Project # SERDP-MR-1572

Camp Butner UXO Data Inversion and Classification Using Advanced EMI Models

Fridon Shubitidze, Sky Research/Dartmouth College

Co-Authors:

Irma Shamatava, Sky Research, Inc

Alex Bijamov, Dartmouth College

Benjamin Barrowes, ERDC-CRREL

Kevin O'Neill ERDC-CRREL

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14. ABSTRACT

Advanced (non-simple-dipole) EMI models? inversion and classification performance is presented for the ESTCP Live-site UXO Discrimination Study at former Camp Butner, NC. The advanced models combine: (1) the joint diagonalization (JD) algorithm for estimating number of potential anomalies from the measured data without inversion, (2) the orthonormalized volume magnetic source (ONVMS) for representing targets? EMI responses and extracting targets? intrinsic parameters feature vector, and (3) the Gaussian Mixture algorithm and probability neural network, that utilizes the extracted discrimination features for classifying buried objects as targets of interest or not. Namely, the studies were conducted for the next generation sensor data: Time-domain Electromagnetic Multi-sensor Towed Array Detection System (TEMTADS) and Metal Mapper (MM) sensors? cued data sets collected at the Camp Bunter, live UXO site. These sensors provide the measured multi-static response (MSR) data matrix. Eigenvalues versus time, which are determined using the JD from the MSR data matrix provide information about the number of targets contributing to the signal and their initial classification features. Once the number of targets is known, then data are inverted and intrinsic parameters, such as the total ONVMS that is a function of target?s geometry and material composition, are determined for each potential target. These intrinsic parameters are grouped using the unsupervised Gaussian mixture approach. For each group an anomaly is identified and ground truth is requested. Once the requested ground truth data are obtained, then each of the groups is classified. In this presentation, the advanced EMI methods? data inversion, processing and discrimination scheme will be reviewed, and the classification results scored by the Institute for Defense Analyses (IDA) will be presented for both the TEMTADS and MM sensors Camp Butner, NC cued data sets.

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CAMP BUTNER UXO DATA INVERSION AND CLASSIFICATION USING ADVANCED EMI MODELS

PROFESSOR FRIDON SHUBITIDZE
Dartmouth College
Thayer School of Engineering
Cummings Hall 800
Hanover, NH 03755
(603) 646-3671
Fridon.Shubitidze@Dartmouth.edu

CO-PERFORMERS: Irma Shamatava (Sky Research); Alex Bijamov (Dartmouth College); Benjamin Barrowes (U.S. Army Corp of Engineers, CRREL)

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Outline

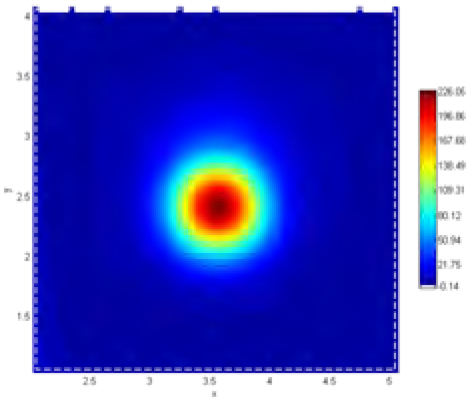
- Advanced EMI Models
  - Normalized Surface Magnetic Source (NSMS) Model
  - Orthonormalized Volume Magnetic Source (ONVMS) Model
- EMI Data Pre-processing and Inversion
  - Joint Diagonalization
  - Direct Search technique for Multi Targets
- Classification
  - Clustering
  - Library Matching
  - Results (IDA Score)
- Summary

UXO classification

The entire UXO classification process can be divided into three parts:

1. Data Collection

Sensor data: d



2. Data Inversion

Forward Operator

$$d = F\,[p]$$

$$p = F^{-1}\,[d\,]$$

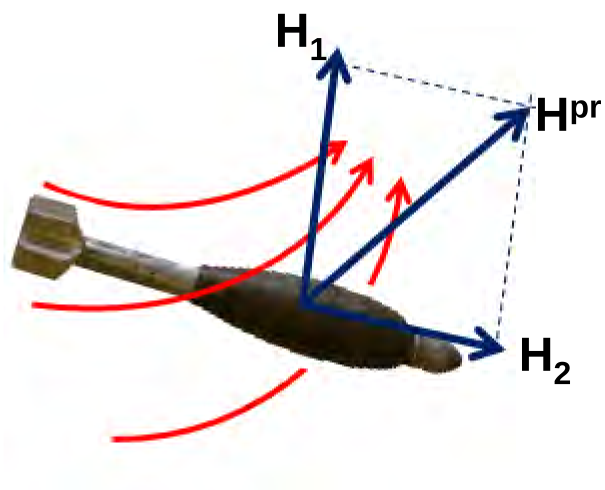
Inverse Operator

3. Decision

Model Parameters: p

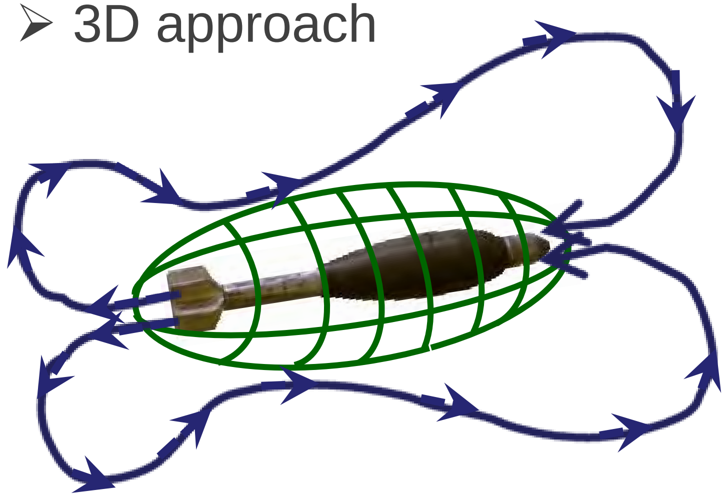
Forward Models: NSMS

Normalized Surface Magnetic Source Model



Primary field induces eddy currents inside metallic objects

- Extended dipole model
- 3D approach



- NSMS model accounts for target's heterogeneity.
- Total NSMS is an intrinsic target parameter.

NSMS Applied to:

1. APG test site (214 anomalies)

APG Targets of interest (TOI)

APG Discrimination results were excellent:

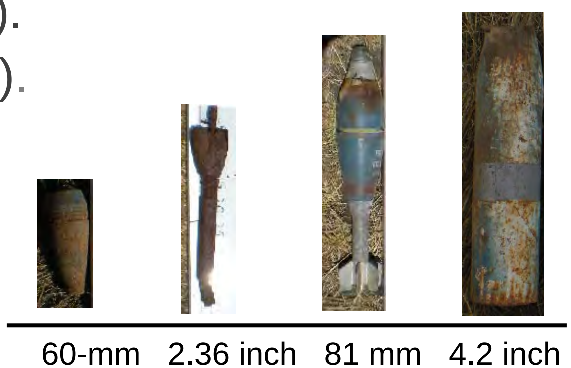
- All UXO items were correctly identified as TOI
- All TOI items were correctly identified by type/caliber
- There was a 5 % false positive rate

2. SLO Live UXO site

SLO Discrimination results:

- One false negative for Metal Mapper (2492 anomalies).
- Seven false negatives for TEMTADS (1464 anomalies).

SLO Targets of interest (TOI)

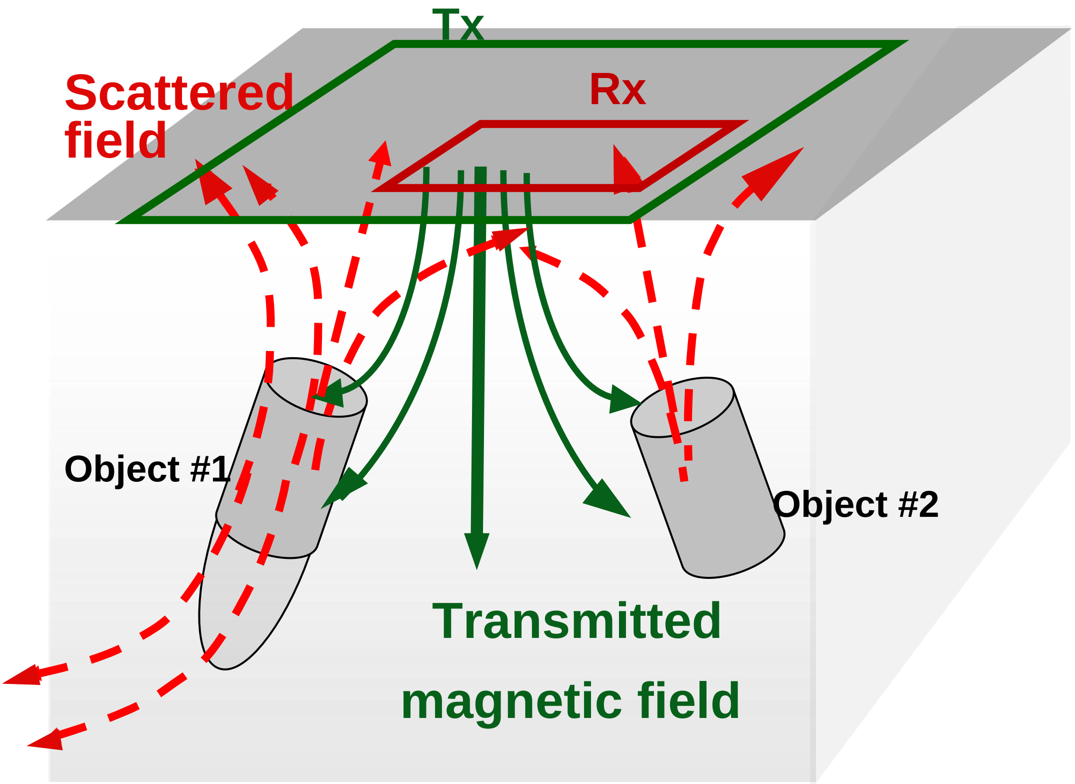


The main challenges there were:

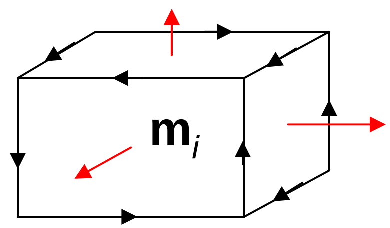
- Multiple overlapping targets
- low signal to noise ratio

Forward Models: ONMVS

Ortho-Normalized Volume Magnetic Source (ONVMS) Model



The ONMVS model divides the computational space into cells**.**



The key elements of the ONMVS are:

- The scattered EMI field is approximated using an orthonormalized function expansion:

$$\mathbf{H}(\mathbf{r}) = \sum_{i=1}^{N_v} \overline{\overline{\psi}}_i(\mathbf{r}) \cdot \boldsymbol{b}_i,$$

Where

$$\int \left(\overline{\overline{\psi}}_i^T \cdot \overline{\overline{\psi}}_k \right) dv = \begin{cases} \overline{\overline{0}}, & i \neq k \\ \overline{\overline{F}}_i, & m = k \end{cases}$$

ONVMS continued

- These orthogonal functions are constructed using the scattered magnetic field's Green function via Gram-Schmidt ortho-normalization process:

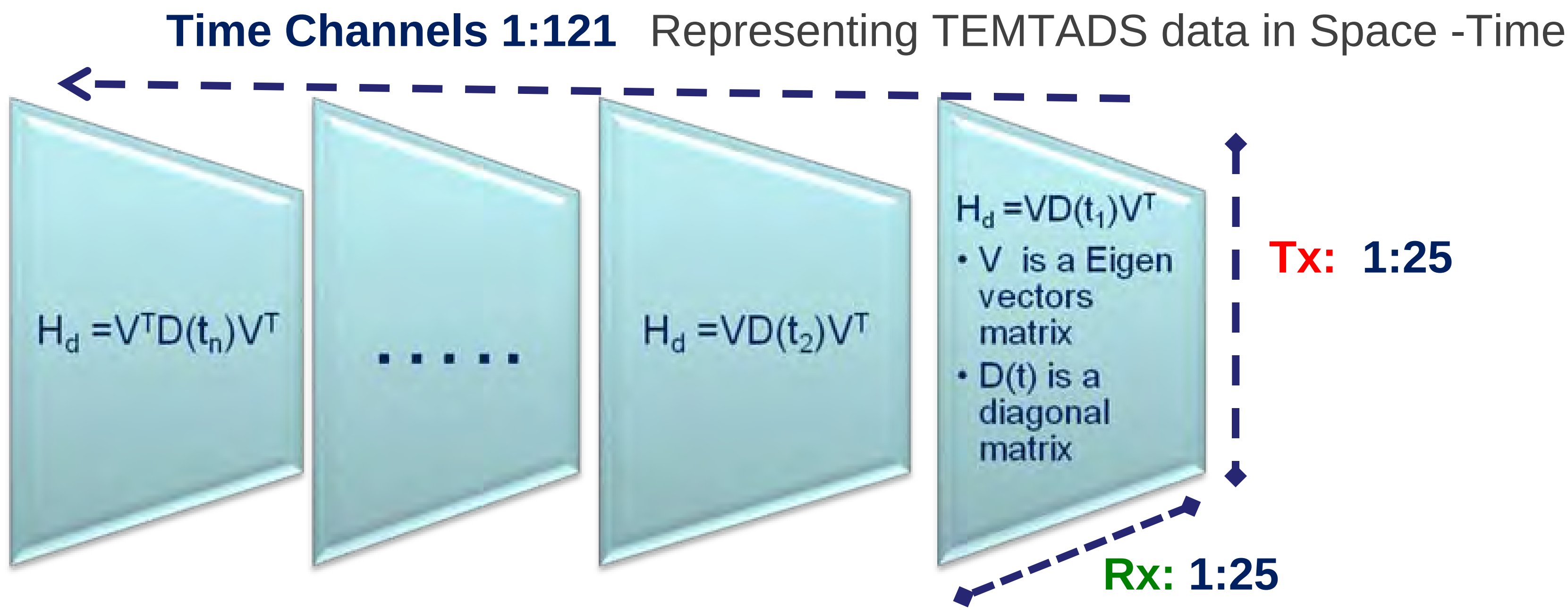
$$\overline{\overline{\psi}}_i(\mathbf{r}) = \overline{\overline{G}}_i(\mathbf{r}) - \sum_{k=1}^{i-1} \overline{\overline{\psi}}_k(\mathbf{r}) \cdot \overline{\overline{A}}_{ik}; \quad \text{where for } i < k,\ \overline{\overline{A}}_{ik} = 0,$$

- The modeled Magnetic field is fitted to measured data, and
- The targets features are extracted

The ONVMS:

- Avoids an ill-conditioned matrix;
- Separates overlapping targets easily;
- Provides total/effective polarizabilities;
- is applicable for non-uniform sub-volumes.

Joint Diagonalization



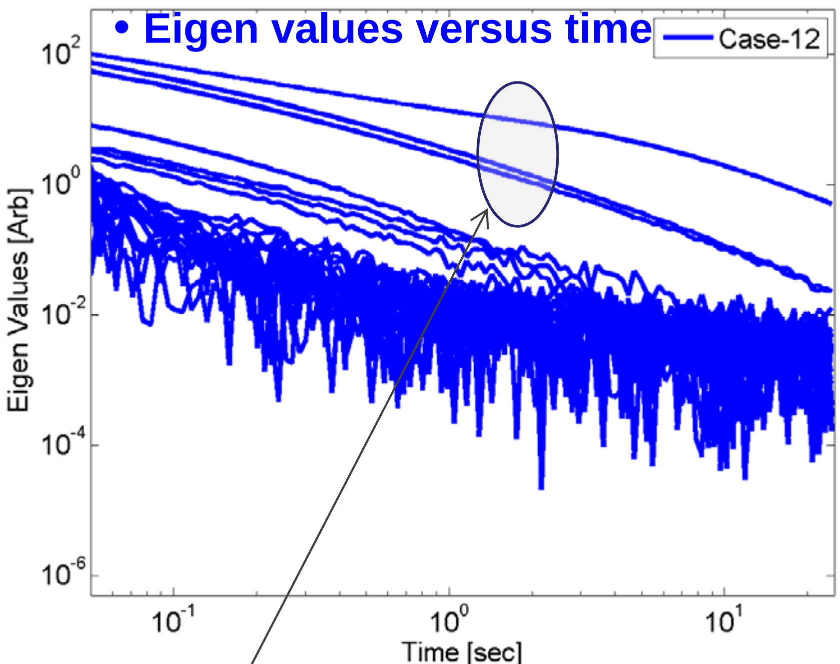
The goal is to:

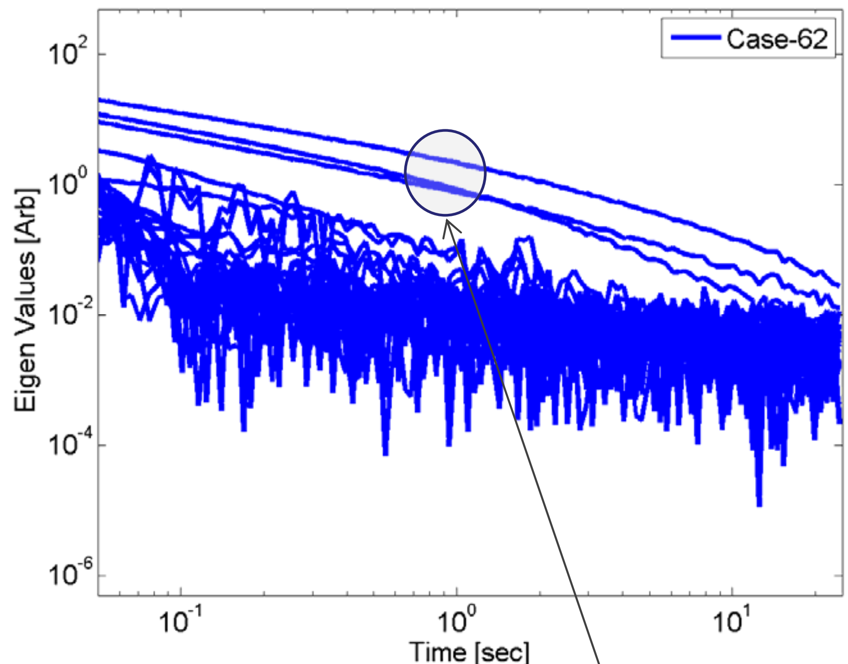
- determine the eigenvalues of H_d tensor for each time channel.
- find an eigenvector V that will be shared by all matrices.

$$D(t_k) = V^T \mathbf{H}_d(t_k)V, \; k=1, 2, ..., n$$

JD applied to CB-TEMTADS data:

eigenvalues for classification



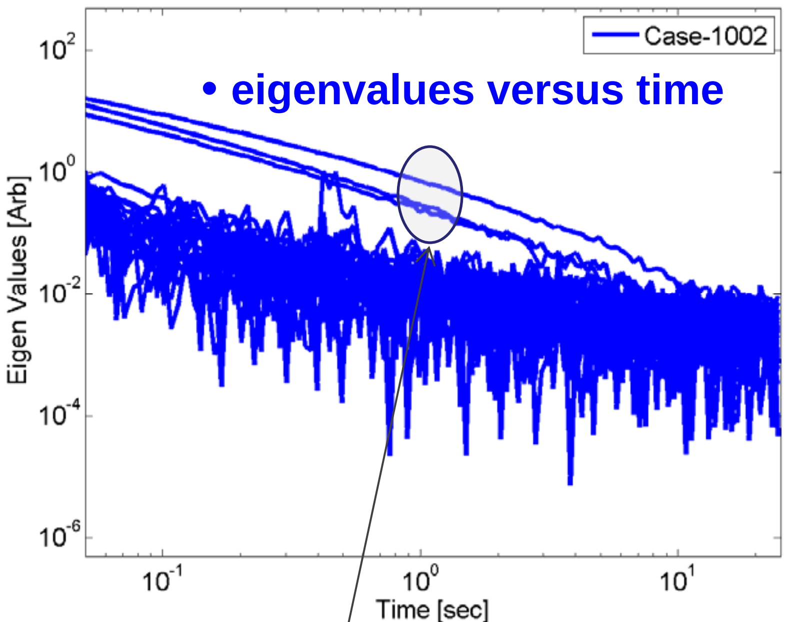


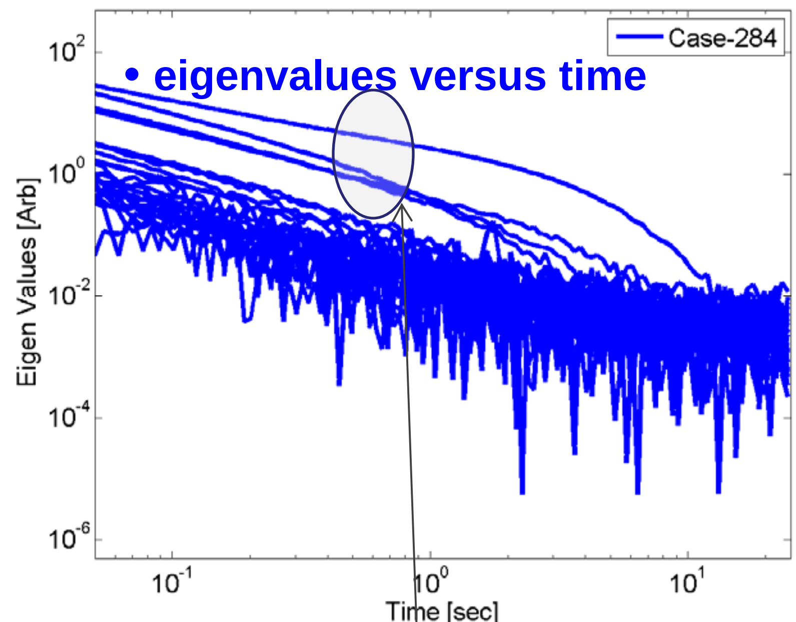
The eigenvalues show targets features:

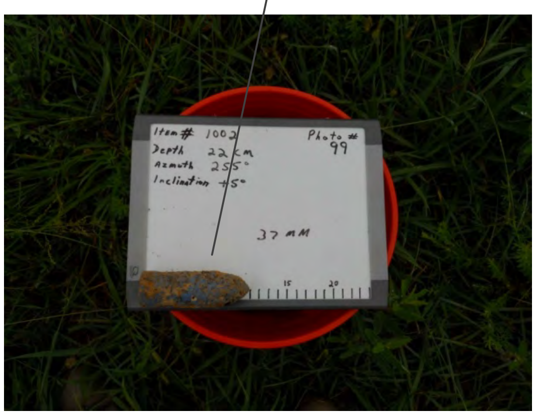
Two targets (105 mm HE and 105 mm HEAT), having same size, but different material properties have different time decaying eigenvalues

JD applied to CB-TEMTADS data:

eigenvalues for classification





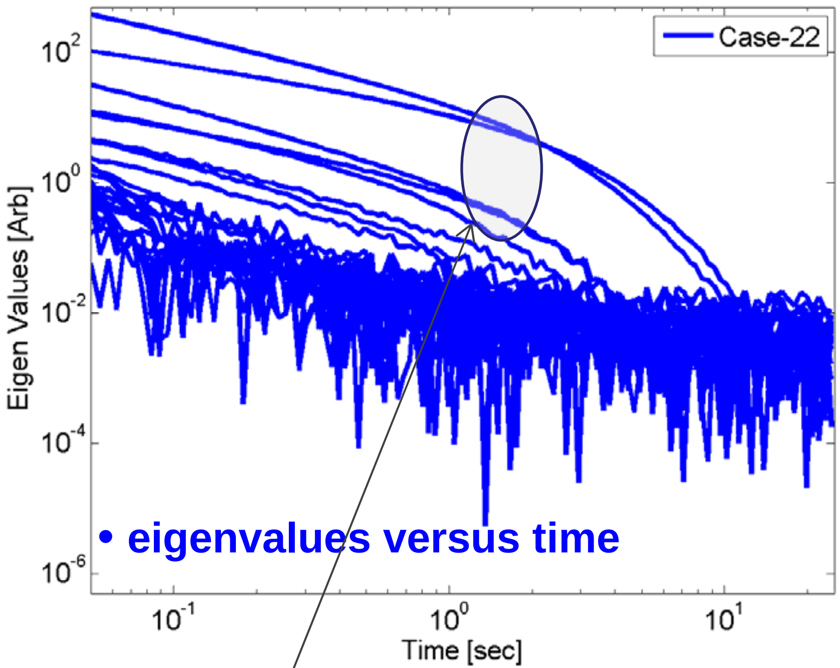


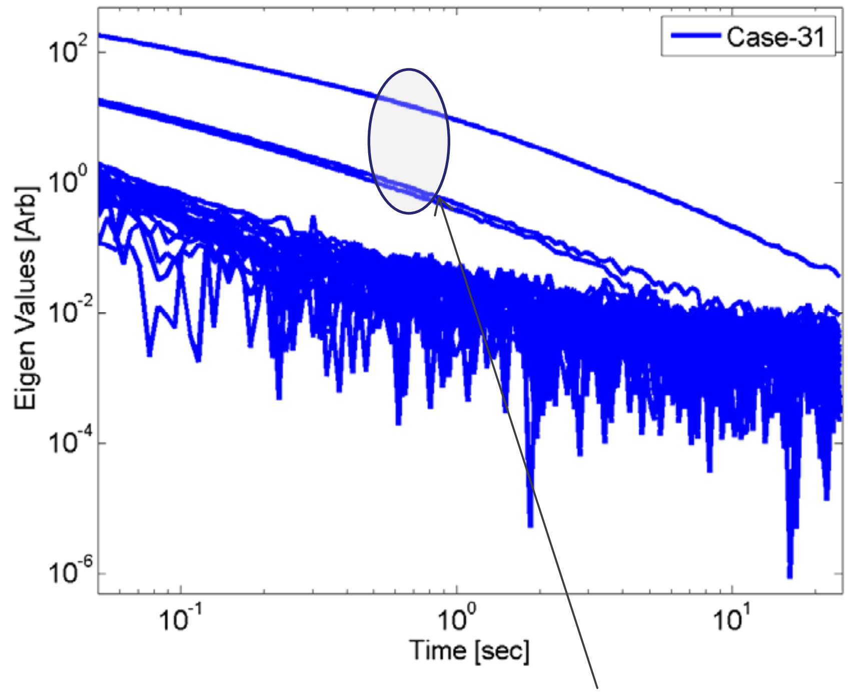
TOIs have slow time decaying eigenvalues

37 mm projectiles with copper bands have distinguishable eigenvalues

JD applied to CB-TEMTADS data:

eigenvalues for classification



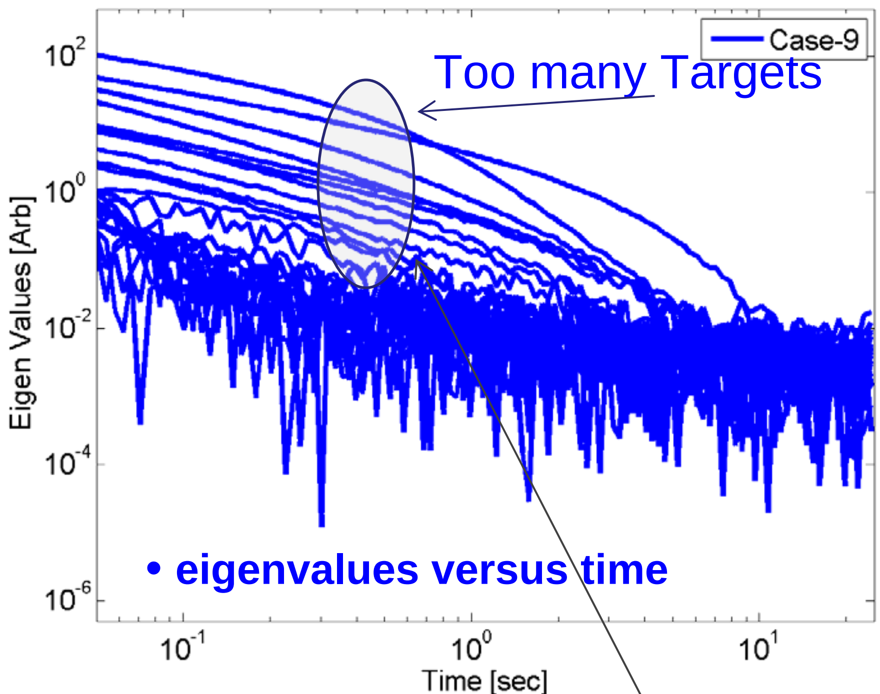


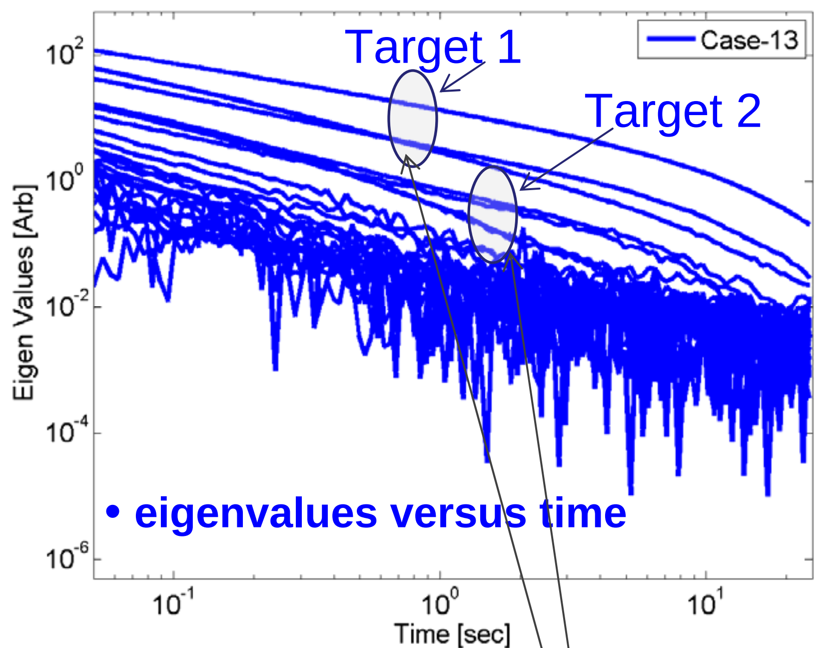
TOIs have slow time decaying eigenvalues

Clutter items have fast time decaying eigenvalues

JD applied to CB-TEMTADS data:

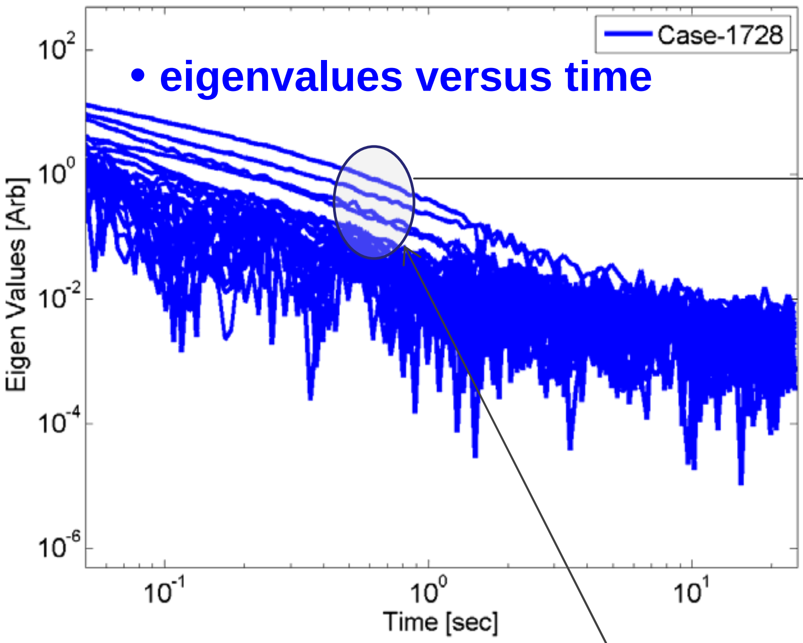
eigenvalues for Multi targets

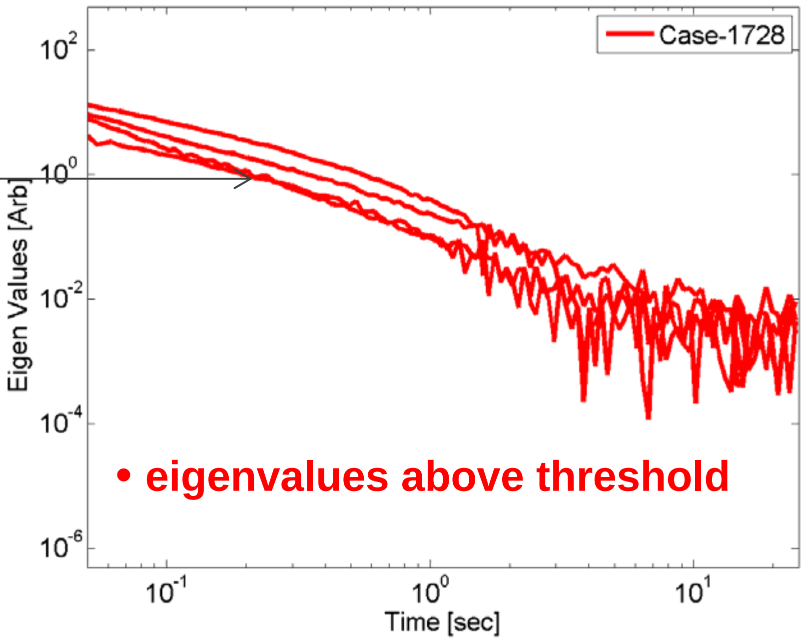




JD applied to CB-TEMTADS data:

Resolving small signal to noise ratio





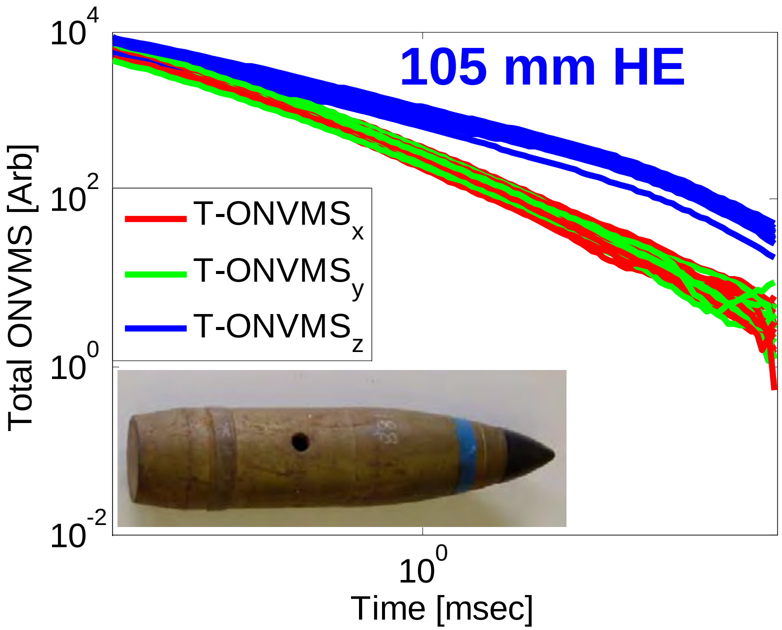
The eigenvalues are small, but decay slowly in time, that means:

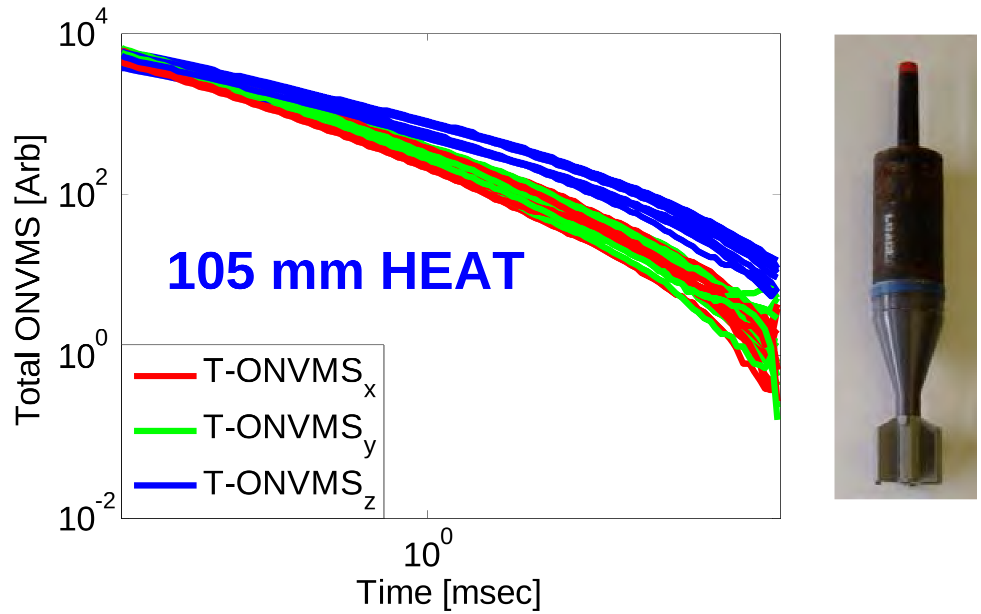
the anomaly is buried deep and it is a potential TOI.

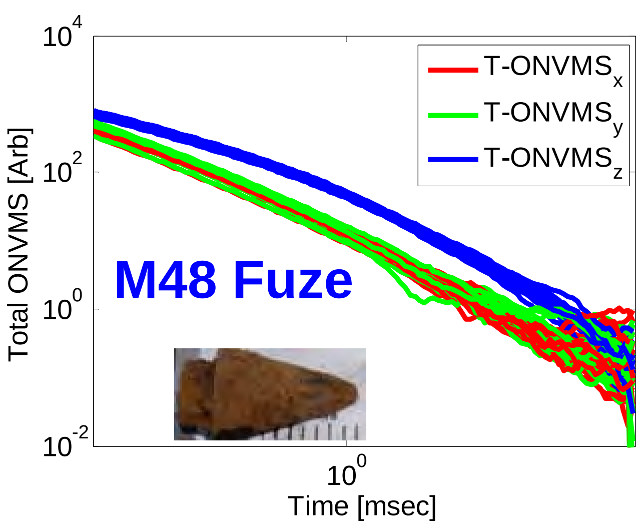
CB-TEMTADS Data Classification Approach:

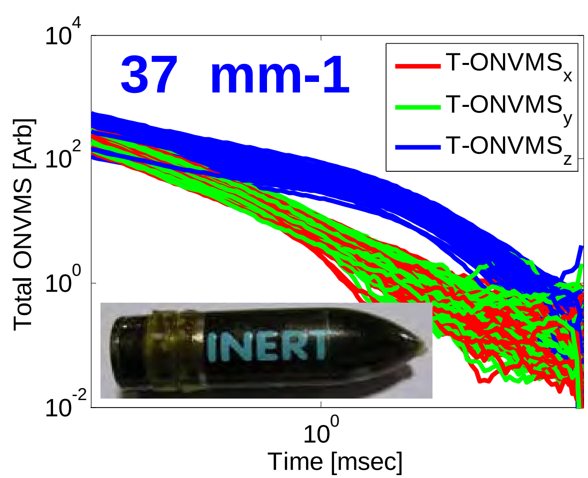
- JD applied to all 2293 CB-TEMTADS data;
- The number of potential targets were estimated using JD;
- The first Dig list was created based on Eigenvalues.
- All data sets were inverted using the ONVMS technique;
- The effective polarazabilities were determined
- 70 Custom training data sets were requested;
- Targets were ranked via Library matching;

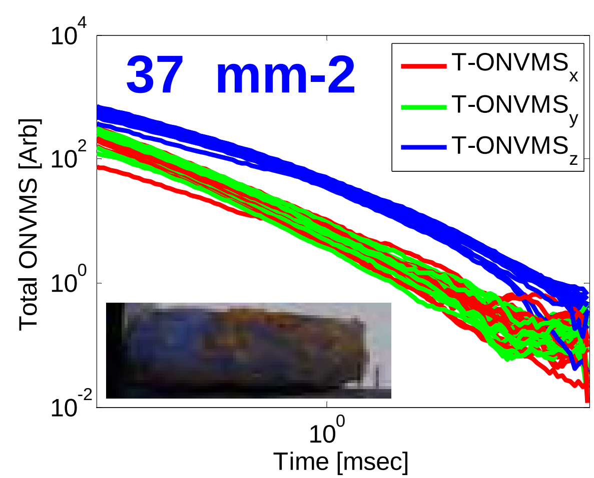
Library Matching applied to CB-TEMTADS data





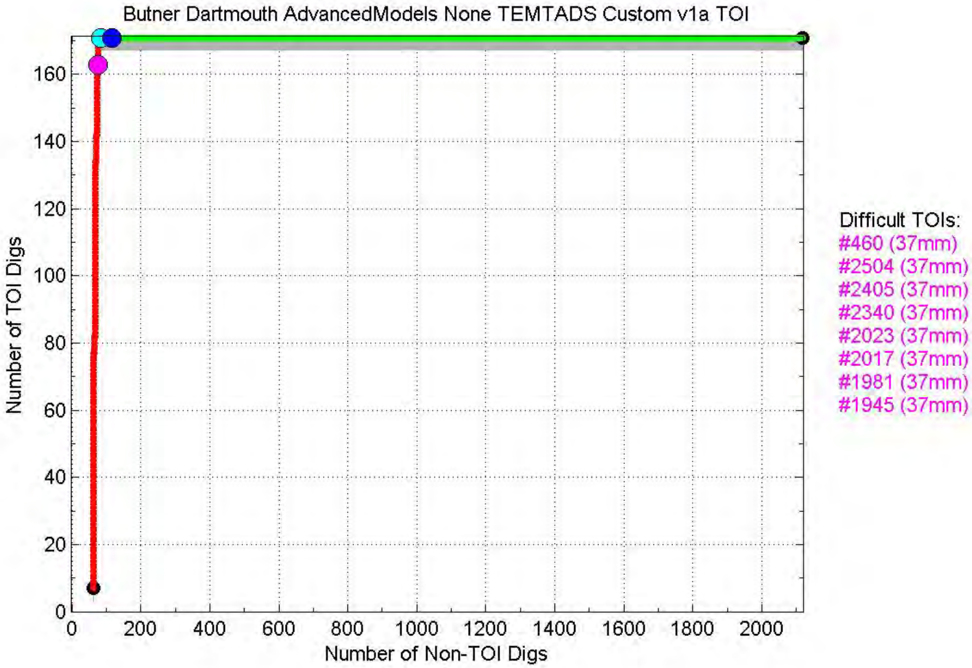


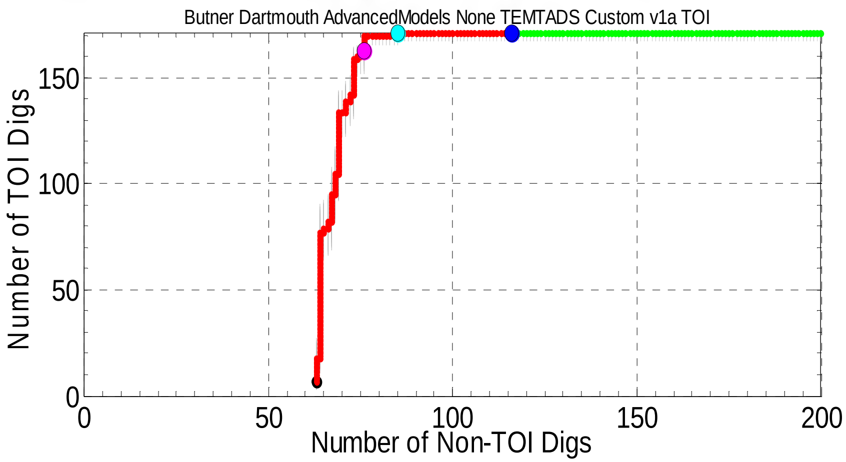




Camp Butner TEMTADS Classification results

Scored Results for the TEMTADS Cued Data Sets:





- All data were inverted and analyzed.
- No False Negatives: all TOI were indentified correctly.
- All 105 mm and 37 mm were identified by caliber/type;

CB-Metal Mapper Data Classification Approach:

- All data sets were inverted as
  - One
  - Two
  - Three

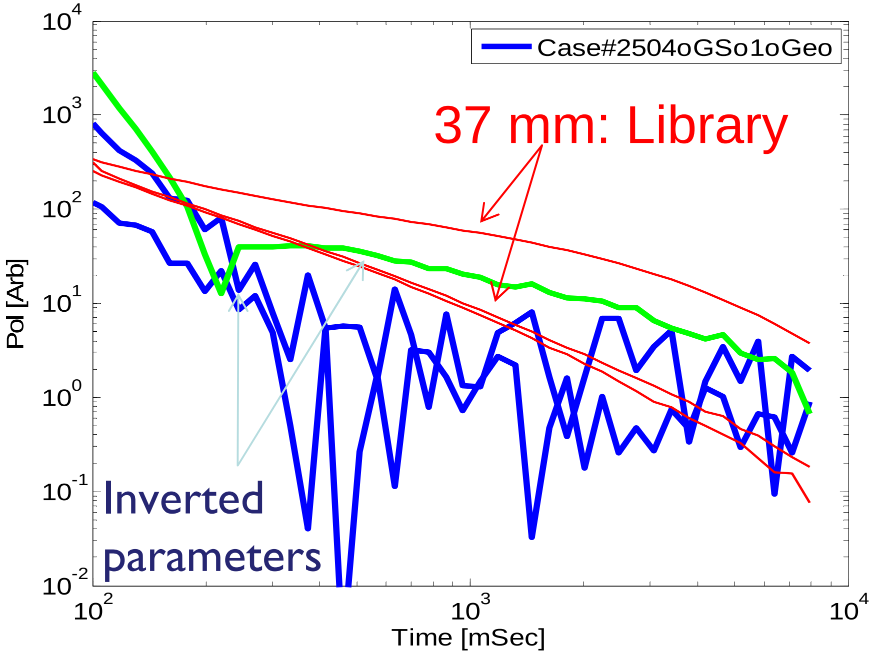
  targets using the ONVMS.

- The effective polarazabilities were determined;

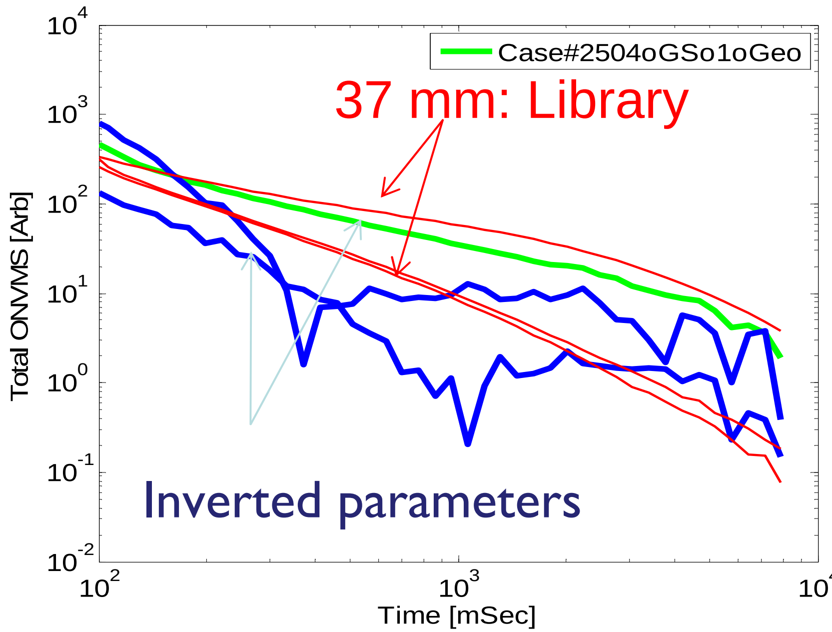
- Targets were clustered using the principal effective polarazabilities ;

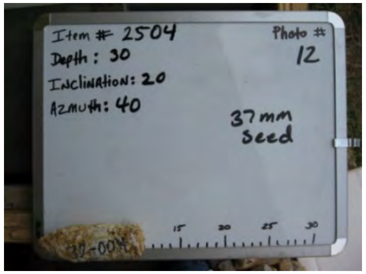
ONVMS applied to CB-Metal Mapper data: Anomaly #2504

Single source inversion



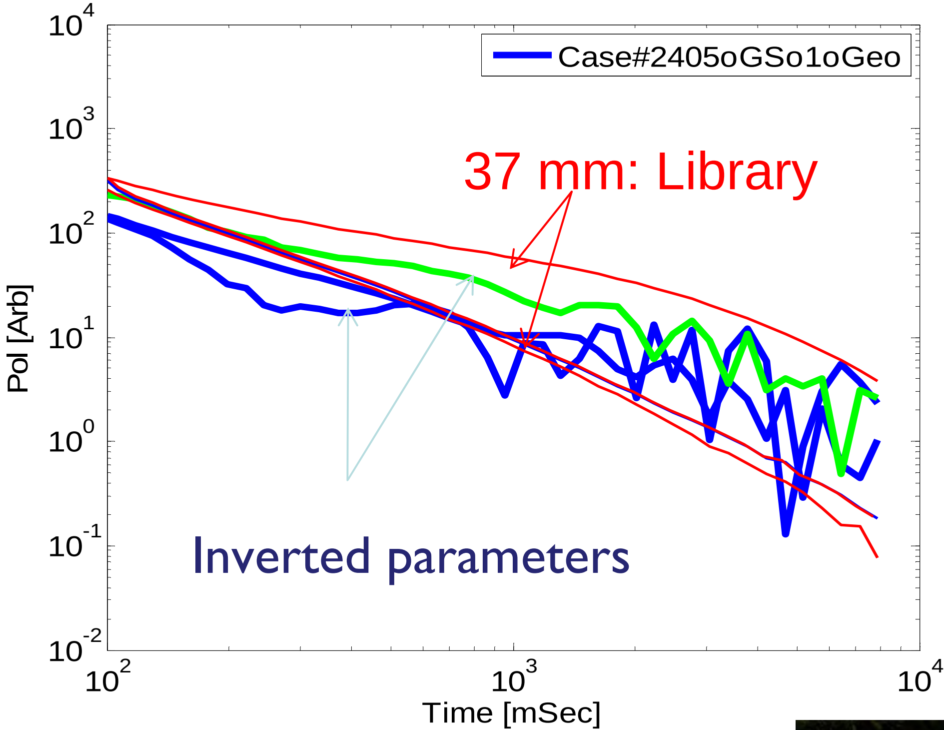
Multi targets inversion



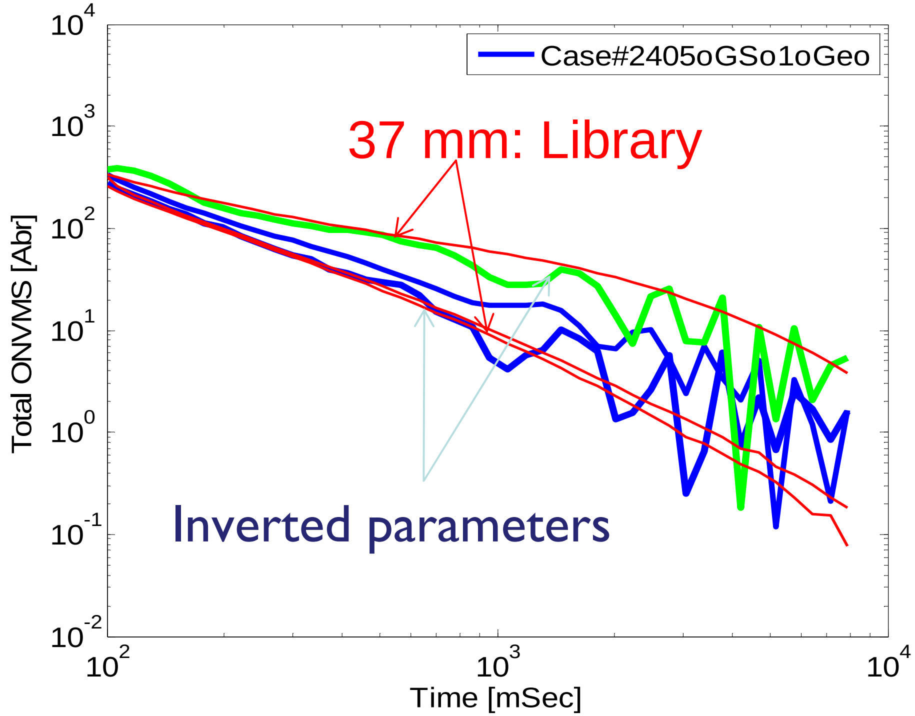


ONVMS applied to CB-Metal Mapper data: Anomaly #2405

Single source inversion

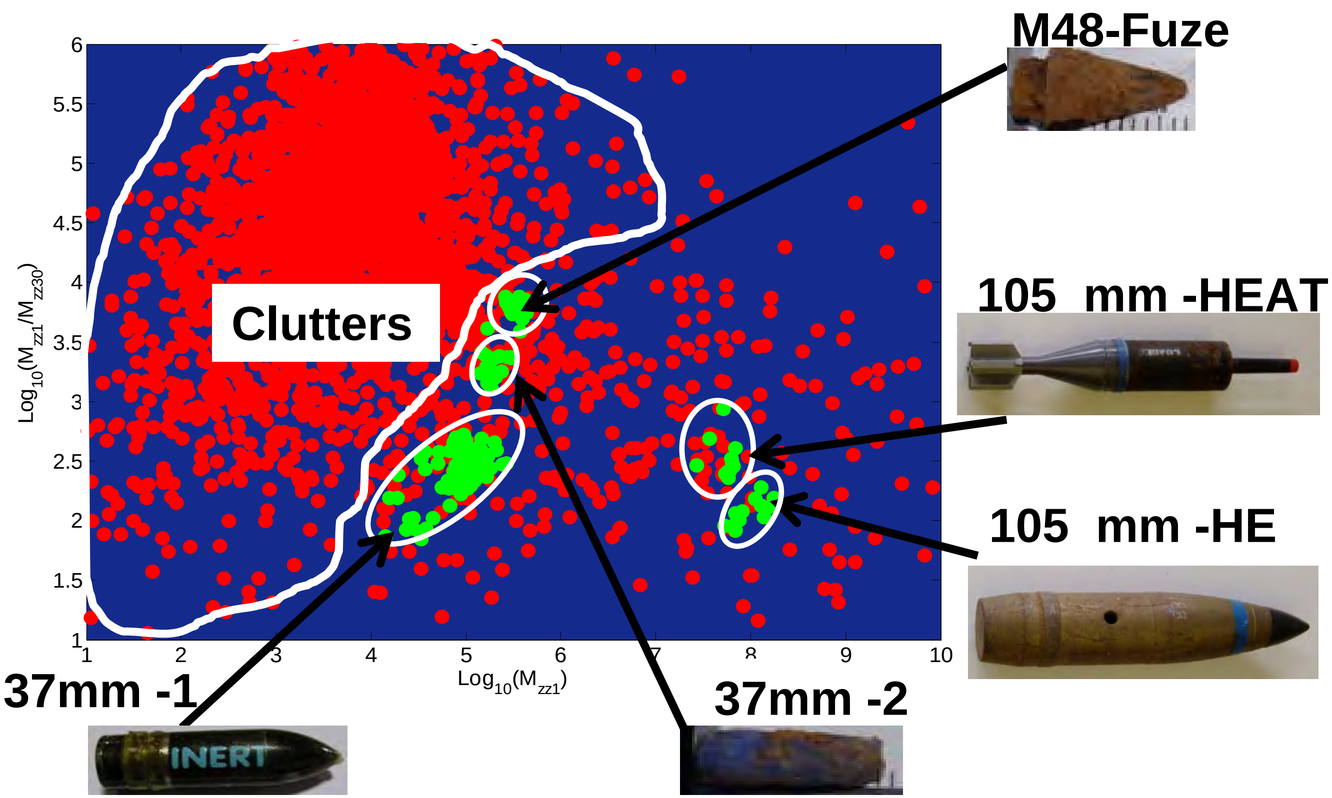


Multi targets inversion



Gaussian mixture model for MM-ONVMS clustering

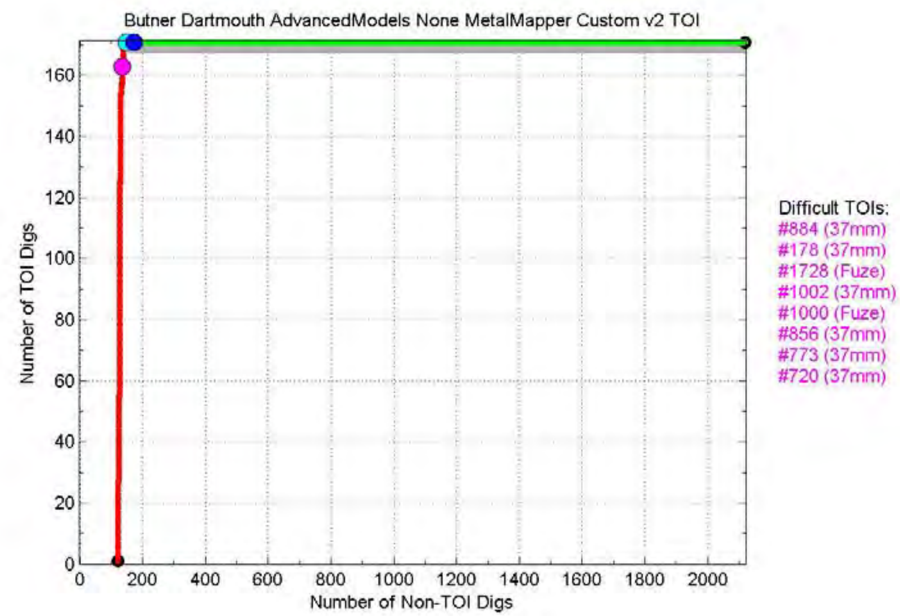
- Uses discrimination features from ONVMS
- Builds the mixture Gaussian distribution for K clusters;
- The expectation-maximization algorithm used to estimate weight, mean and variance for each of the K clusters;

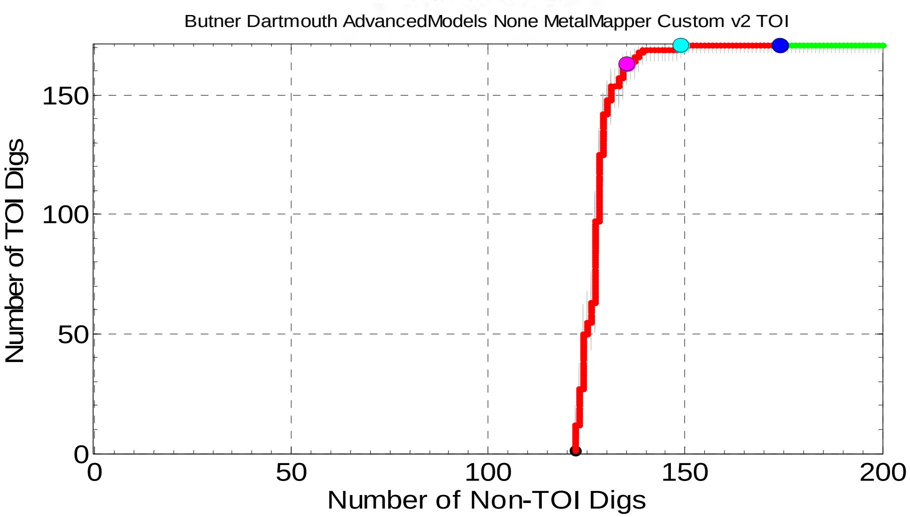


$M_{zz}(t_1)$ and $M_{zz}(t_1)/M_{zz}(t_{30})$ are used as discrimination features.

Camp Butner Metal Mapper Classification results

Scored Results for the Metal Mapper Cued Data Sets:





- ➢ 121 Custom training data sets requested
- ➢ All data were inverted and analyzed.
- ➢ No False Negatives.
- ➢ All TOI-s were identified by caliber/type;

Summary

- Advanced EMI models applied to CB Cued Data sets.
- The Models are robust and noise tolerant.
- They are applicable for single and multi targets.
- Classifications are done using LM, JD and Gaussian mixture clustering.
- Excellent classifications were demonstrated.
- No False Alarms.
- The models are adapted for all advanced EMI sensors.
- The technology will be tested further under the new ESTCP # MR-201101.