ESTCP Project # ESTCP-MR-201101

Camp Beale Live-Site UXO Data Inversion and Classification Using Advanced EMI Models

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14. ABSTRACT
The advanced EMI and statistical classification models are applied to the cued data sets of the Metal Mapper and two next-generation portable sensors: MPV and 2x2 3D TEMTADS. The advanced models combine: (1) the joint diagonalization (JD) algorithm for estimating the number of potential anomalies from the measured data without inversion, (2) the orthonormalized volume magnetic source (ONVMS) model for representing the EMI responses and extracting the intrinsic parameters (feature vector) of the targets, and (3) the Gaussian Mixture algorithm that utilizes the extracted features to classify buried objects as targets of interest (TOI) or not. The inversion and classification schemes of these advanced models consist of the following steps: (i) build the multi-static-response (MSR) data matrix by combining the Tx and Rx data points of the advanced sensors; (ii) apply the JD to the MSR data matrix to determine its eigenvalues; (iii) estimate the data quality and the number of potential targets, based on the eigenvalues; (iv) study the temporal decay of the eigenvalues to identify the signal to noise ratio (SNR); (v) invert all data sets using the ONVMS-Differential Evolution algorithm; (vi) apply the semi-supervised GM clustering algorithm to the inverted total ONVMS to determine the clusters of anomalies; (vii) select anomalies from each cluster to build a custom training list (viii) request the ground truth for the selected targets; (ix) use the obtained ground truth to score the unknown targets using the GM weights for the ONVMS clusters; and (x) submit the final dig-list to the ESTCP office for independent scoring. In this presentation the data inversion processing and discrimination schemes of the advanced EMI models will be reviewed, and the classification results scored by the Institute for Defense Analyses (IDA) will be presented for Camp Beale, CA cued data sets of both MM and portable EMI sensors.

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CAMP BEALE LIVE-SITE UXO DATA INVERSION AND CLASSIFICATION USING ADVANCED EMI MODELS

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The advanced EMI and statistical classification models are applied to the cued data sets of the Metal Mapper and two next-generation portable sensors: MPV and 2x2 3D TEMTADS. The advanced models combine: (1) the joint diagonalization (JD) algorithm for estimating the number of potential anomalies from the measured data without inversion, (2) the ortho-normalized volume magnetic source (ONVMS) model for representing the EMI responses and extracting the intrinsic parameters (feature vector) of the targets, and (3) the Gaussian Mixture algorithm that utilizes the extracted features to classify buried objects as targets of interest (TOI) or not. The inversion and classification schemes of these advanced models consist of the following steps: (i) build the multi-static-response (MSR) data matrix by combining the Tx and Rx data points of the advanced sensors; (ii) apply the JD to the MSR data matrix to determine its eigenvalues; (iii) estimate the data quality and the number of potential targets, based on the eigenvalues; (iv) study the temporal decay of the eigenvalues to identify the signal to noise ratio (SNR); (v) invert all data sets using the ONVMS-Differential Evolution algorithm; (vi) apply the semi-supervised GM clustering algorithm to the inverted total ONVMS to determine the clusters of anomalies; (vii) select anomalies from each cluster to build a custom training list; (viii) request the ground truth for the selected targets; (ix) use the obtained ground truth to score the unknown targets using the GM weights for the ONVMS clusters; and (x) submit the final dig-list to the ESTCP office for independent scoring. In this presentation the data inversion, processing and discrimination schemes of the advanced EMI models will be reviewed, and the classification results scored by the Institute for Defense Analyses (IDA) will be presented for Camp Beale, CA cued data sets of both MM and portable EMI sensors.

Camp Beale TOI

Main TOI

Fuze and Fuze-parts as TOI

Goals:

1. Identify all TOIs.
2. Assess technology.
3. Keep at least 75% non-TIOs in ground

Challenges at CBE

- ❑ Magnetic soil noise.
- ❑ Small S/N ratio.
- ❑ TOI types: There were six types of main TOIs and eight types of native TOIs.
- ❑ There were only a few (1 to 5) fuzes of the same size;
- ❑ Small size (3cm and 5 cm) unexpected native fuzes as TOI.
- ❑ Multi Targets

UXO classification

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

1. Data Acquisition

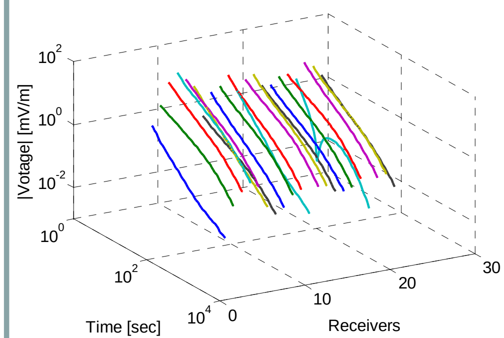
Metal Mapper

MPV

2x2 Array

Hand Held BUD

2. Feature extraction



Forward Operator

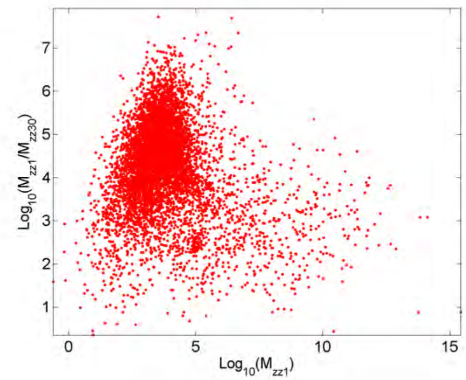
$$d = F\,[p]$$

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

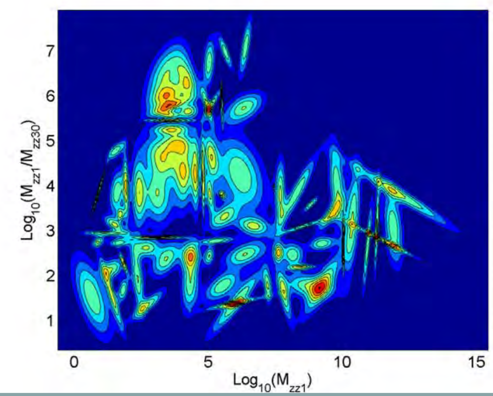
Inverse Operator

3. Decision

Feature selection

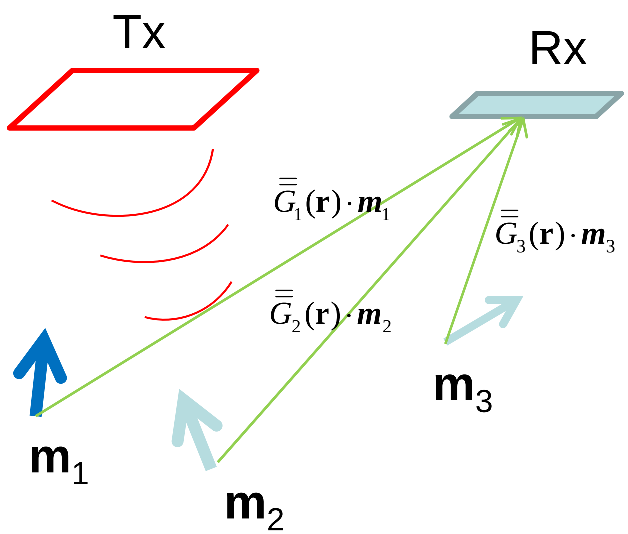


Clustering and Classification



Forward Models

Multi dipole mode



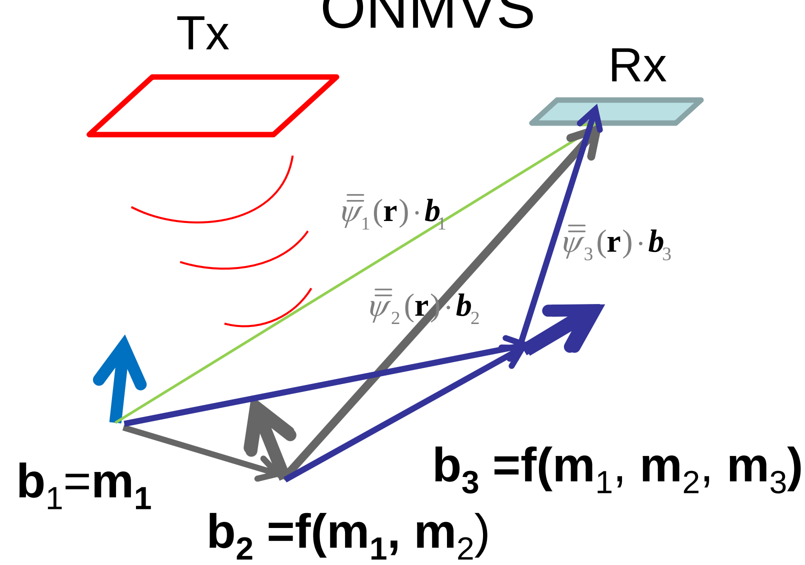
The scattered EMI field is approximated as superposition of magnetic fields from each individual dipole, using the dyadic Green's function:

$$\mathbf{H}(\mathbf{r}) = \sum_{i=1}^{N_v} \overline{\overline{G}}_i(\mathbf{r})\cdot \boldsymbol{m}_i$$

where

$$\overline{\overline{G}}_i(\mathbf{r}) = \frac{1}{4\pi R_i^3}\left(3\vec{R}_i\,\vec{R}_i - \overline{\overline{I}}\right)\;;\quad \vec{R}_i = \mathbf{r}_i\text{-}\mathbf{r}$$

ONMVS



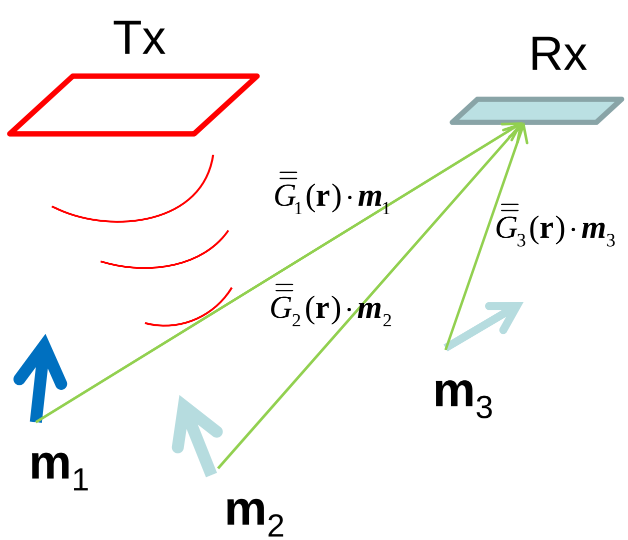
The scattered EMI field is approximated as magnetic field from **groups of interacting dipoles** using an ortho-normalized function expansion:

$$\mathbf{H}(\mathbf{r}) = \sum_{q=1}^{Q} \overline{\overline{\psi}}_q(\mathbf{r})\cdot \boldsymbol{b}_q,$$

where $\overline{\overline{\psi}}_q(\mathbf{r}) = \overline{\overline{G}}_q(\mathbf{r}) - \sum_{k=1}^{q-1} \overline{\overline{\psi}}_k(\mathbf{r})\cdot \overline{\overline{A}}_{qk}\,;$

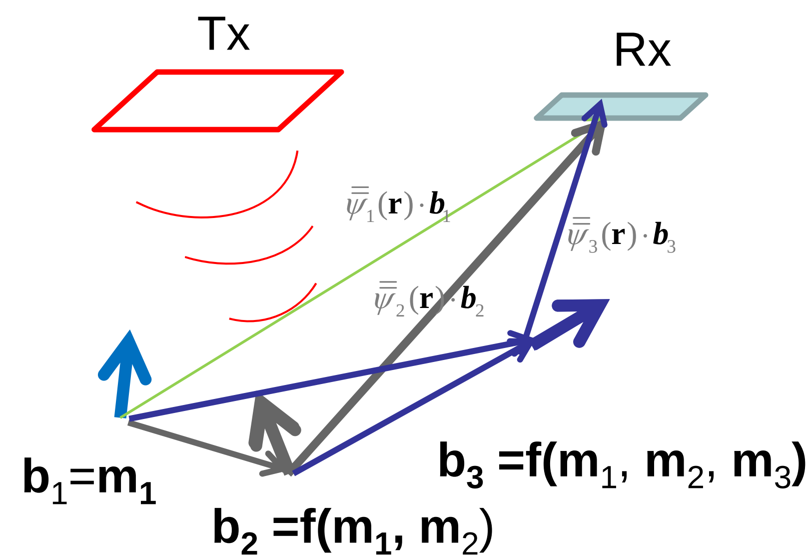
Forward Models

Multi dipole mode



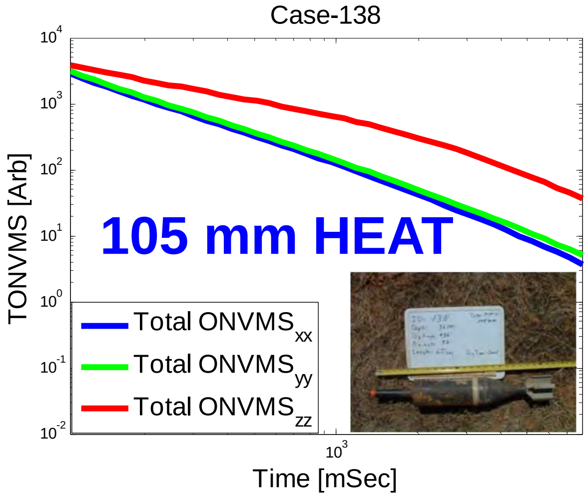
- $\mathbf{m}_i$ are determine from the measured data **by solving** a linear system of equations.
- Uses **individual dipole polarizabilities** for classification

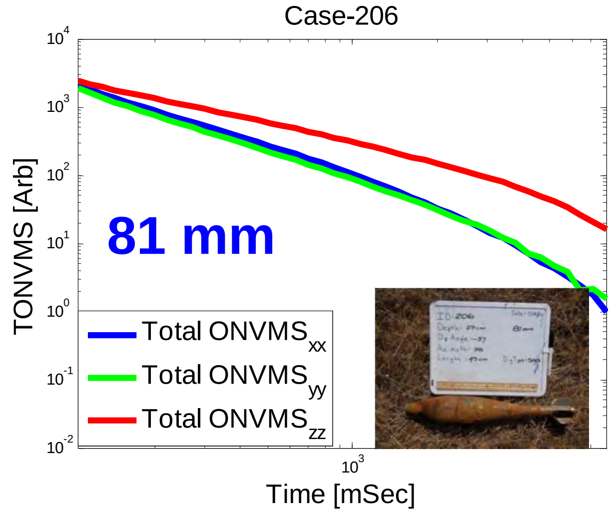
ONMVS

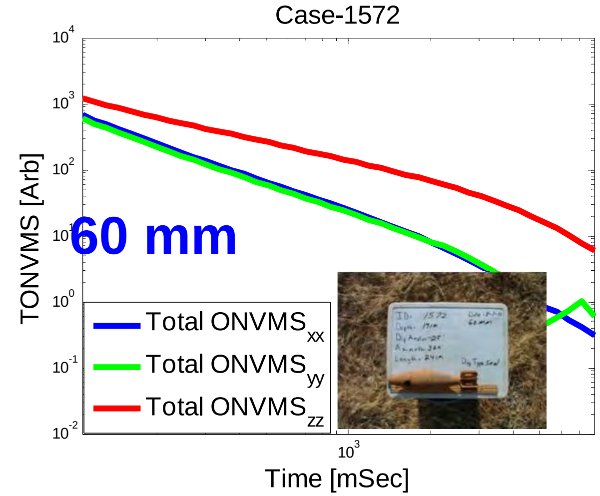


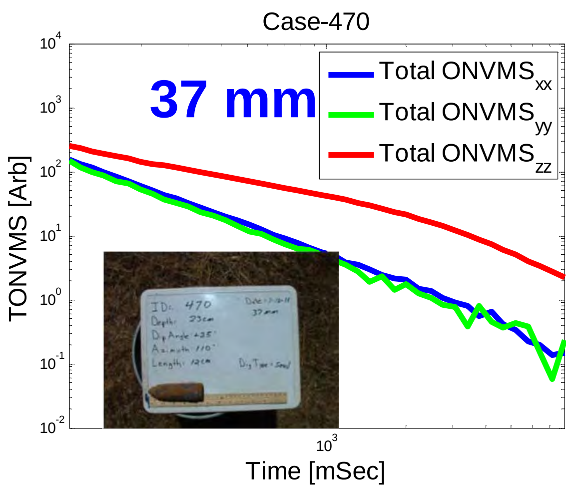
- First it determines b_q from the measured data **without solving** a linear system of equations, then it backs out $\mathbf{m}_i$
- Uses **total ONVMS/effective polarizabilities** for classification

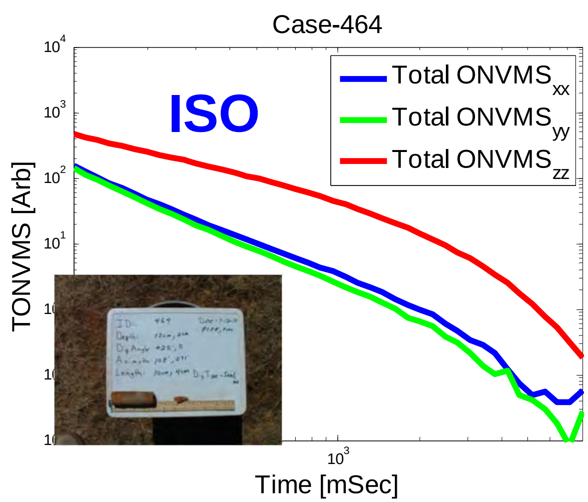
Inverted total ONVMS for different objects at CBE-MM data

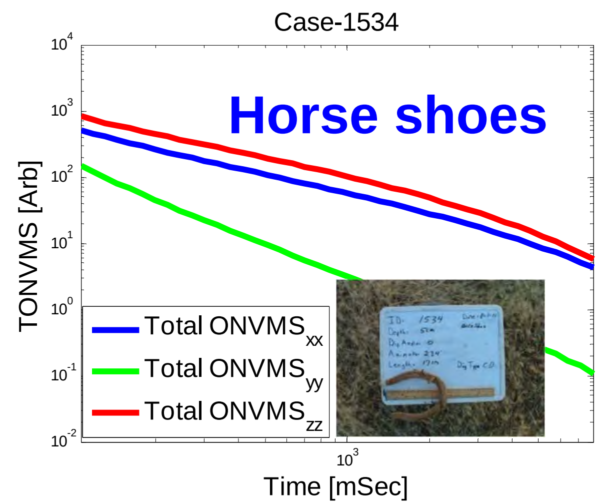








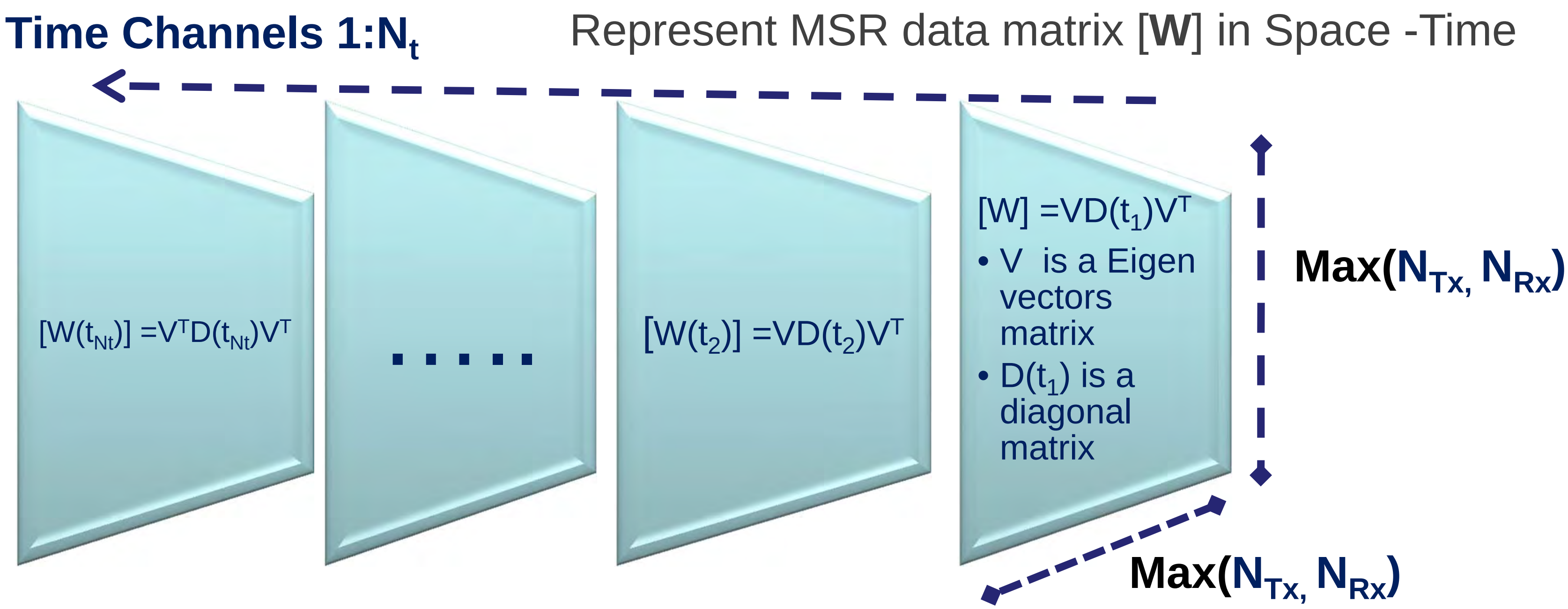




QC using Joint Diagonalization

Build a Multi Static Response (MSR) data matrix [**W**] as:

$$[\mathrm{W}](\mathrm{t_k}) = \left[\mathbf{H}^{T}(\mathrm{t_k})\right]\cdot\left[\mathbf{H}(\mathrm{t_k})\right],\ \mathrm{k}=1, 2, ..., \mathrm{N_t}$$



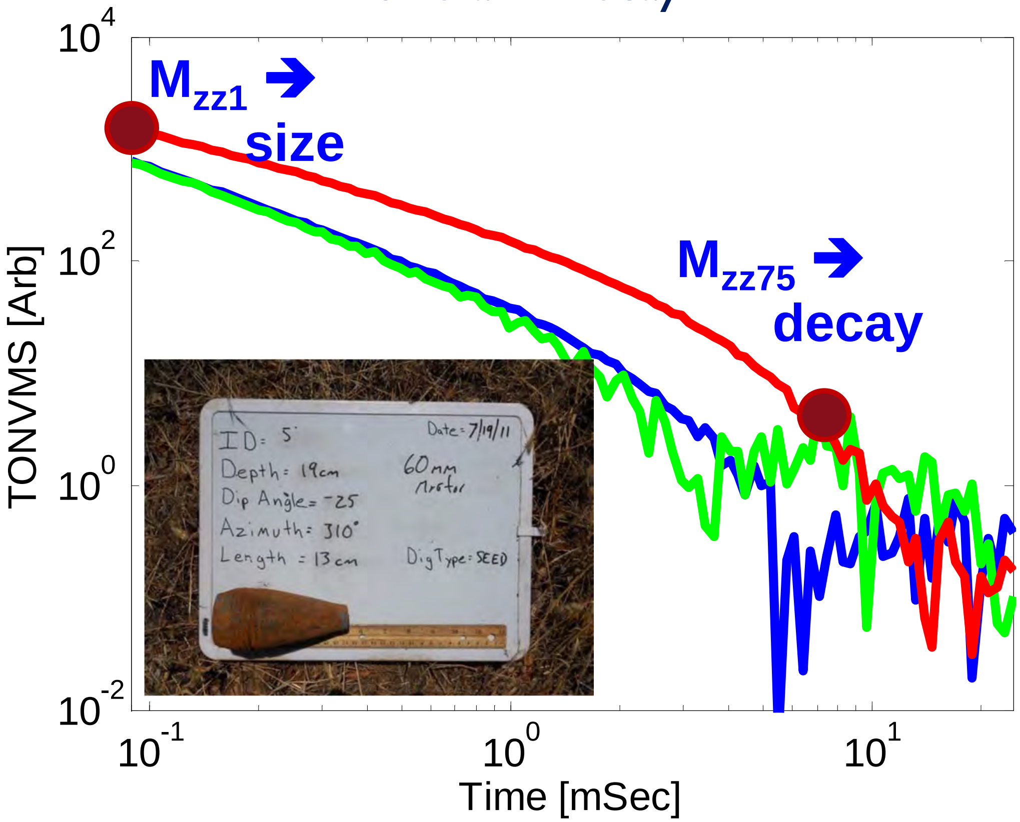
The goal is to:

- determine the eigenvalues of [W] matrix for each time channel.
- find an eigenvector V that will be shared by all matrices.

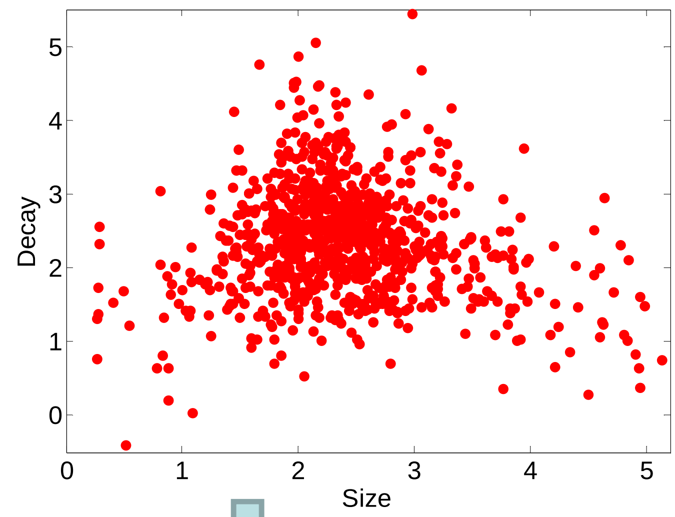
$$D(t_k) = V^T[W(t_k)]V,\ k=1, 2, ..., N_t$$

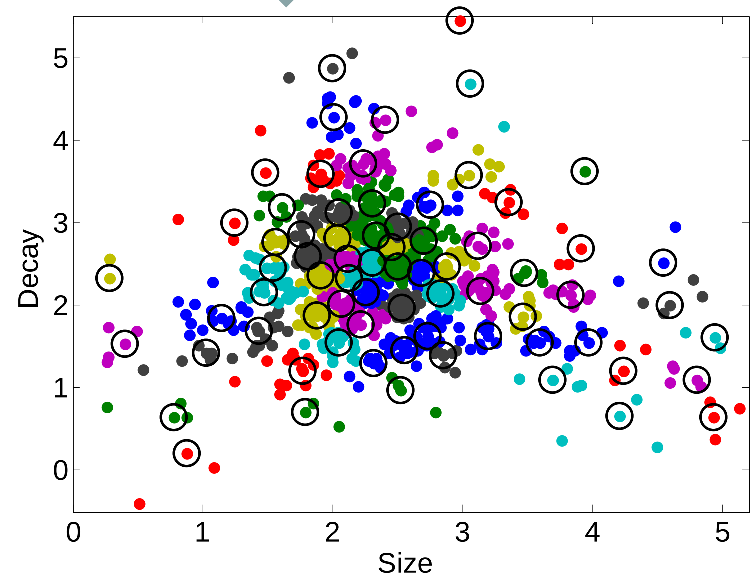
Training data selection

Choose discrimination features:
size and decay



Cluster the discrimination features





Identify an anomaly from each cluster,
build a custom training list.

Camp Beale MPV Classification Approach

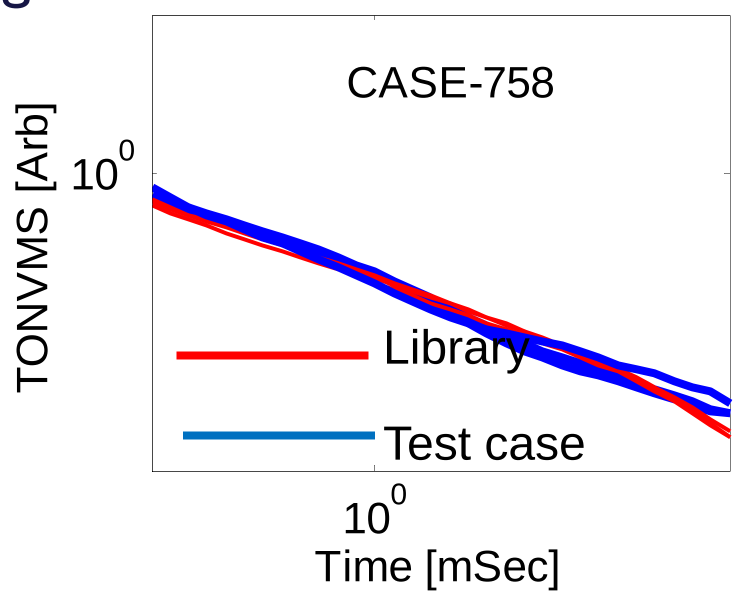
- Invert all data for one, two and three targets;

- Create custom training data using a statistical clustering (for example Matlab function “clusterdata”, with “Ward Linkage”) and time decay curves of the inverted ONVMS.

- Request Custom training data and update TOI library.

- Invert as N=4, 5 targets, if necessary.

Three targets inversion for cell #758

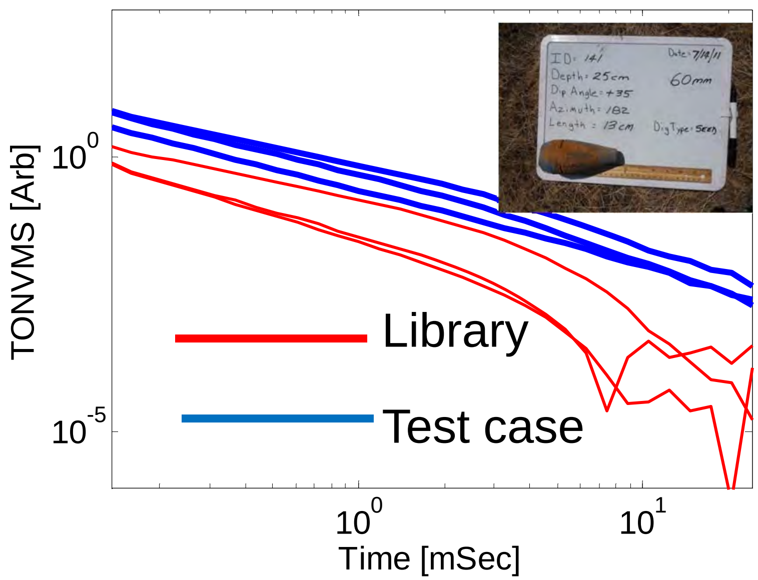


Library target

Camp Beale MPV Classification Approach

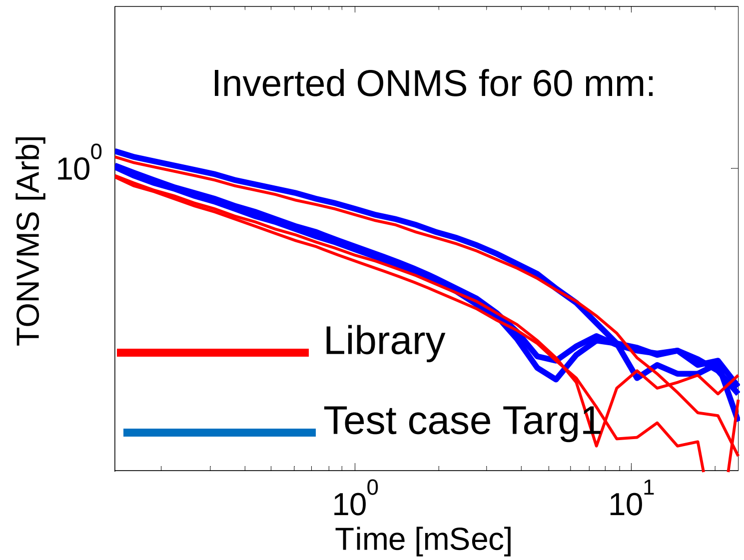
At CBE MPV2 suffered from magnetic soil. This was mostly due to the deployment strategy, i.e. the sensor was placed on the ground.

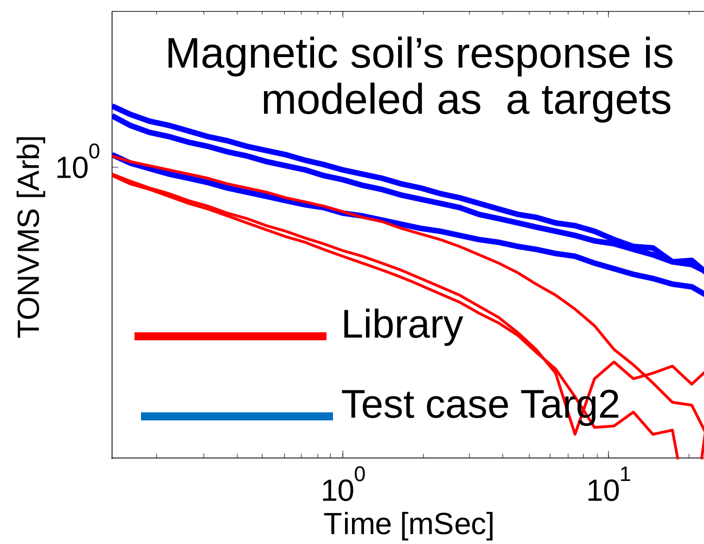
Single object inversion results



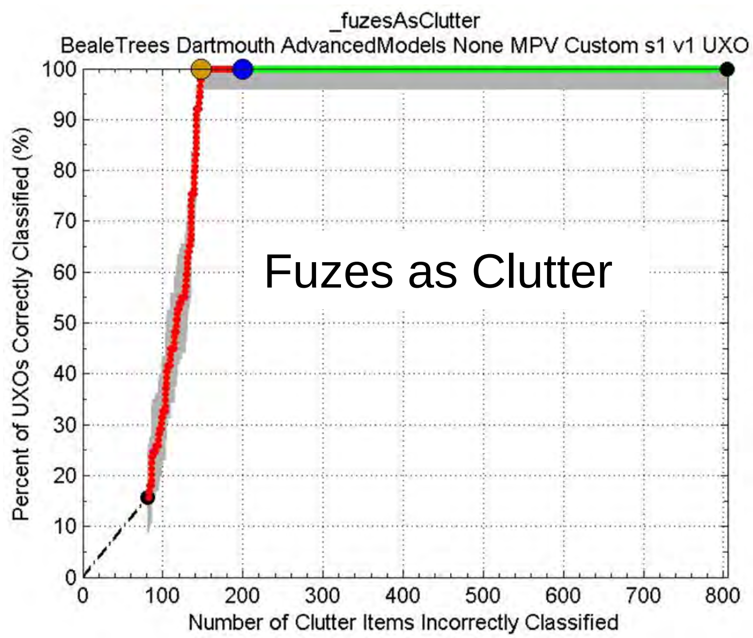
The ONVMS technique was able to model the magnetic soil's EMI responses as a response from a target. The technique extracted the real target features from the noisy data.

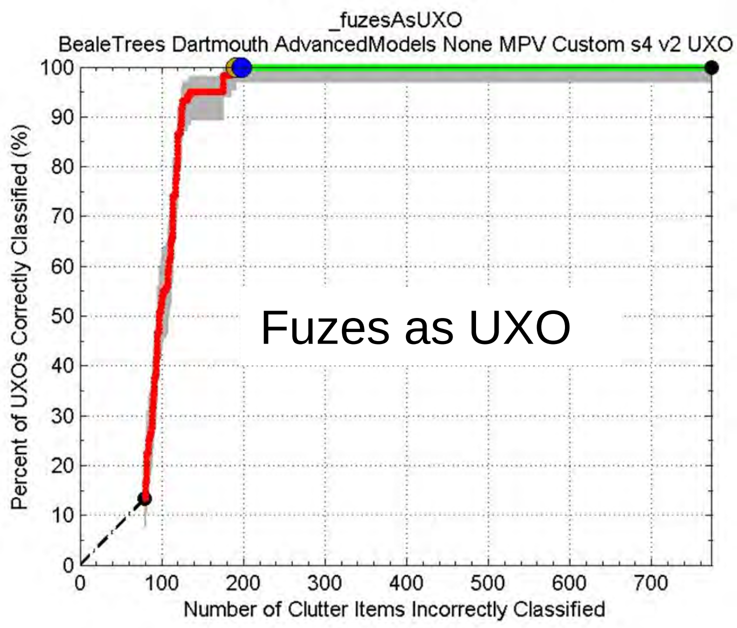
Multi objects inversion results





Camp Beale MPV Classification results





- **95 anomalies were requested for custom training, out of those 16 were TOI and 79 were scrap.**
- **All available MPV2 data were inverted and analyzed.**
- **No False Negatives: all TOI, total 124= 89 (UXO) + 35(Fuzes), were indentified correctly.**
- **200 holes with clutter dug,**
- **587 holes with clutter were not dug. i.e ~75 % of non-TOI left in the ground.**

Camp Beale 2x2 Array Classification Approach

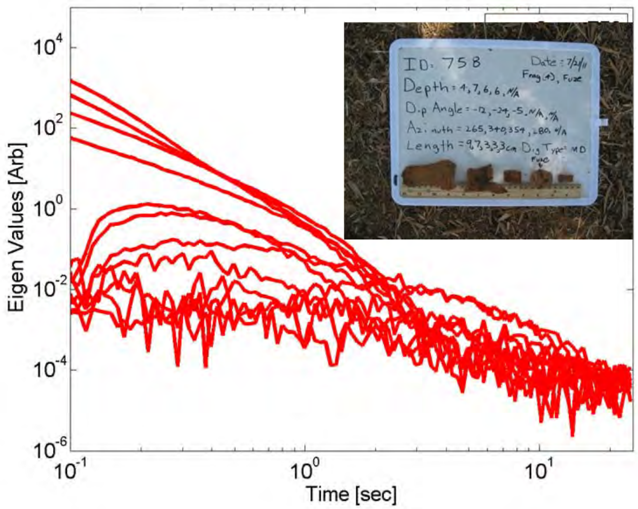
- Conduct data QC using the JD technique, determine the number (N) of potential targets.

- Invert all data as N targets, with N is estimated from the JD.

- Create custom training data using a statistical clustering, and eigenvalues time decay curves.

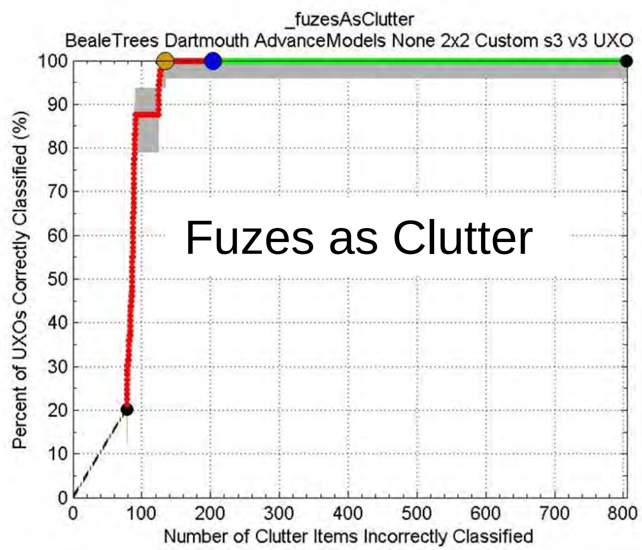
- Request Custom training data and update TOI library.

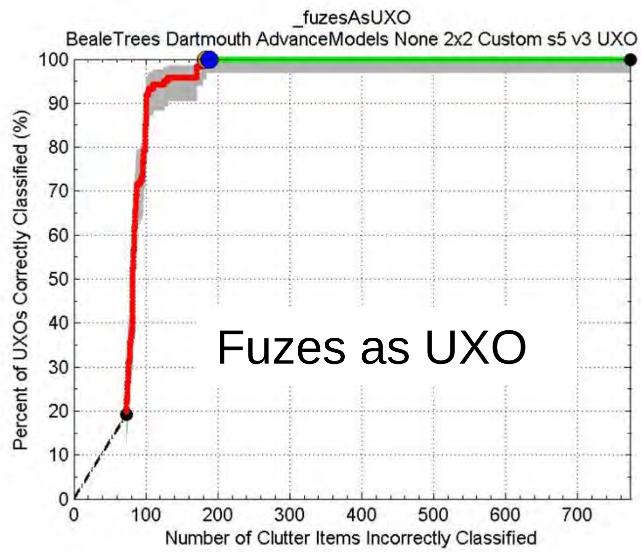
- Invert all data as more than N targets, if necessary.



The JD eigenvalue analysis indicated that cell #758, contained more than one targets and signal from a target was highly disturbed, therefore the cell was included in the training data.

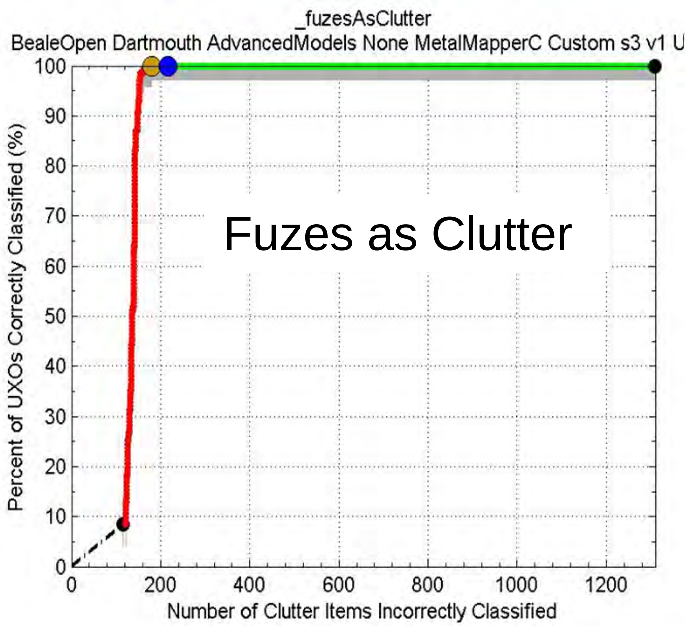
Camp Beale 2x2 Array Classification results

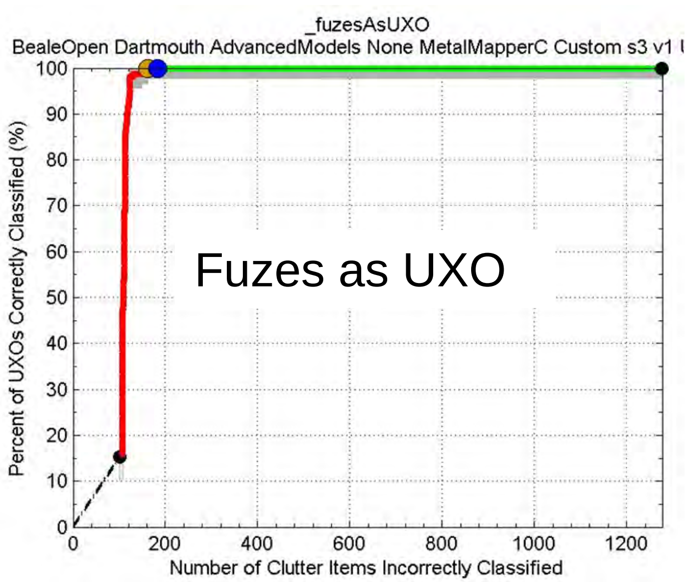




- **98 anomalies were requested for custom training, out of those 24 were TOI and 74 were scrap.**
- **All available 2x2 array data were inverted and analyzed.**
- **No False Negatives: all TOI, total of 124 = 89 (UXO) + 35(Fuzes), were indentified correctly.**
- **191 holes with clutter dug,**
- **596 holes with clutter were not dug.**
  i.e ~76 % of non-TOI left in the ground.

Camp Beale CH2MHILL MM Classification results



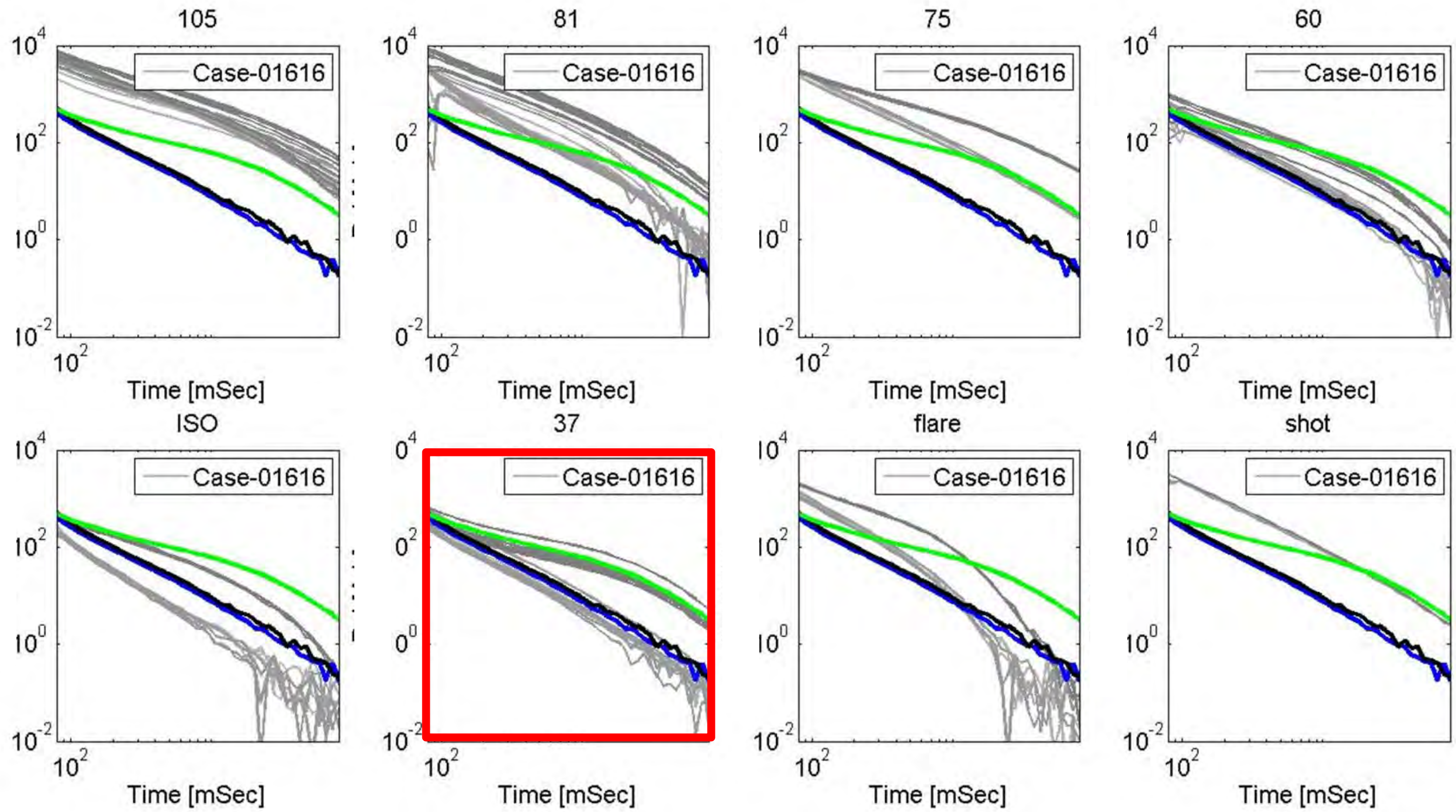


- **132 anomalies were requested for custom training, out of that 25 were TOI and 107 were scrap.**
- **All available CBE CH2MHILL data were inverted and analyzed.**
- **No False Negatives: all TOI, total 170= 137 (UXO) + 33(Fuzes), were indentified correctly.**
- **183 Holes with clutter dug,**
- **1117 holes with clutter were not dug. i.e ~86 % of non-TOI left in the ground.**

Camp Beale Parsons MM Classification results

Obtained by Sky Research Production team:

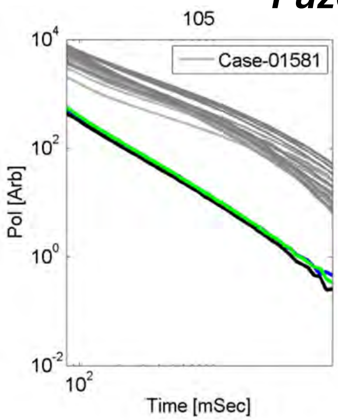
Step 1:



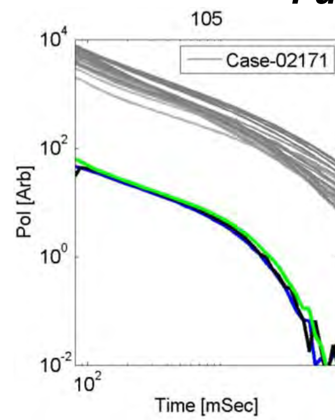
- Used test pit data collected at site to establish feature libraries (grey lines) for potential TOI
- Plotted anomaly total ONVMS (green, blue, black lines) against feature libraries to identify high probability TOIs (37mm shown in red outline)

Step 2: Identify the anomalies

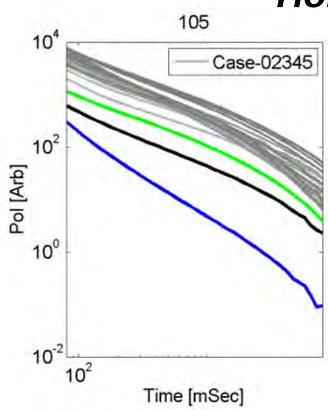
Fuze Type 1



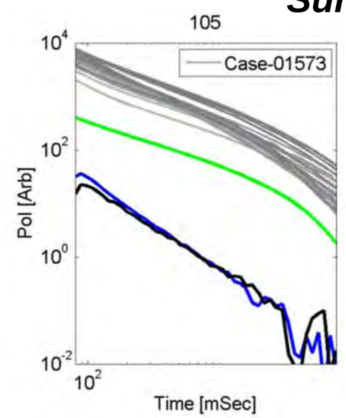
Fuze Type 2



Horseshoe



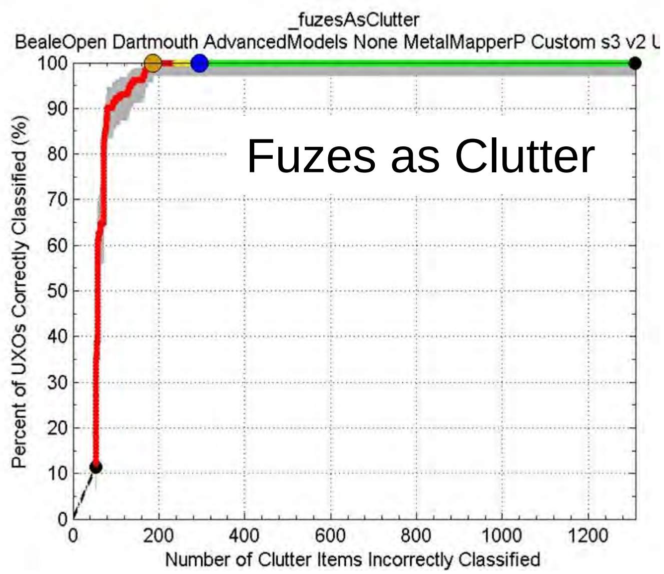
Survey Nail

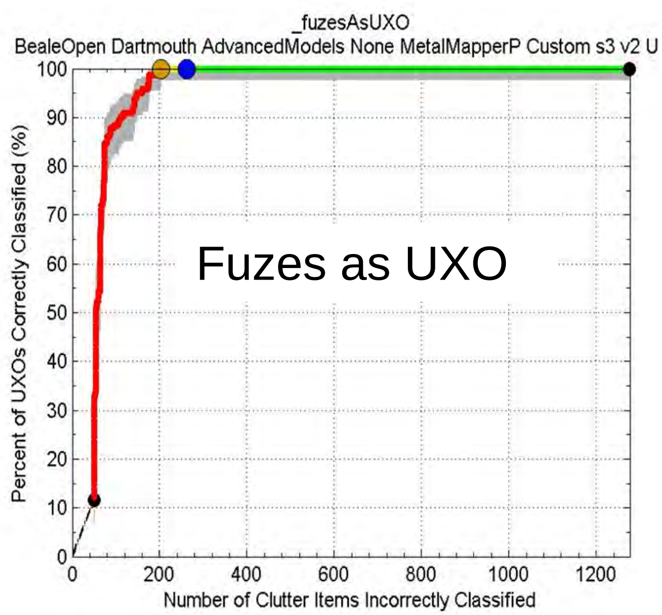


- Identified “suspicious” anomalies that did not match feature library responses
- Requested ground truth for select group of possible TOIs
- Discovered two TOI fuze types and two clutter types (horseshoe and survey nail)
- Added the new TOI and clutter polarizabilities to the feature library

Camp Beale Parsons MM Classification results

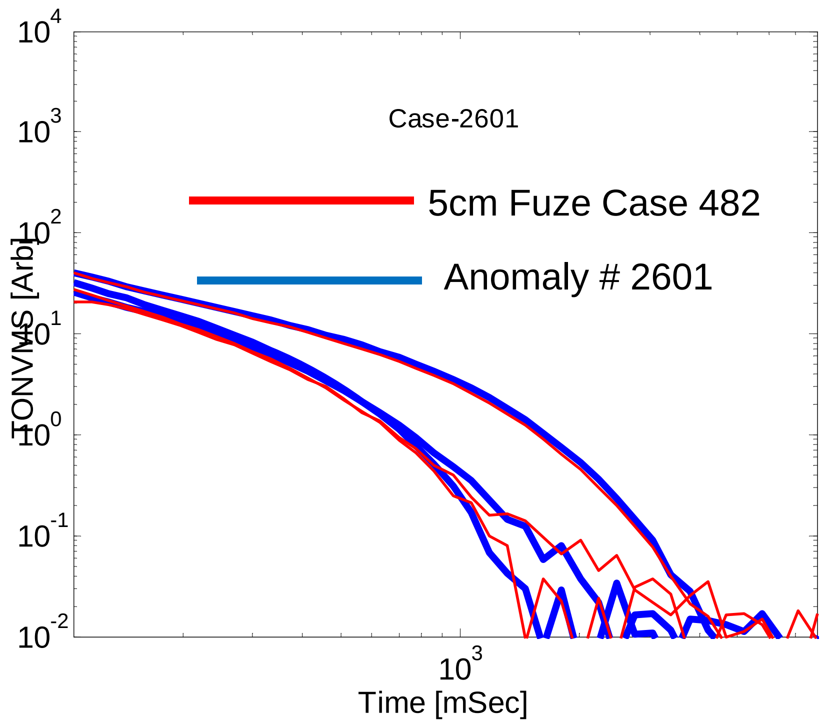
obtained by Sky Research Production team

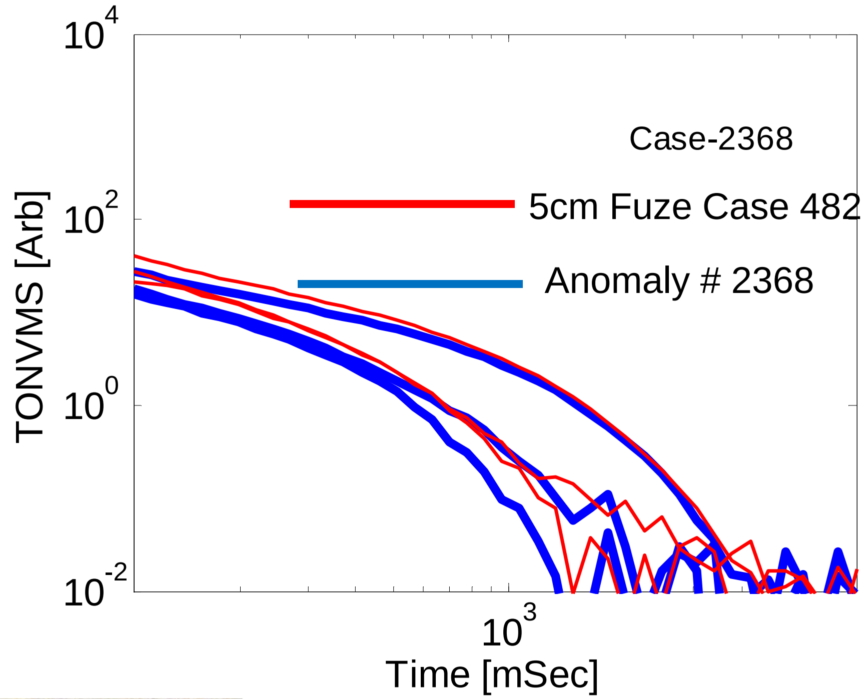


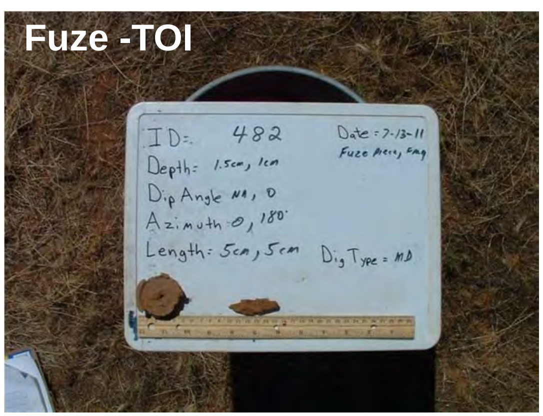


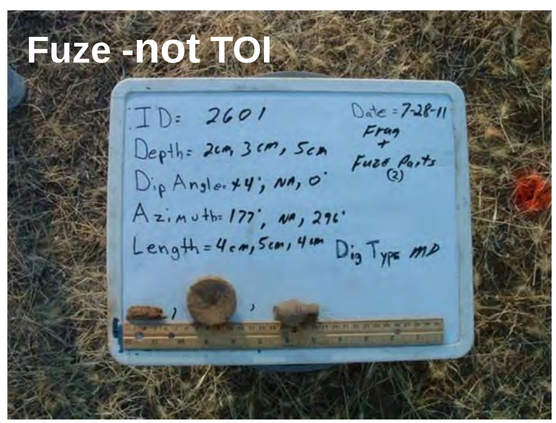
- **69 anomalies were requested for custom training, out of that 19 were TOI and 50 were scraps.**
- **All available CBE Parsons data were inverted and analyzed.**
- **No False Negatives: all TOI, total 170= 137 (UXO) + 33(Fuzes), were indentified correctly.**
- **253 Holes with clutter dug,**
- **1047 Holes with clutter were not dug.**
  i.e ~81 % of non-TOI left in the ground.

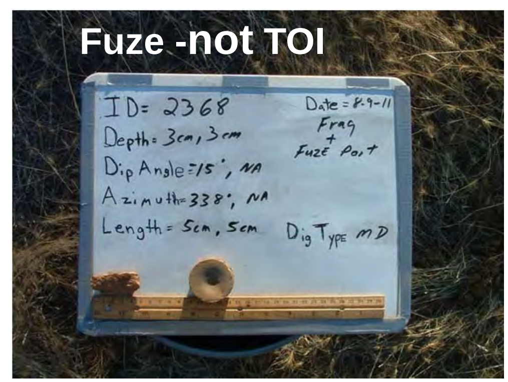
Targets that produced Unnecessary digs



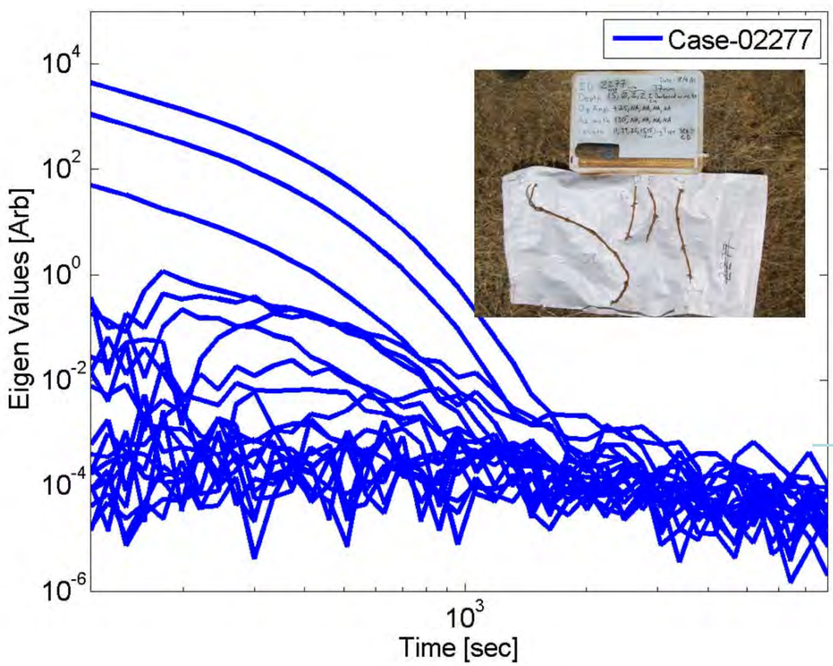


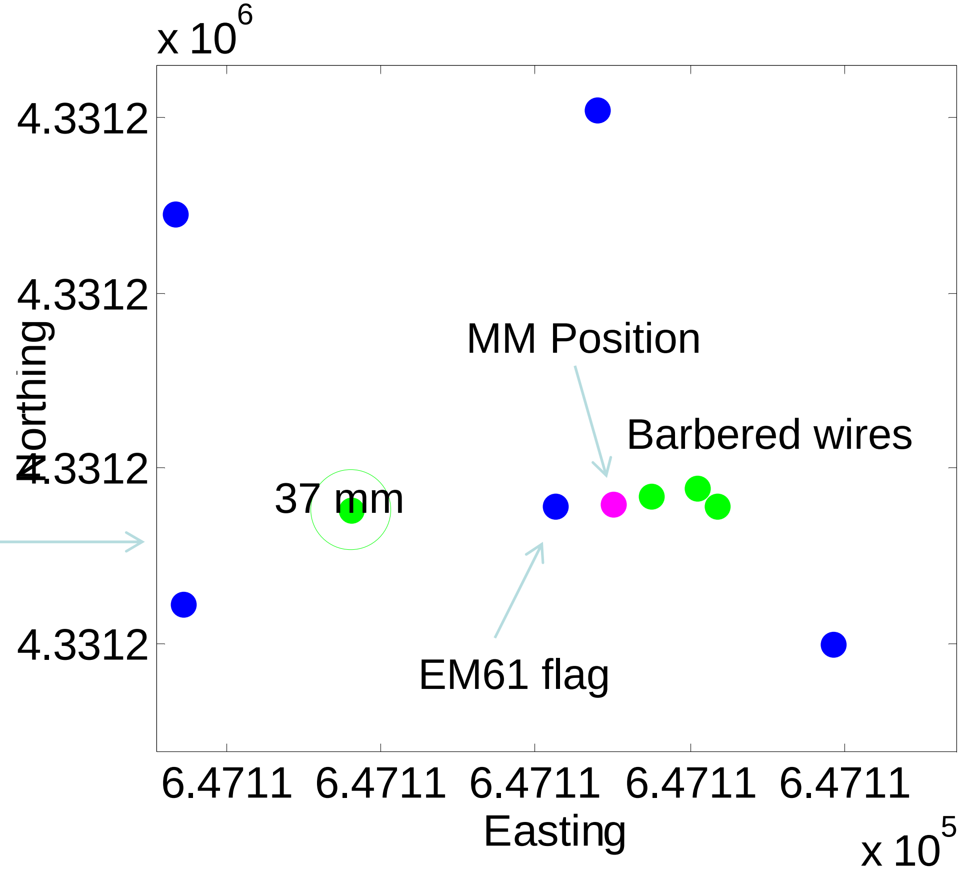






Difficult cases: JD applied to CBE anomaly #2277





The curves of the MM MSR data matrix eigenvalues versus time do not show any evidence of the 37 mm target.

The ground truth revealed, in fact, that the 37mm target was 90 cm away from the MM center.

Summary

- Advanced EMI models were applied to CBE Cued Data sets.
- Studies showed that the models are able to deal effectively with cluttered environment.
- Classifications were demonstrated for both R&D and production EMI sensors.
- No False Alarms.
- The models are easy to use for general users.
- The models were able to classify targets as small as 3 cm size fuzes.

Acknowledgments:

This work was supported by the ESTCP Project # MR-201101