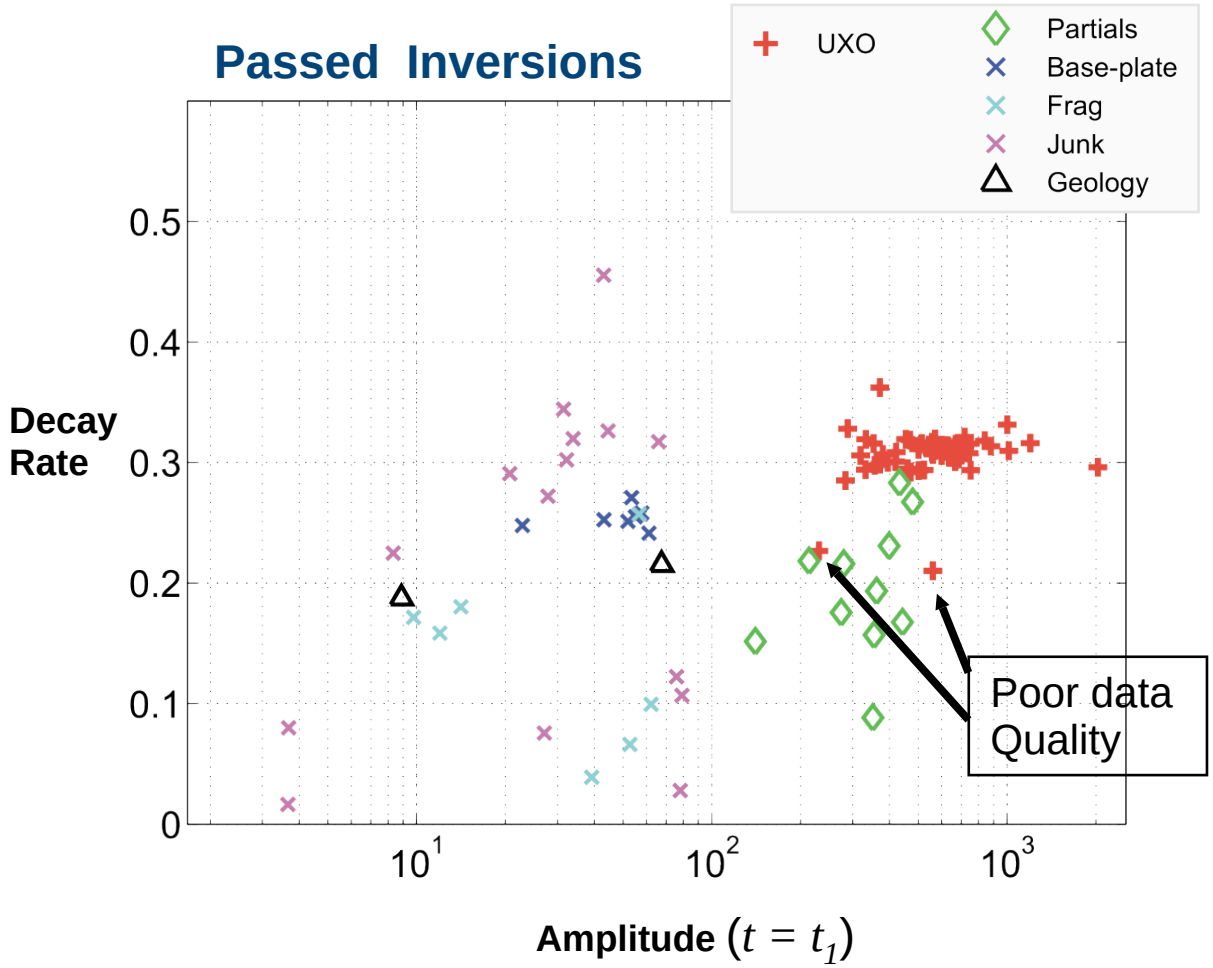
# Technical Approach

Task 3: **Characterizing data quality using a Figure of Merit (FOM)**

Example: Inversion of MTADS data collected at Camp Sibert

- 59 UXO
- 115 Non-UXO

- Decay and amplitude of primary polarization is a good discriminant



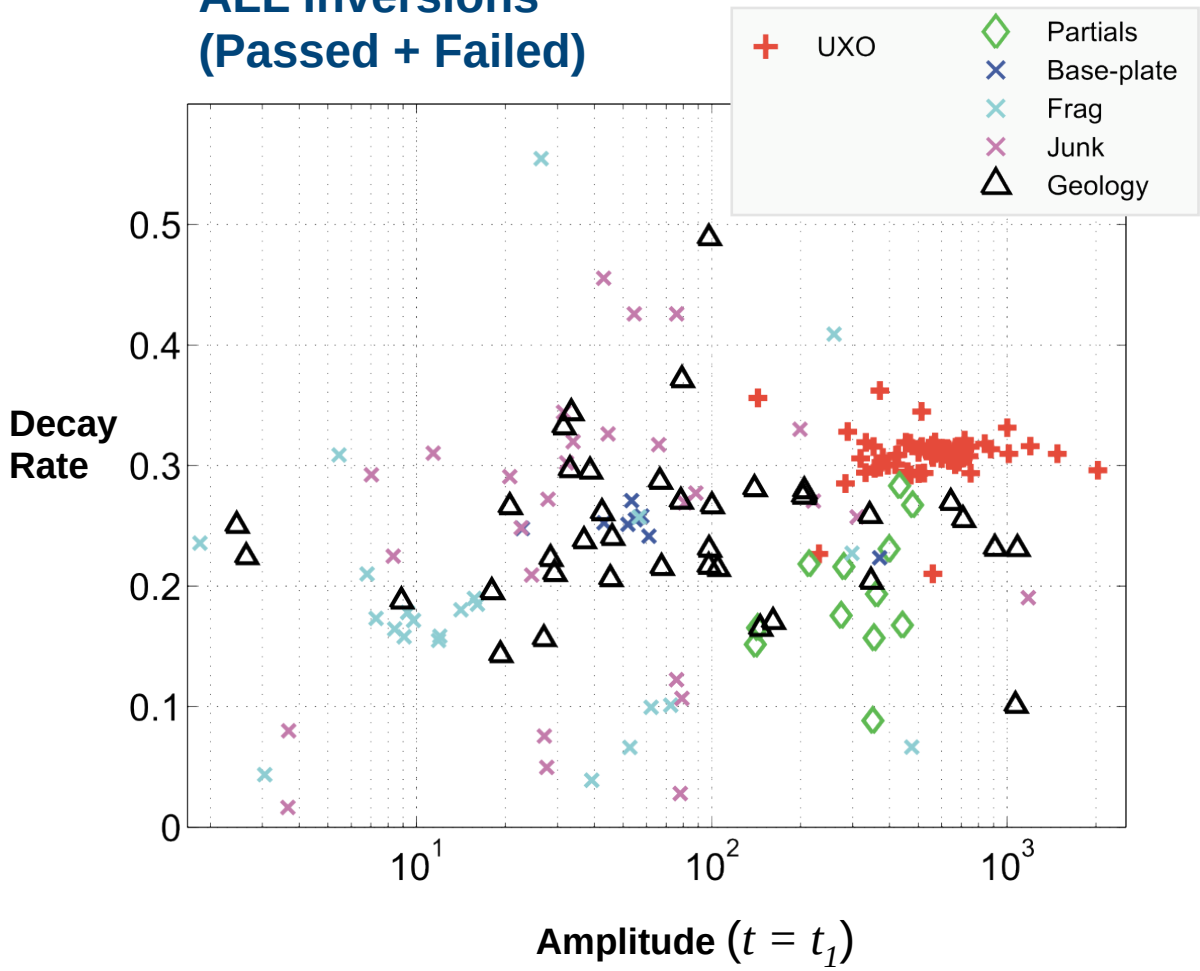
# Technical Approach

Task 3: **Characterizing data quality using a Figure of Merit (FOM)**

- 59 UXO
- 115 Non-UXO

- Decay and amplitude of primary polarization is a good discriminant

**ALL Inversions (Passed + Failed)**



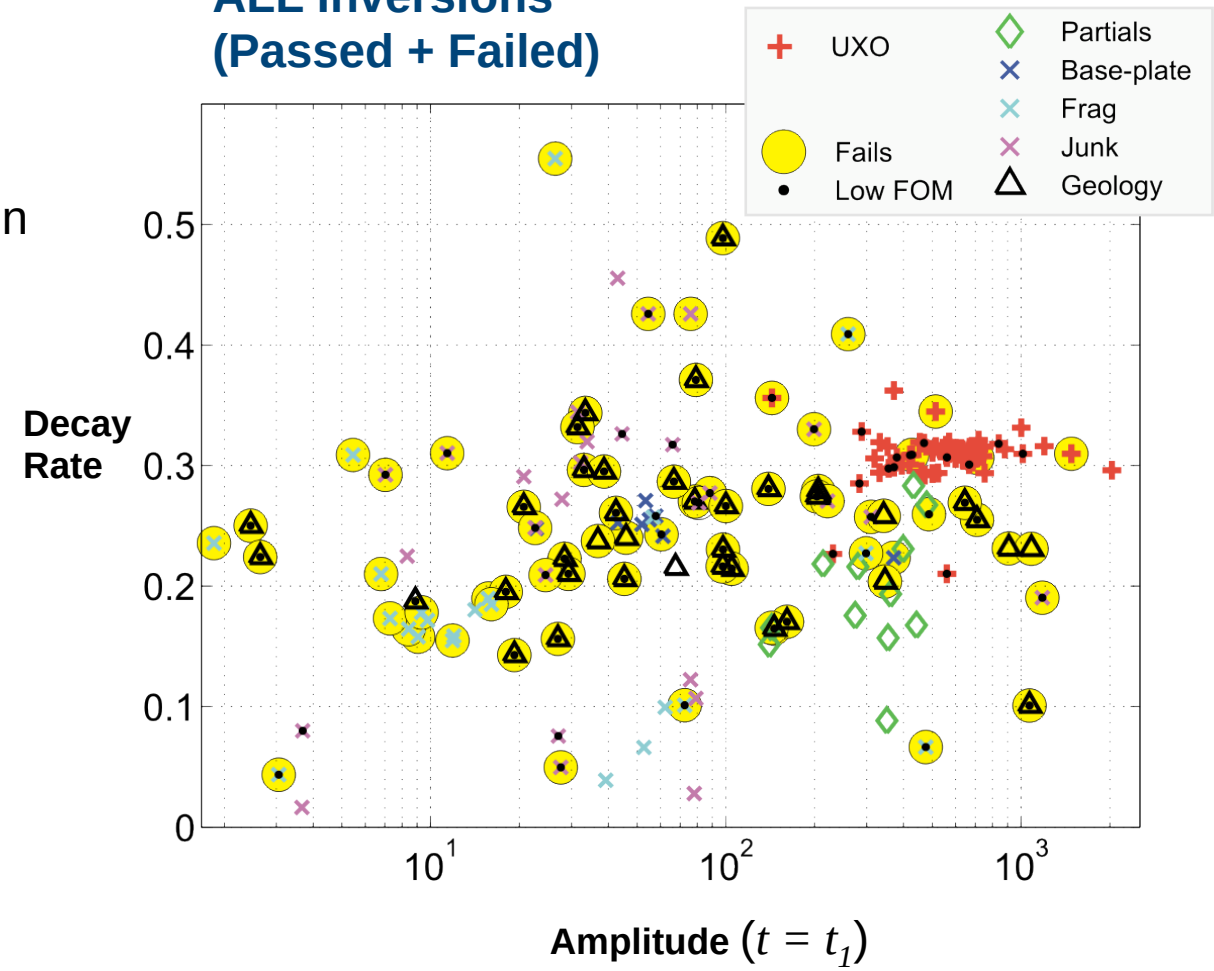
# Technical Approach

Task 3: **Characterizing data quality using a Figure of Merit (FOM)**

Define an FOM based on:

1. Spatial coverage
2. Signal-to-Noise Ratio
3. Ability for data to constrain depth

**ALL Inversions (Passed + Failed)**



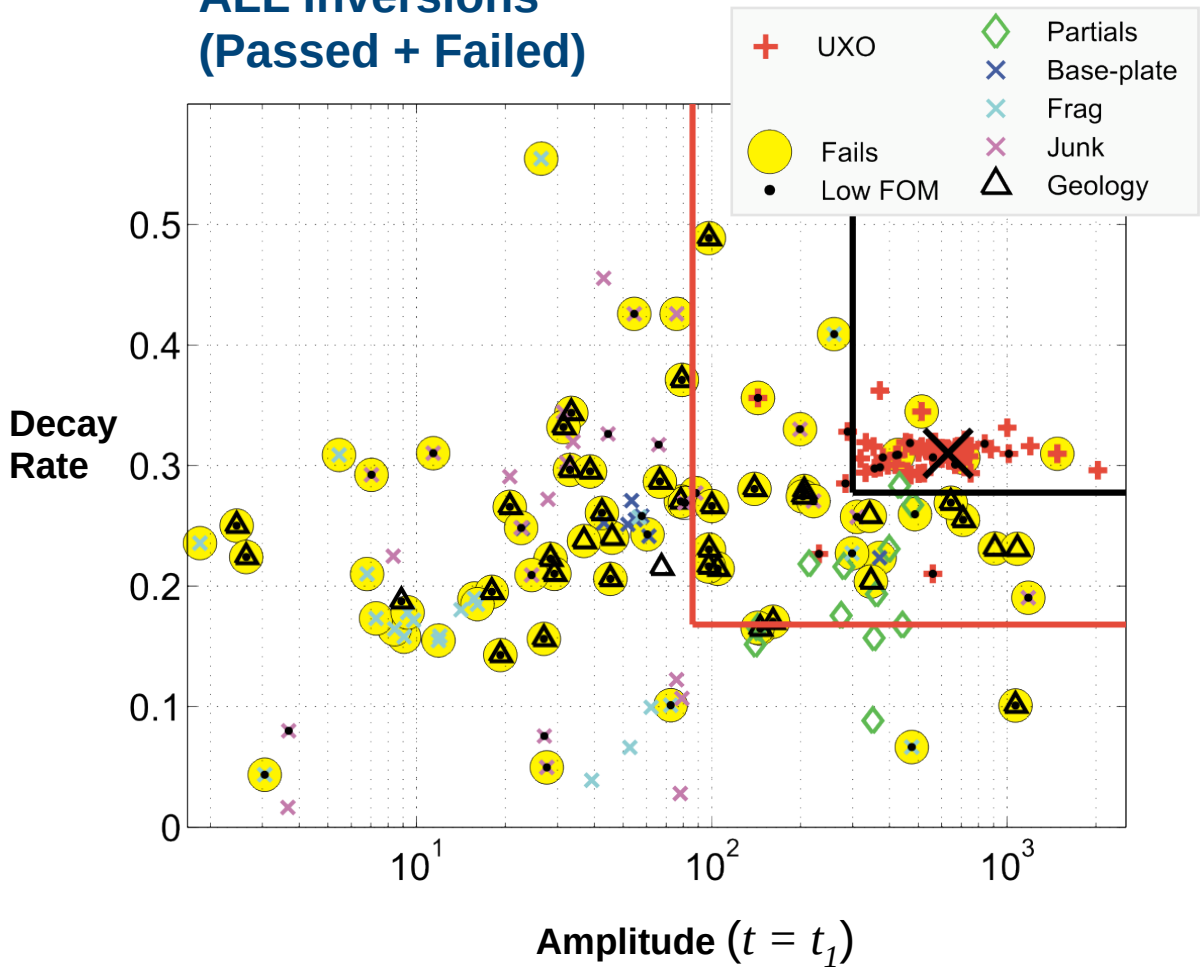
# Technical Approach

Task 3: **Characterizing data quality using a Figure of Merit (FOM)**

One possible strategy for dig list:

1. Identify region with cluster of UXO with high FOM
2. Define buffer zone around UXO cluster in which there is a lower FOM
3. Leave rest in the ground if we're confident enough

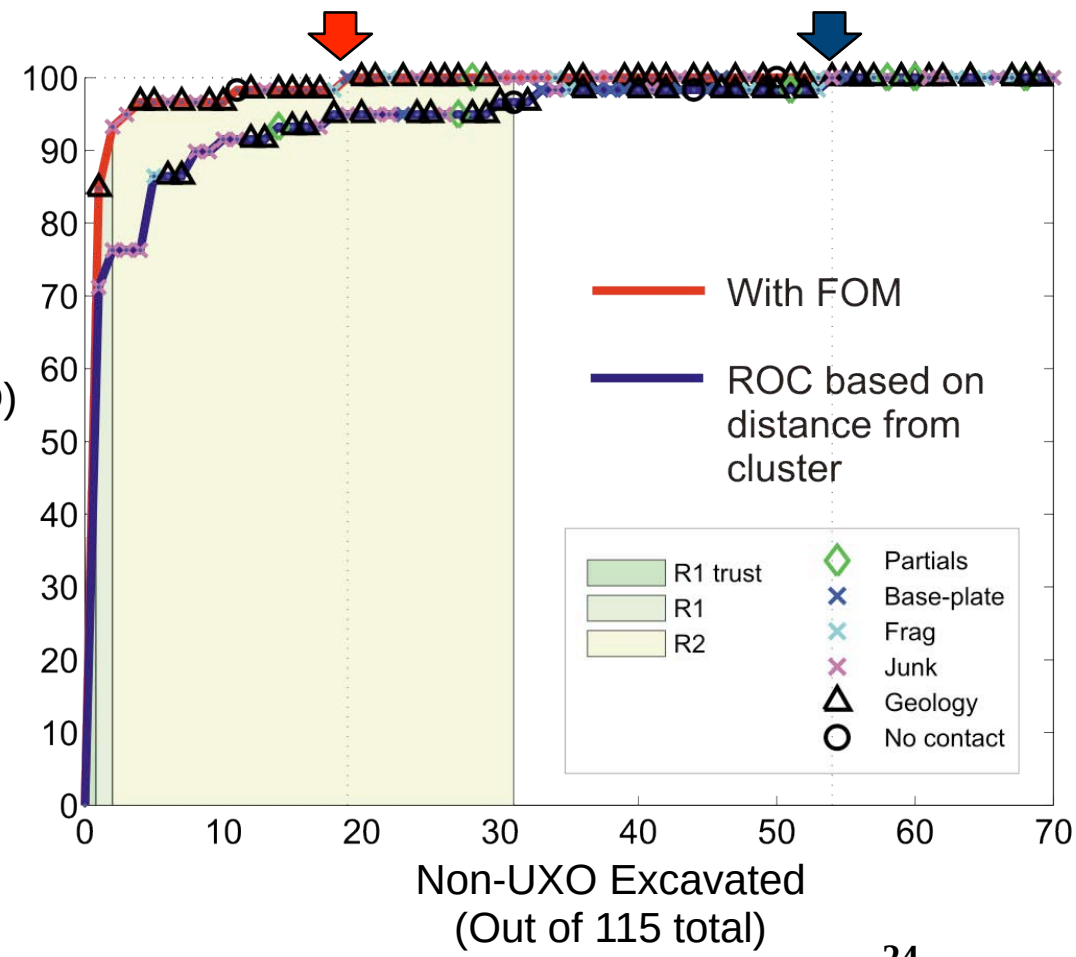
**ALL Inversions (Passed + Failed)**



# Technical Approach

Task 3: **Characterizing data quality using a Figure of Merit (FOM)**

- Including a data quality measure when forming a target list may reduce the number of excavated scrap




- **With FOM:**
  - ***19 Non-UXO Excavated***
- **Using distance from cluster**
  - ***54 Non-UXO Excavated***

# Year 1 Project Plan

- Establish Applicability of Dipole models vs. Charge Models $81K
- Optimizing the dipole model parameterization $81K
- Characterizing data quality using a FOM $81K

TOTAL $243K

# Overall Project Plan

| | Year One | Year Two |
|---|---|---|
| **Objective 1: Establish Applicability of Dipole Model vs. Charge Models** | | |
| Analyze the variance of recovered dipole and charge model parameters based on simulated and test stand data | | |
| Fit noise-free, SEA generated synthetic data with dipole models to determine the extent to which non-dipolar components bias the dipole parameters. | | |
| For cases where the dipole parameter produces large class cluster variances, invert for the SMC model and compare the class cluster variance to the dipole model. | | |
| **Objective 2: Optimizing the dipole model parameterization** | | |
| Examine the data quality required to constrain the two-transverse polarizations for UXO targets, and three unique polarizations for non-axial symmetric targets | | |
| Assess the discrimination abilities of different time and frequency domain parameterizations of the polarization tensor | | |
| Develop strategies for determining the number of independent polarizations | | |
| Assess effectiveness of including parameter variance and misfit in UXO discrimination algorithms | | |
| **Objective 3: Characterizing data quality using a Figure of Merit** | | |
| Define the Figure of Merit using Monte Carlo simulations | | |
| Apply Figure of Merit to Field Data | | |

# Project Funding

| | SERDP |
|---|---|
| | $K |
| Year 1 | 243 |
| Year 2 | 247 |
| Total | 490 |

# Deliverables

- An understanding of the conditions when surface charge models are superior to point dipole models (and vice versa).
- A greater understanding of how data quality affects our ability to recover model parameters
- The development of metrics to quantify data quality
- Peer reviewed articles in journals such as *IEEE transactions on Geoscience and Remote Sensing* and *Geophysics*
- A post doctoral fellow will be funded from this project
- All algorithms will be coded in Matlab, and implemented in UXOLab if the techniques are successful

# Backup Slides

# Reviewer Comments

*Reviewer 2*: "… given other modeling and verification efforts that have been conducted, it is not expected that the proposed effort will add significant values to the existing state of the art or improvement in detection performance."
*Reviewer 3*: "… it is not clear what is innovative in this proposal."

*Response*: The current state of the art in processing electromagnetic data for UXO detection is estimating dipole parameters from sensor data. This proposal addresses some of the difficulties associated with using dipole models:

- We want to determine which scenarios are dipole models appropriate for modeling UXO, and in which scenarios there is an improvement when switching to a more complex charge-type model. This question has yet to have been addressed.
- When applying dipole models there are instances where the data are not of high enough quality to constrain the parameters. The accuracy with which parameters are recovered is due to the complexity of the forward model and the quality of the data from which we hope to estimate those parameters. Until the relationship between data quality, model complexity and dipole parameter accuracy can be addressed in a quantitative way, we will have limited confidence in the parameters we estimate.

# Reviewer Comments

*Reviewer 1*: "Object classification using a model with a larger number of degrees of freedom (number of parameters), such as the magnetic surface charge model, capable of modeling the near fields of large UXO, is a fairly difficult task when some combinations of the parameters are poorly constrained, and may take a while to find an adequate method."

*Response*: In SERDP SEED 1446, we recognized the difficulty of constraining the potentially large number of parameters in the magnetic surface charge model. Our approach was to develop a regularized solution for the ill-posed inverse problem. In this project we plan to use the same solution. However, we are in contact with Dr. Fridon Shubitidze who, in SERDP MM-1572 is developing different approaches to obtaining the surface magnetic charge problem. Should a new method for solving the inverse problem be developed in SERDP MM-1572, we will adopt that method.

# Transition Plan

- **Technical publications and presentations:**
  - Results will be reported in appropriate peer-reviewed journals and conference publications

- **Industry Usage:**
  - All codes will be implemented in the UXOLab software environment

# Relationship to Other Projects

| Project # | Title | Project Description | Unique Attributes |
|---|---|---|---|
| **ESTCP 0504**<br>FY 2005 to present<br><br>PI: Billings | **Practical Discrimination Strategies for Application to Live Sites** | The objective of this project is test and evaluate previously developed dipole based inversion procedures and statistical classification algorithms that use the resulting feature vectors. | • Test and evaluation of previously developed techniques.<br><br>• Uses dipole model |
| **SERDP 1573**<br>FY07 new-start<br><br>PI: Pasion | **Simultaneous Inversion of UXO Parameters and Background Response** | This research concerns the process of extracting physically realistic models of buried unexploded ordnance from magnetic, TEM and FEM data. methodologies for modeling and simultaneous inversion of objects and background host material will be researched. Simultaneous inversion will lead to better accuracy in the recovered target parameters. | • Development of new techniques to simultaneously invert for the parameters of a buried object AND the parameters of the background.<br><br>• Uses dipole model |
| **SERDP 1572**<br>FY07 new-start<br><br>PI: Shubitidze | **Complex Approach to UXO Discrimination: Combining Advanced EMI Forward and Statistical Signal Processing** | Extend physically complete forward models, such as the normalized surface magnetic charge model (NSMC) to treat complex datasets in the presence of heterogeneous background noise. Develop robust inversion algorithms using novel methods of regularization based on Mixed Theory. | • Solves the inversion problem using a different paradigm to the other projects (mixed theory).<br><br>• Concentrates on the use of non-dipolar models |
| **SERDP MM-04-019**<br>Proposed<br><br>PI: Pasion | **Selecting Optimal Models for Inverting TEM Data** | The goal of this research is to delineate the circumstances for which a particular type of modeling should be chosen, and to generate methodologies and software that would allow the user to more efficiently extract meaningful parameters from their data and thus improve discrimination. | • Concentrates on model-selection (number of objects, dipole parameterization etc).<br><br>• Uses dipole model |
| **SERDP MM-01-005**<br>Proposed<br><br>PI: Billings | **Robust Statistics and Regularization for Feature Extraction and UXO Discrimination** | This research represents an attempt to provide more statistically rigorous solutions to the inversion problems that occur as integral parts of any UXO discrimination scheme. | • Concentrates on statistics including non-Gaussian and robust, regularization methods, model parameter uncertainties.<br><br>• Uses dipole model but could be adapted to other models |