Advances in Classification Methods for Military Munitions Response

Herb Nelson

ESTCP

Objective of the Course

Provide an update on the sensors, methods, and status of the classification of military munitions using geophysical methods

- Advanced processing of data collected with existing commercial instruments
- Significant improvements possible using advanced EMI sensors

Report Documentation Page

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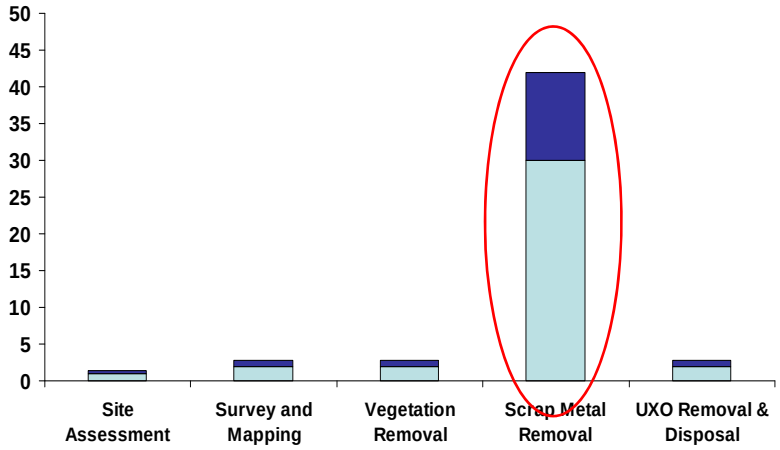
Presenters

- Dr. Steve Billings (Sky Research)
- Dr. Thomas Bell (SAIC)
- Dr. Dean Keiswetter (SAIC)

The Munitions Problem

- There are over 3,000 sites suspected of contamination with military munitions
- They comprise 10s of millions of acres
- The current annual cleanup effort is on the order of 1% of the projected total cost
- To make real progress on this problem, we need a better approach

Munitions Response Cost Breakout



Defense Science Board Task Force on UXO

Classification

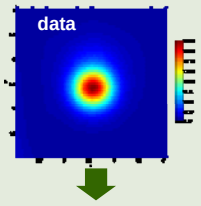
- Classification offers the chance to divide anomalies into those caused by targets-of-interest and those caused by other things
- Recognize that current field methods involve implicit discrimination
  - Mag & Flag – instrument sensitivity setting and human interpretation
  - Digital Geophysics – threshold selection; what is a target?
- Our goal is a principled, data-based approach to classify targets as either “non-hazardous” or “targets of interest”

Standard Processing Stream

- The standard processing stream for detection and classification of munitions using geophysical data

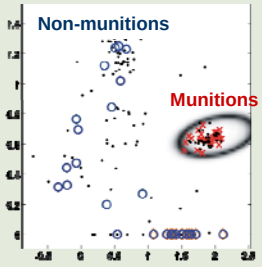
1. Data Collection

2. Parameter Estimation (Target Attributes)



Parameters

3. Classification



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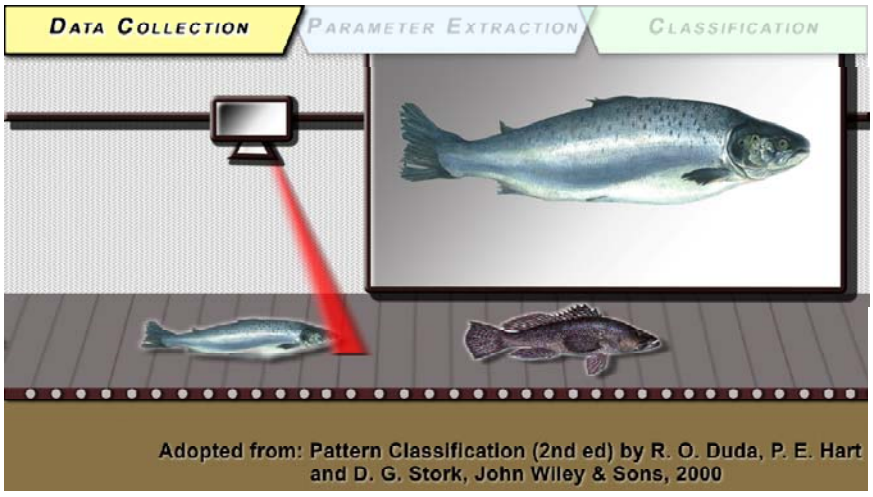
Collect Data



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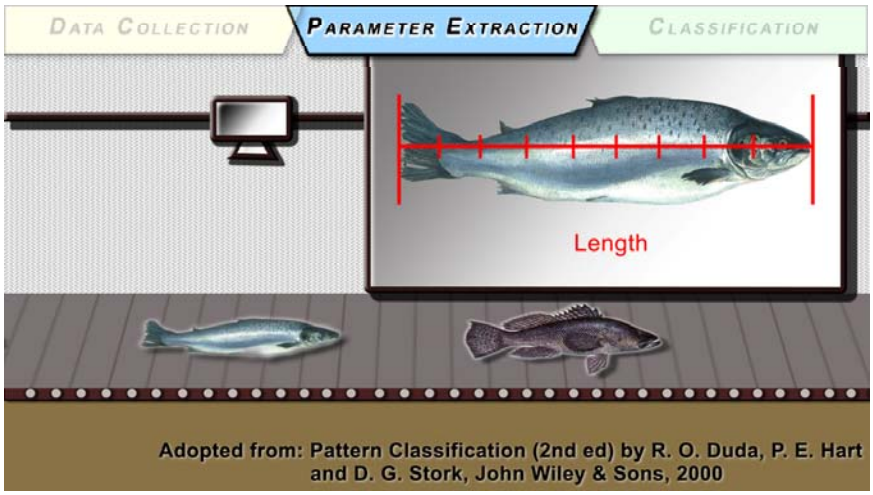
Extract Parameters



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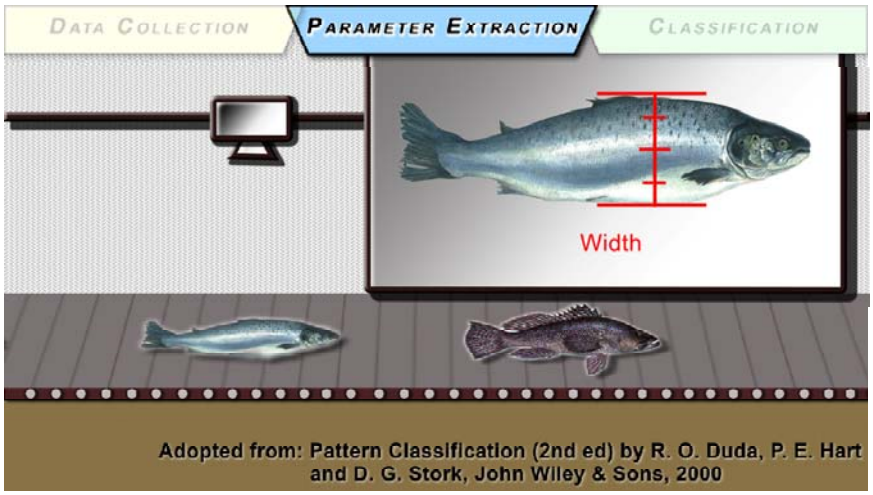

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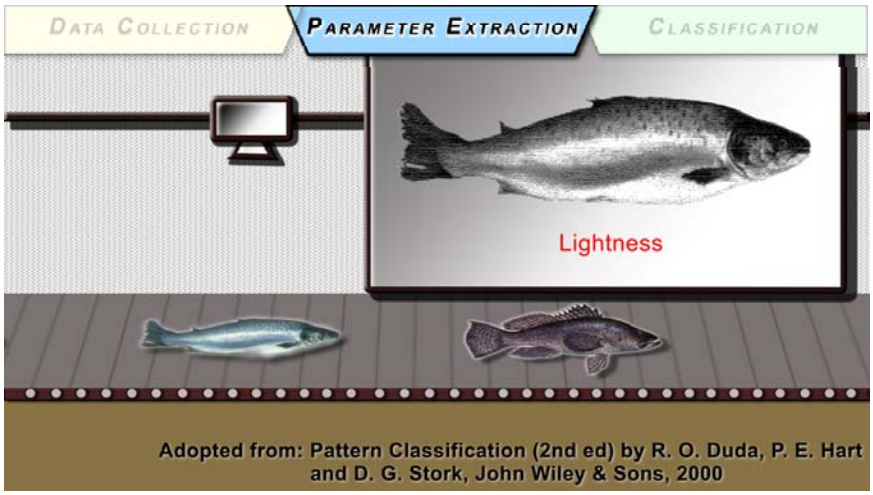

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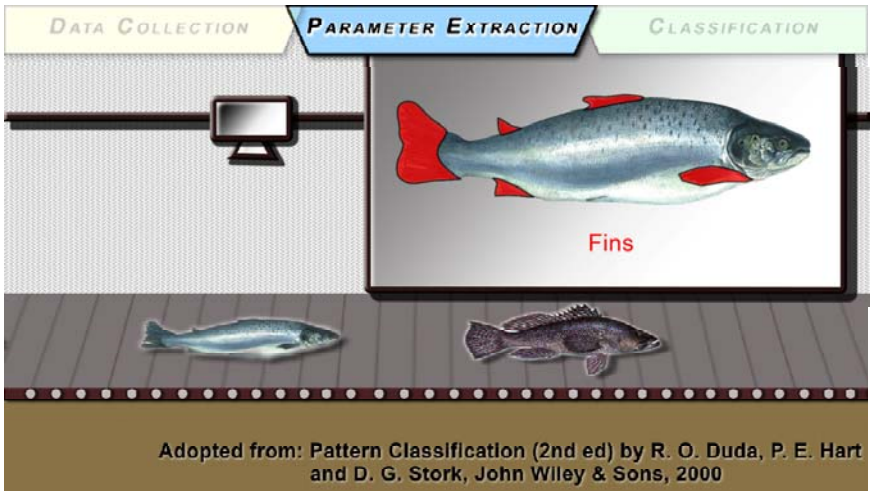

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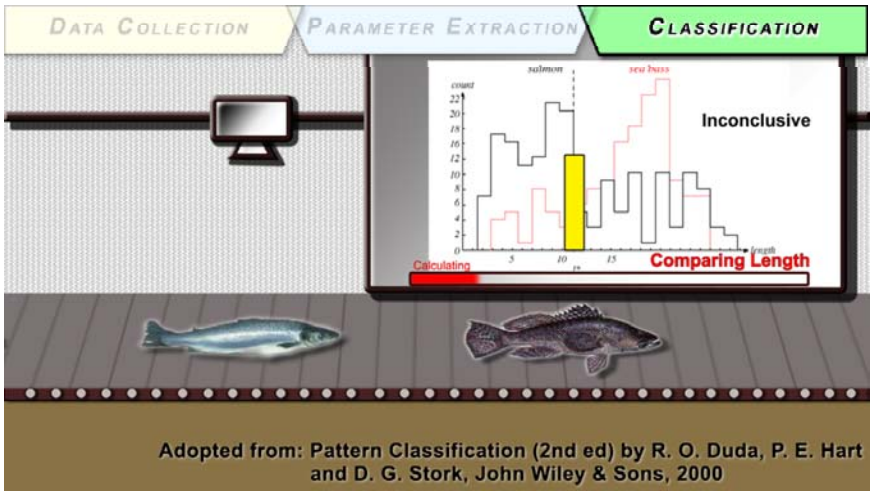
Are These Parameters Useful for Classification?



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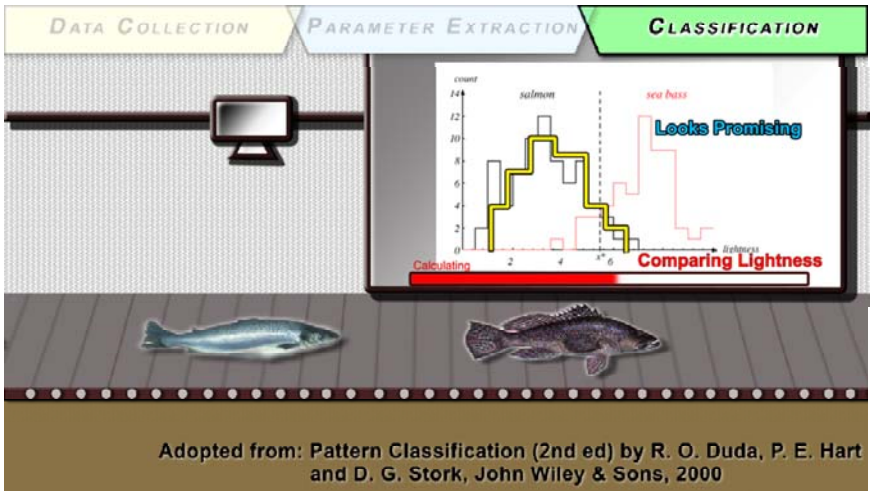

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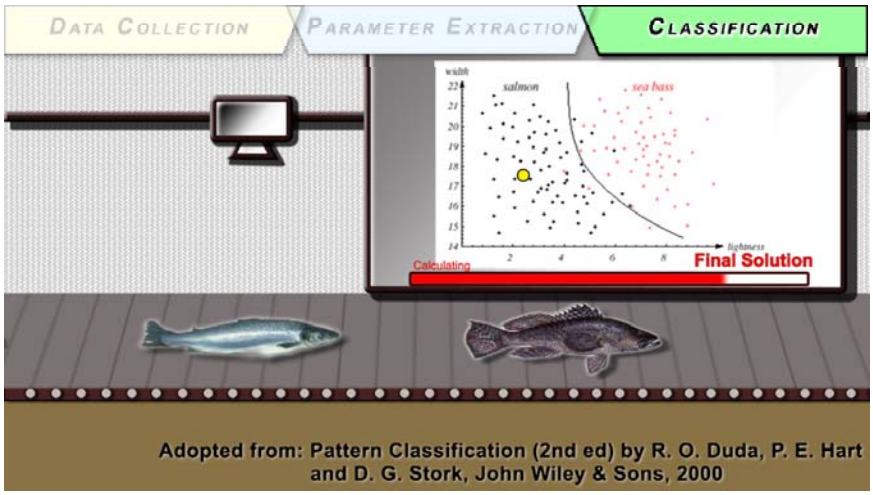
We Have Our Classifier



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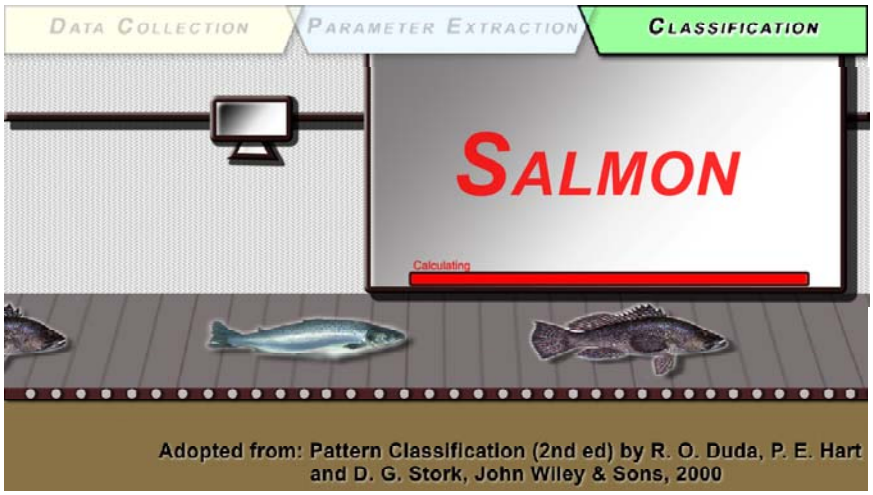
Successful Classification



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Electromagnetics (EM): Fundamentals and Parameter Extraction

Stephen Billings

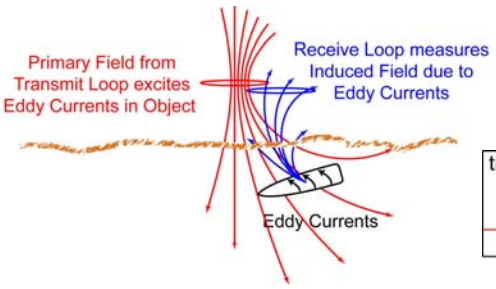
ESTCP

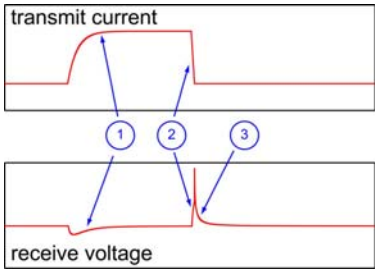
EM Module Outline

- EMI Fundamentals
  - How EMI sensors work and what they measure
  - Principal axis polarizabilities
- Data collection
  - Survey and mapping
  - Target illumination
- Parameter extraction
  - Dipole inversion to determine principal axis polarizabilities

Electromagnetic Induction

Basic EM Concepts

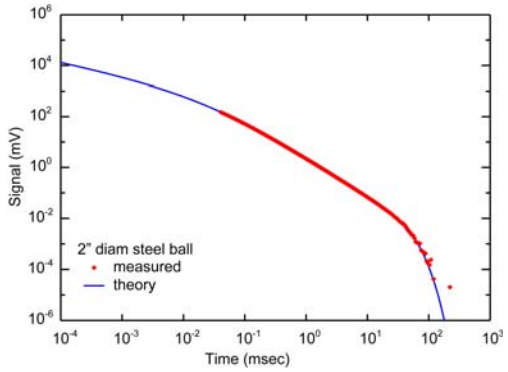




1. The primary field magnetizes the buried object (similar to magnetics)
2. Abrupt change in the primary field excites eddy currents in the object.
3. Eddy currents diffuse throughout the object and decay (basic EM response which applies to all metal objects)

EMI Signal vs. Time

Example – EMI response of 2” diameter carbon steel ball measured with TEMTADS sensor, compared with theory



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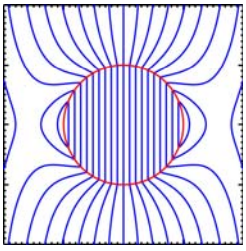
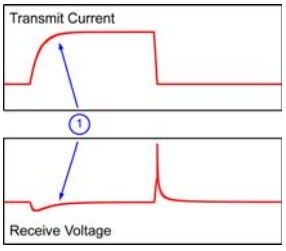
Stages in the EMI Response





1. Target magnetized by primary field

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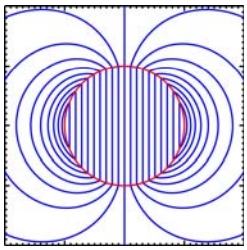
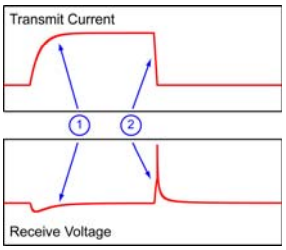
Stages in the EMI Response





1. Target magnetized by primary field
2. Primary field shuts off
   - Field inside target cannot react immediately
   - Currents form on surface
   - Secondary field created

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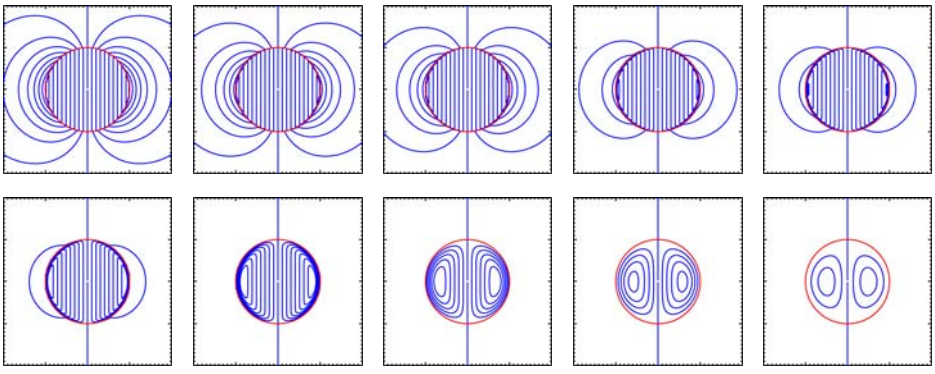
Stages in the EMI Response

Decaying induced field



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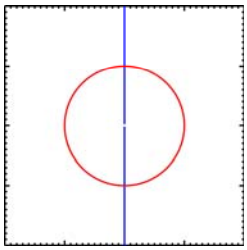
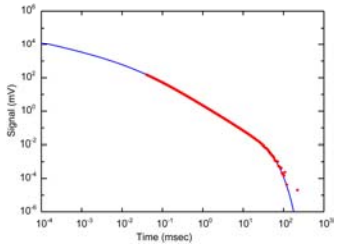
Stages in the EMI Response





1. Target magnetized by primary field
2. Primary field shuts off
   - Field inside target cannot react immediately
   - Currents form on surface
   - Secondary field created
3. Induced field decays away as currents diffuse into target

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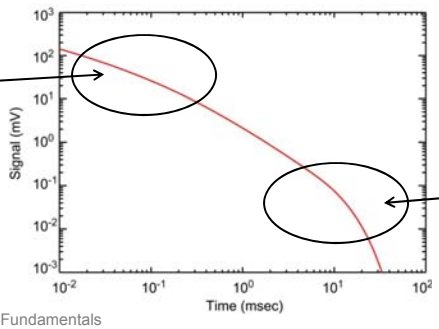
Eddy Current Decay Regimes

- Shape of EMI response determined by target properties
  - Size, shape, thickness, composition
  - Decay times from 10's of μsec to 10's of msec can provide information useful for classification

Early time
Eddy currents at surface, object's size and shape determine the response.



Late time
Eddy currents diffused through object, response is determined by wall thickness.

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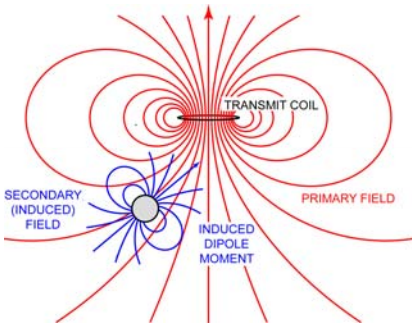
Polarizability

- Standard theory represents EMI response in terms of an oscillating magnetic dipole moment that is induced in the target by an oscillating primary field $H_0\, exp(i\omega t)$



- For a sphere, this dipole moment is oriented in the same direction as the primary field, with strength proportional to the primary field amplitude H_0
- Proportionality factor is the magnetic polarizability $\beta(\omega)$
- For transient EM, polarizability is Fourier/Laplace transform $\beta(t)$

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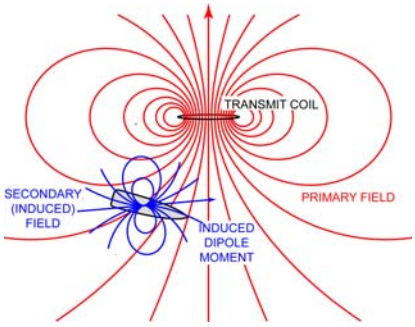
Dipole Response Model

- For arbitrary target shapes, induced dipole moment is typically not aligned with primary field
  - Polarizability is second rank tensor $\mathbf{B}(t)$ relating responses in $\boldsymbol{x}$, $\boldsymbol{y}$, $\boldsymbol{z}$ directions to primary field components in $\boldsymbol{x}$, $\boldsymbol{y}$, $\boldsymbol{z}$ directions



$$\mathrm{B}(t) = \begin{pmatrix} \beta(t)_{xx} & \beta(t)_{xy} & \beta(t)_{xz} \\ \beta(t)_{yx} & \beta(t)_{yy} & \beta(t)_{yz} \\ \beta(t)_{zx} & \beta(t)_{zy} & \beta(t)_{zz} \end{pmatrix}$$

$\beta(t)_{ij}$ relates dipole moment induced in $\boldsymbol{i}$ direction to primary field component in $\boldsymbol{j}$ direction

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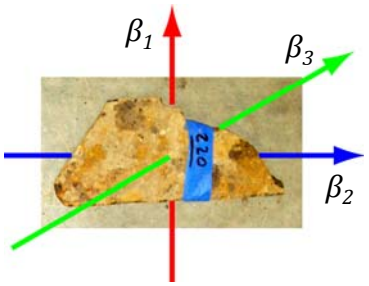
Principal Axes

- Suitable yaw/pitch/roll rotation aligns field components with target's three orthogonal principal axes
  - $\mathbf{B}(t)$ is then diagonal & elements are principal axis polarizabilities $\beta_1, \beta_2, \beta_3$ corresponding to excitations in the three principal axis directions



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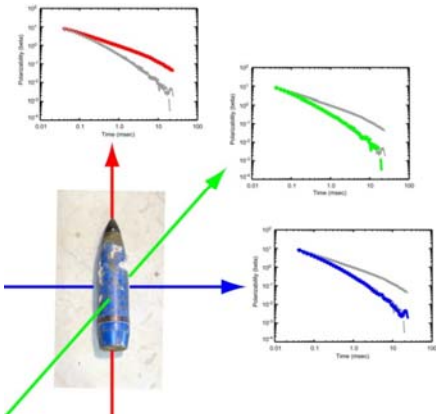
Principal Axis Polarizabilities

- Normalized response (polarizability) for excitation in object's principal axis directions are the fundamental EMI attributes
  - UXO items are symmetric, so two of the principal axis responses are the same.



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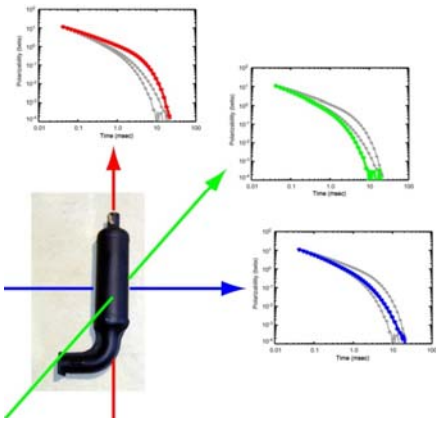
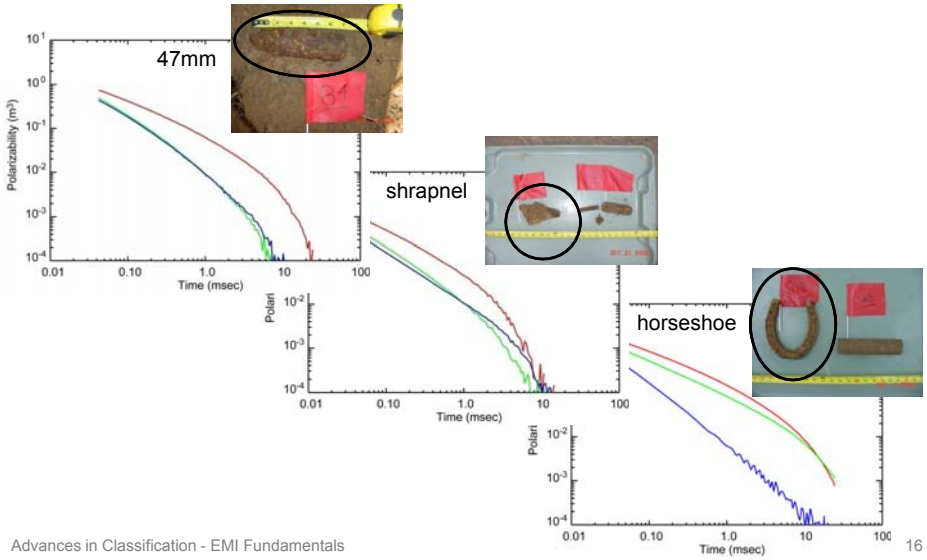
Principal Axis Polarizabilities

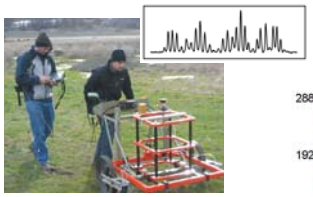
- Normalized response (polarizability) for excitation in object's principal axis directions are the fundamental EMI attributes of the object
  - UXO items are symmetric, so two of the principal axis responses are the same.
  - Irregular clutter items have three different principal axis responses.



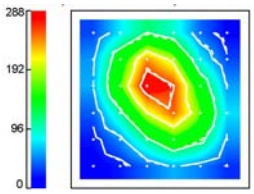
Examples of Polarizabilities



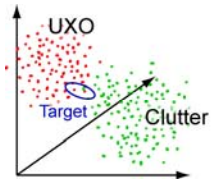
Stages in the Classification Process



1. Acquire EMI data over target



2. Invert data using dipole model and extract target features



3. Classify target using decision rules applied to target features

Stages in the Classification Process

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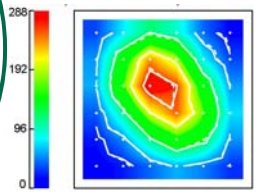

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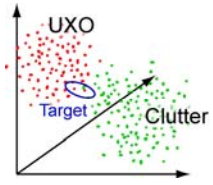
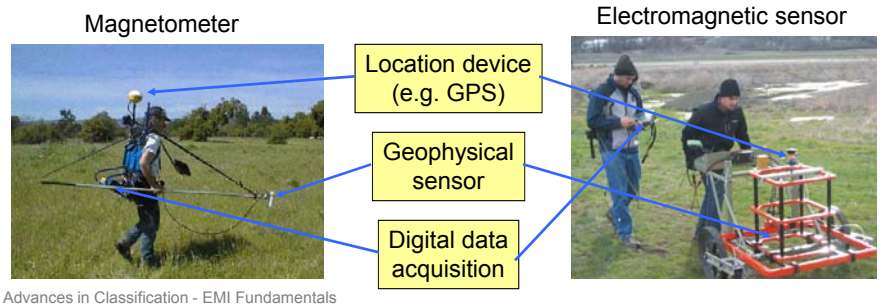


3. Classify target using decision rules applied to target features

Digital Geophysics

- Requires a geophysical sensor system (based on either magnetometry or electromagnetic induction)
- A positioning device (e.g. Global Positioning System, GPS)
- A computer for digital data acquisition



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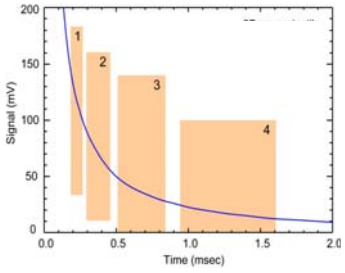
Geonics EM61 Mk2

- Industry standard for geophysical surveys at munitions response sites
- Best UXO detection performance at 1994-96 Jefferson Proving Ground demonstrations
- Measures eddy current decay signal over four time gates centered at 216, 366, 660, and 1266 µsec



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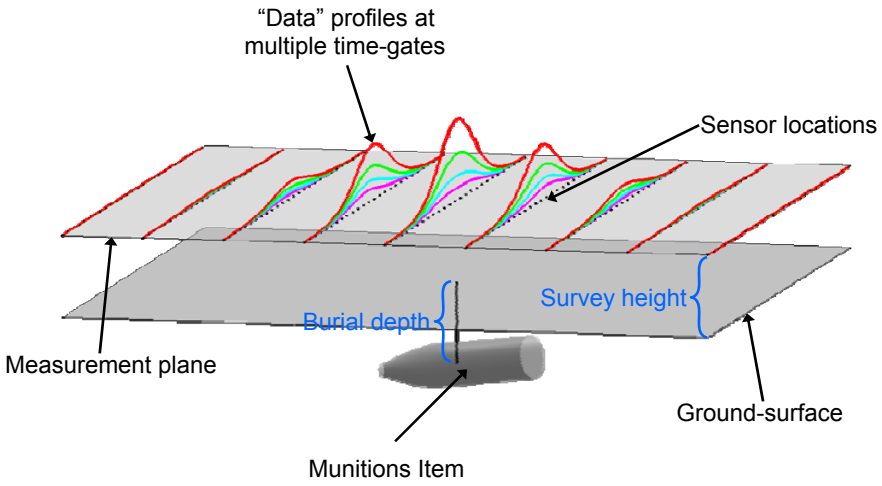
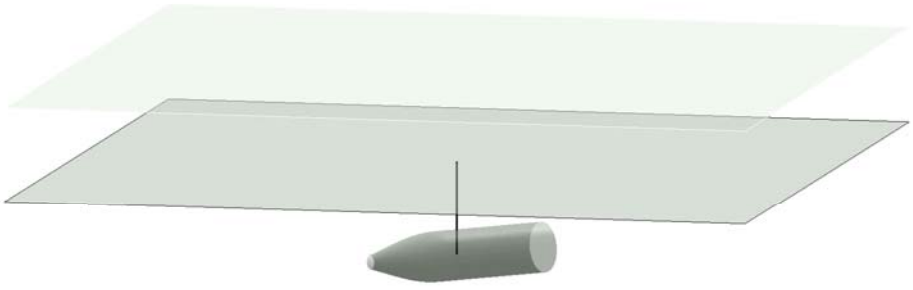
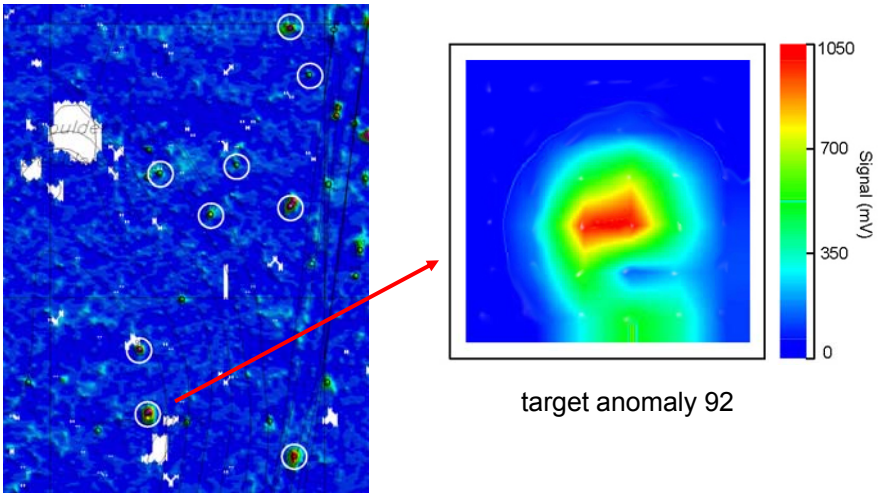
EM Survey



EM Survey



Mapped Survey Data & EM Anomalies



target anomaly 92

Stages in the Classification Process

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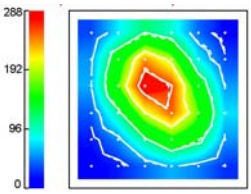

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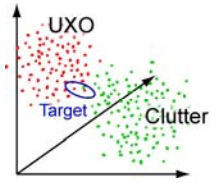
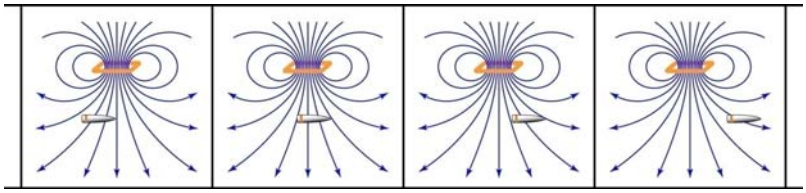


3. Classify target using decision rules applied to target features

Calculating Polarizabilities from EM Data

- Data collected at different locations over a target sample different combinations of the principal axis responses



- We can use the dipole response model to sort out the different contributions

$$V(t) = \mu_0 n_R n_T I_0 \mathbf{C}_R \cdot \mathbf{C}_T \mathbf{B}(t)$$

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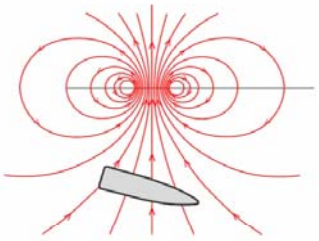
Sampling the Full EM Response

MEASURED EMI RESPONSE



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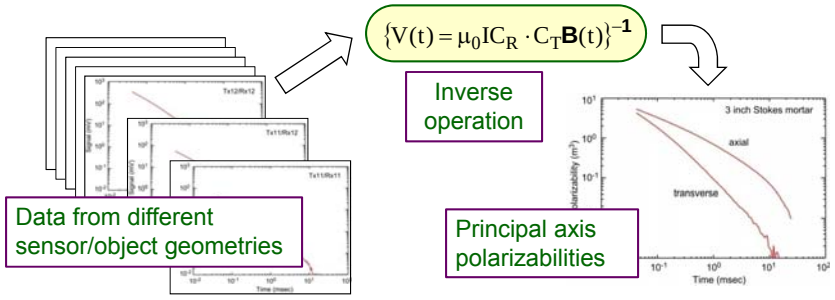
Inversion of EM Data

- EM measurements from enough locations to sample all principal axis responses is inverted using the dipole response model to determine the polarizabilities
  - Inversion also determines target location, depth and orientation



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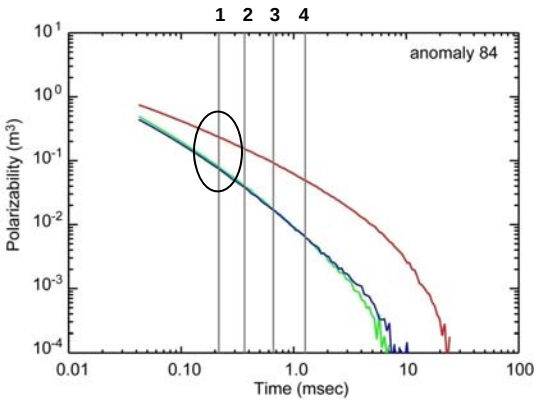
EM61 Target Attributes



Based on polarizabilities (βs) at the 4 EM61 time gates

Size attribute

Size $\propto \sqrt[3]{\Sigma\beta}$ (gate 1)

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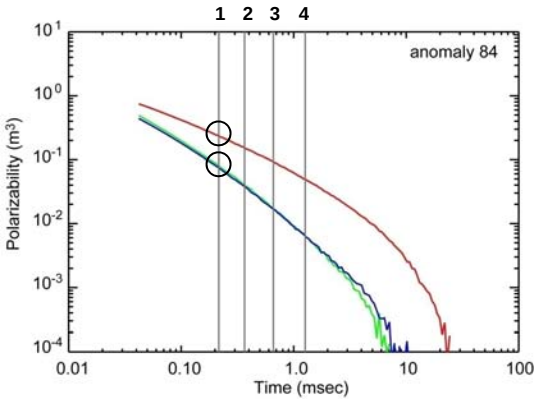
EM61 Target Attributes



Based on polarizabilities (βs) at the 4 EM61 time gates

Shape attributes

Symmetry = $(\beta_2-\beta_3)/\beta_1$

Aspect Ratio = $½(\beta_{2+}\beta_3)/\beta_1$ (usually gate 1)

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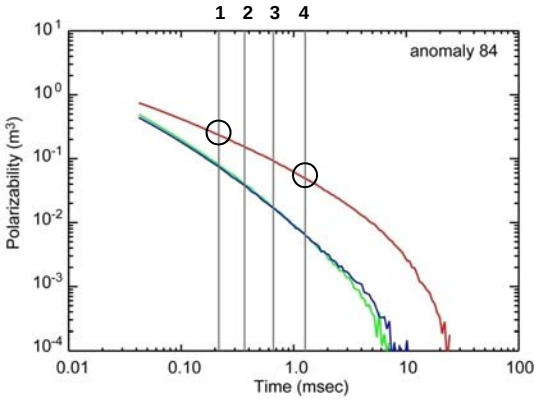
EM61 Target Attributes



Based on polarizabilities (βs) at the 4 EM61 time gates

Decay attribute

Decay = $\beta_1(4)/\beta_1(1)$

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Examples of EM61 Attributes



Target	Type	Size	Symmetry	Aspect	Decay
84	47 mm	0.055	0.022	0.33	0.20
116	5”x6” shrapnel	0.054	0.078	0.30	0.14
118	horse shoe	0.071	0.455	0.34	0.23

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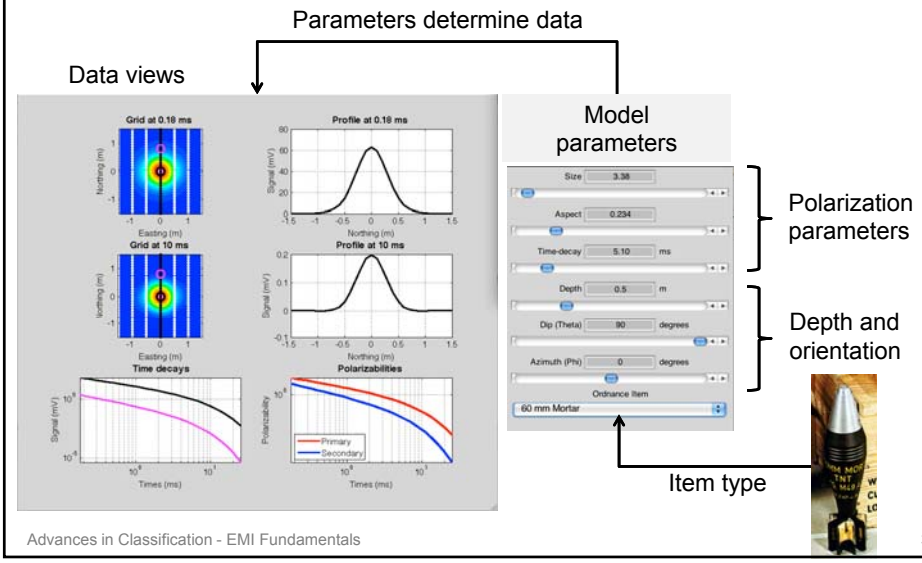
Forward modeling demonstration



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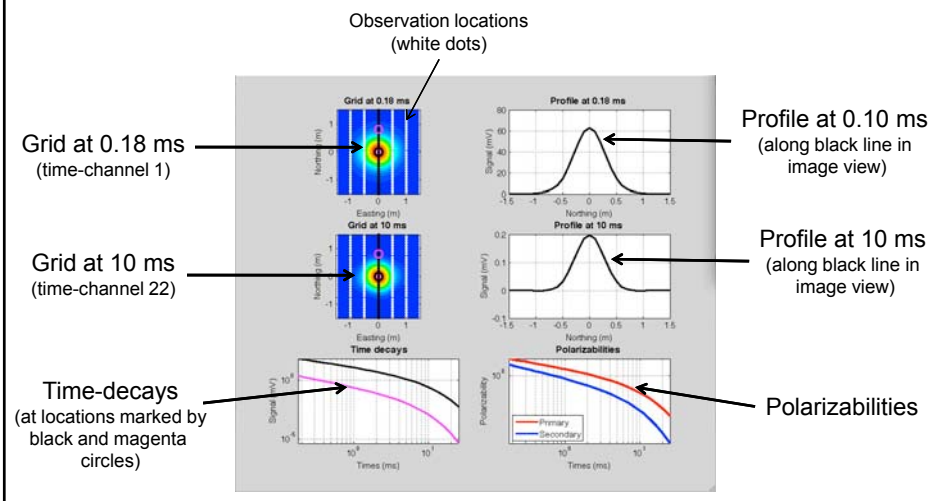
Layout of the data view

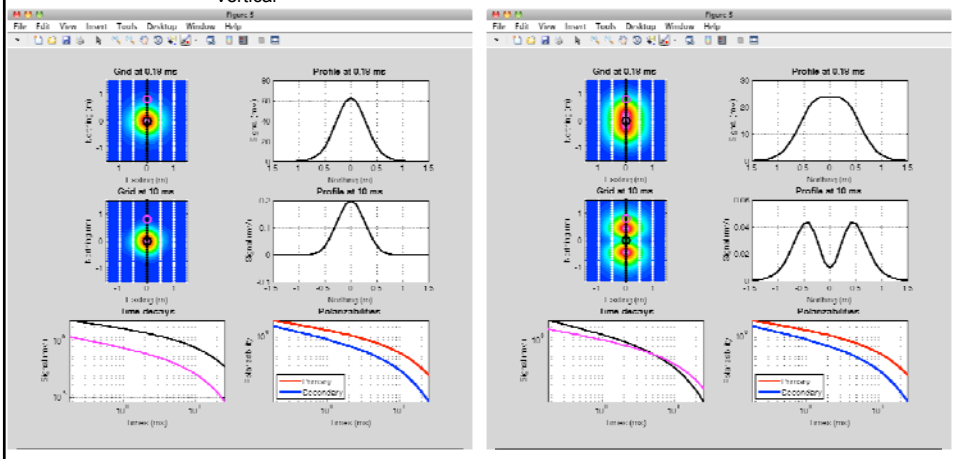


Advances in Classification - EMI Fundamentals 33

Effect of item orientation

60 mm mortar
Vertical

60 mm mortar
Horizontal, North facing



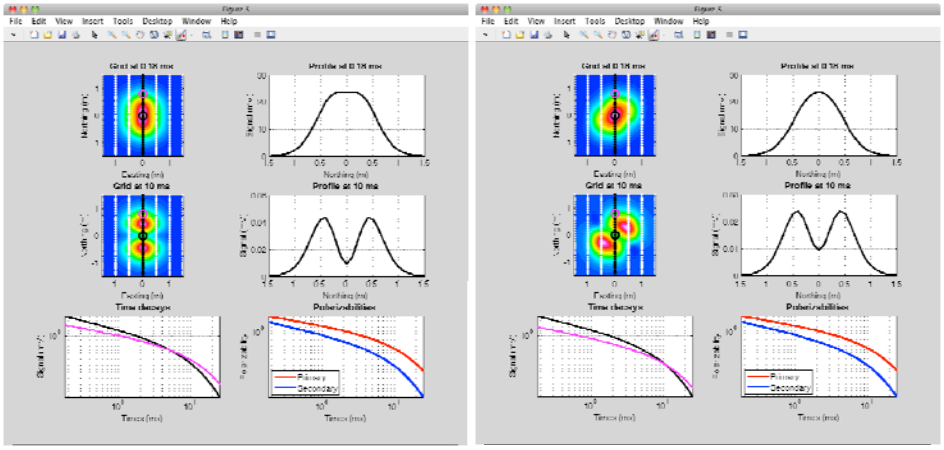
Note the change in shape and the decrease in amplitude

Advances in Classification - EMI Fundamentals 34

Effect of item orientation

60 mm mortar
Horizontal, North facing

60 mm mortar
Horizontal, 45 degree azimuth

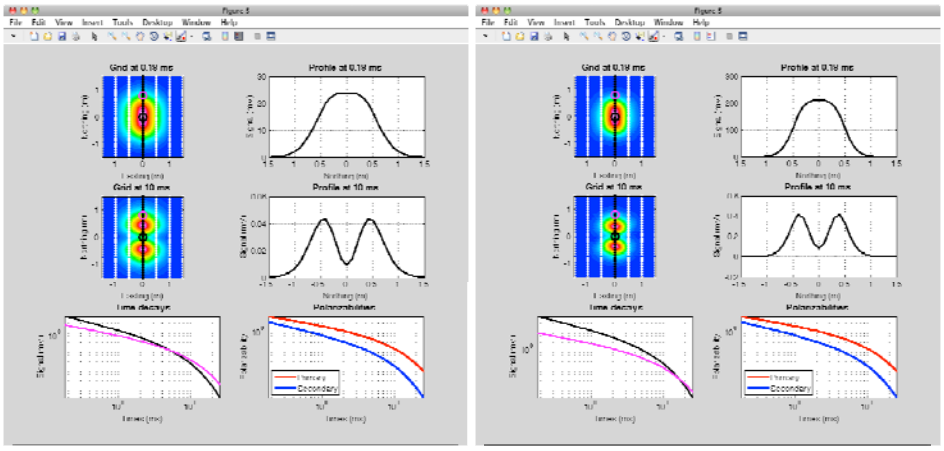


Note the change in shape

Effect of item depth

60 mm mortar
Depth of 50 cm (0.5 m)

60 mm mortar
Depth of 20 cm (0.2 m)

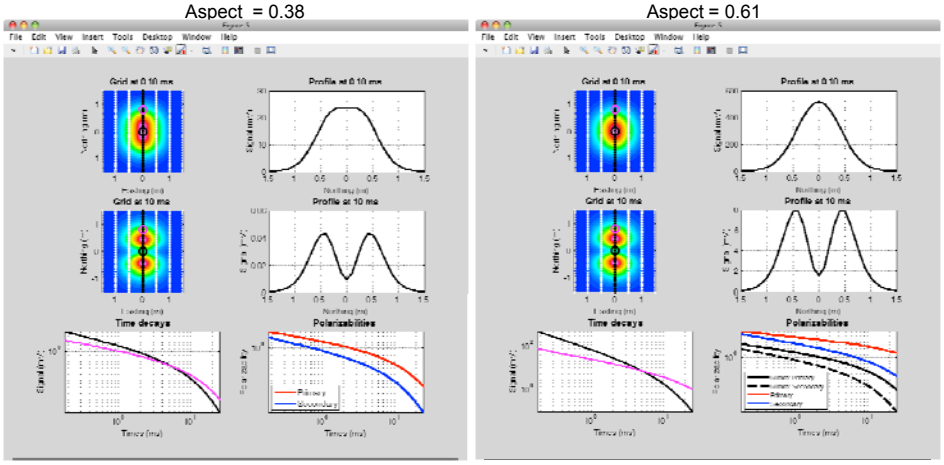


Note the change in spatial extent and amplitude of the data

Effect of item shape

60 mm mortar
Aspect = 0.38

105 mm projectile
Aspect = 0.61

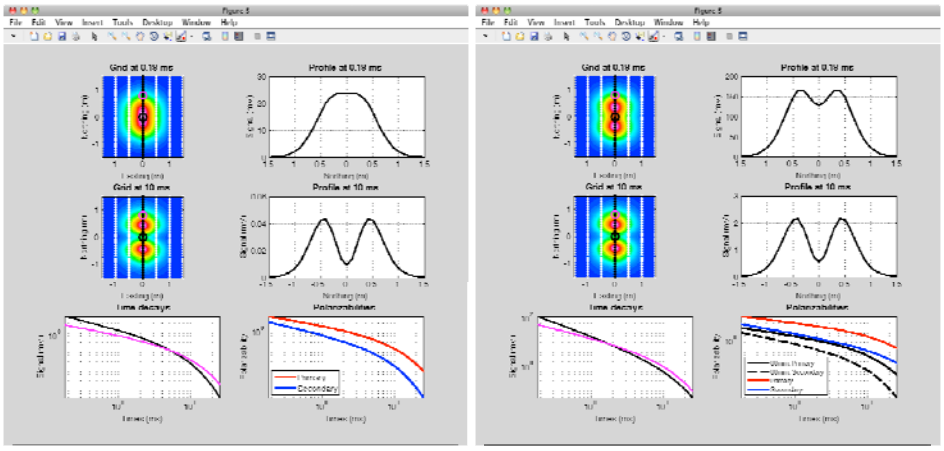


Lower aspect at early time results in sharper anomaly peak

Effect of item shape

60 mm mortar
Aspect = 0.38

Stokes mortar
Aspect = 0.21

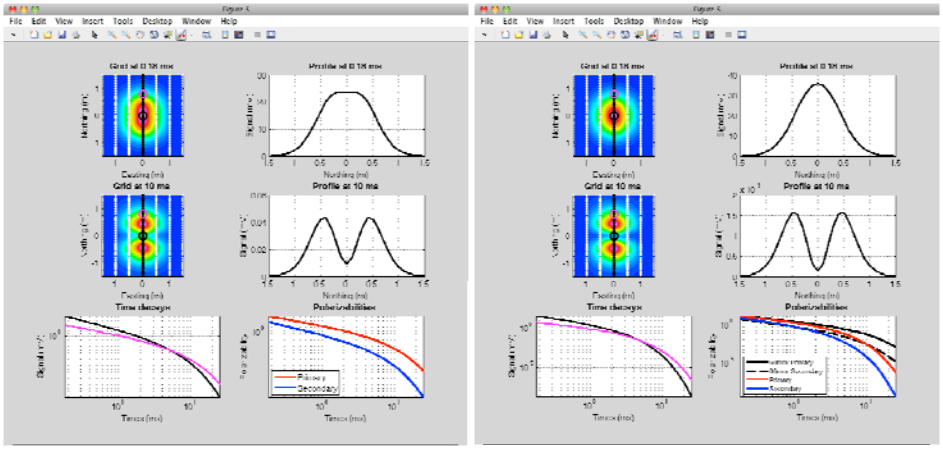


Higher aspect at early time results in double humped anomaly

Effect of item decay behavior

60 mm mortar
Time-decay = 5.1 ms

Thinner walled item
Time-decay = 2 ms

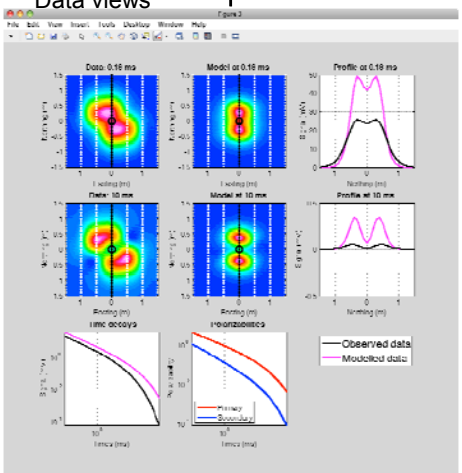


Note the more rapid decrease in late time-data with the faster decay rate

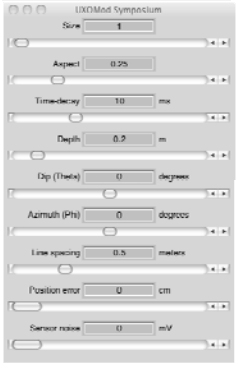
Parameter extraction demonstration

Data constrains parameters

Data views



Model parameters



Polarization parameters

Depth and orientation

Survey parameters

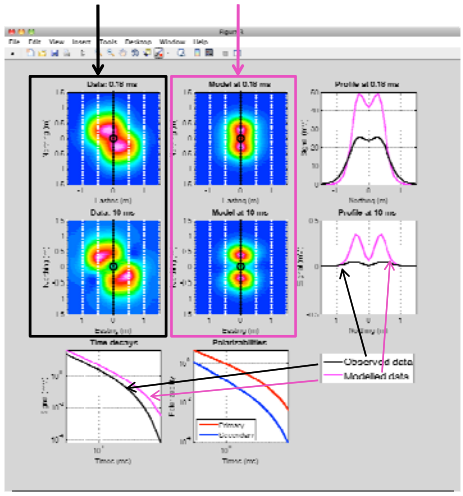
Layout of the data view

Observed data

Modeled data

Layout very similar to forward modeling data-view with the addition of a column for observed data

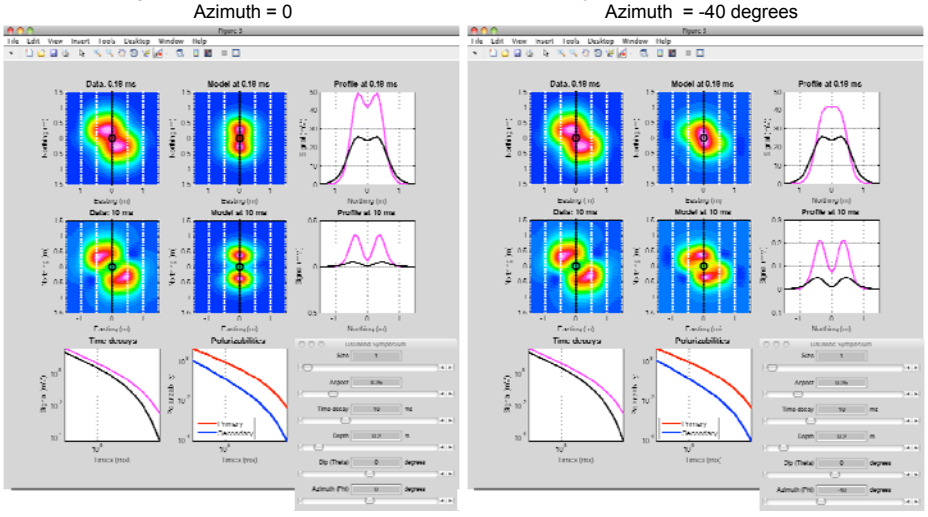
Objective is to change the model parameters until the observed and modeled data agree as closely as possible



Adjust orientation

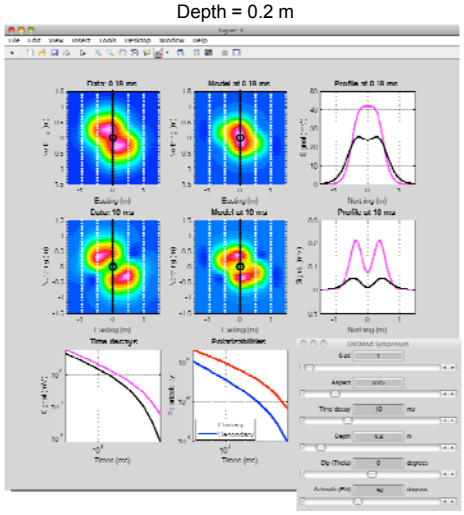
Original model parameters
Azimuth = 0

Adjusted model parameters
Azimuth = -40 degrees

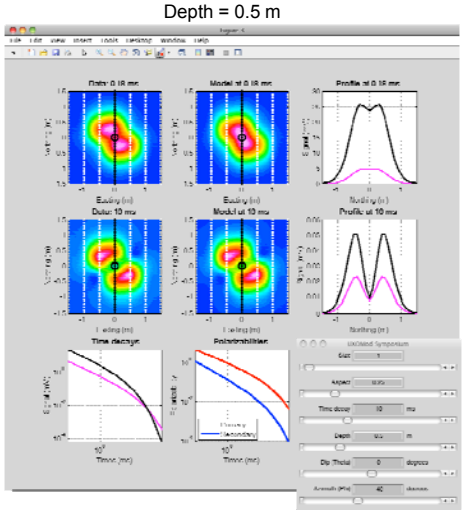


Adjust depth

Model from last step
Depth = 0.2 m



Adjusted model parameters
Depth = 0.5 m



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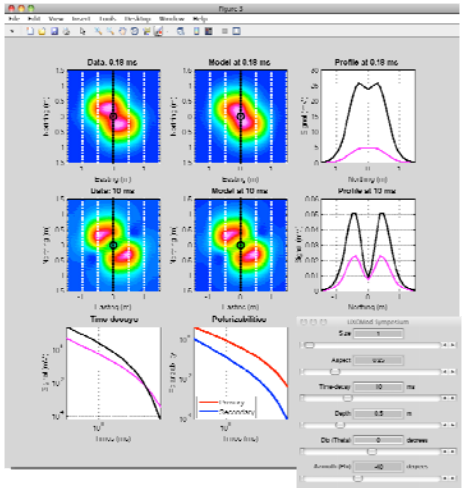
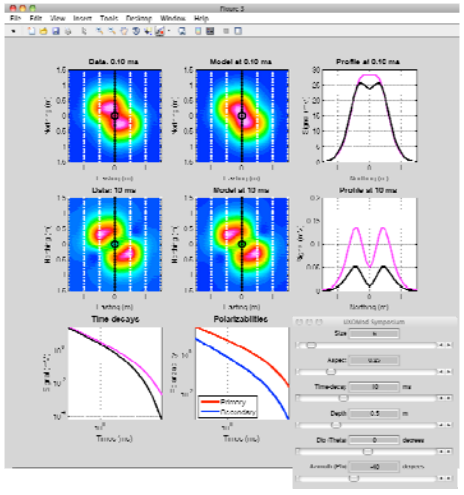
Adjust size

Model from last step
Size = 1



Adjusted model parameters
Size = 6



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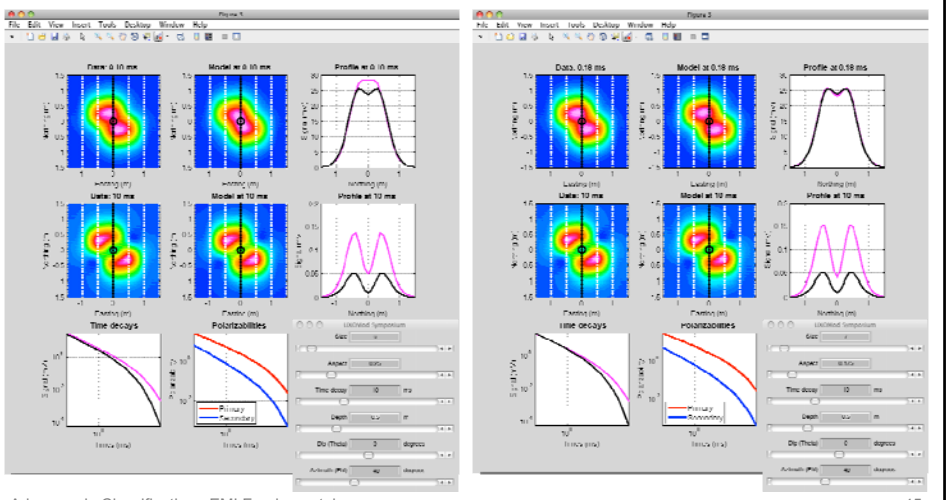
Adjust aspect (and size a little)

Model from last step
Aspect = 0.25

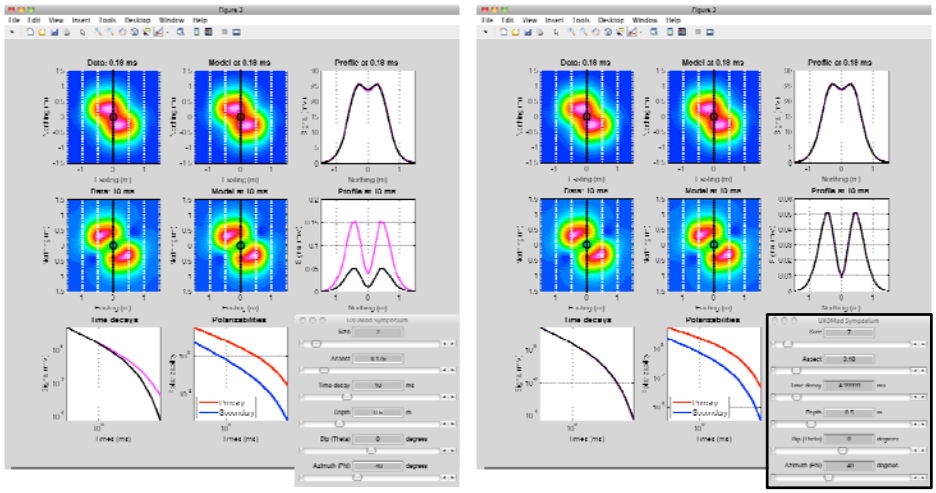
Adjusted model parameters
Size = 6



Adjust time-decay
(and we're done)

Model from last step
Decay = 10 ms

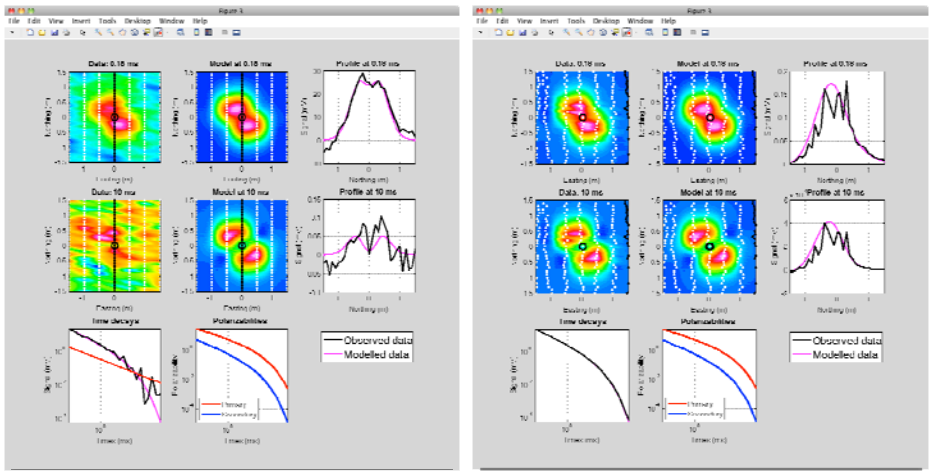
Final model parameters
Decay = 5.0 ms



Parameter extraction from noisy data

Model of sensor noise
2 mV (at first time-channel)

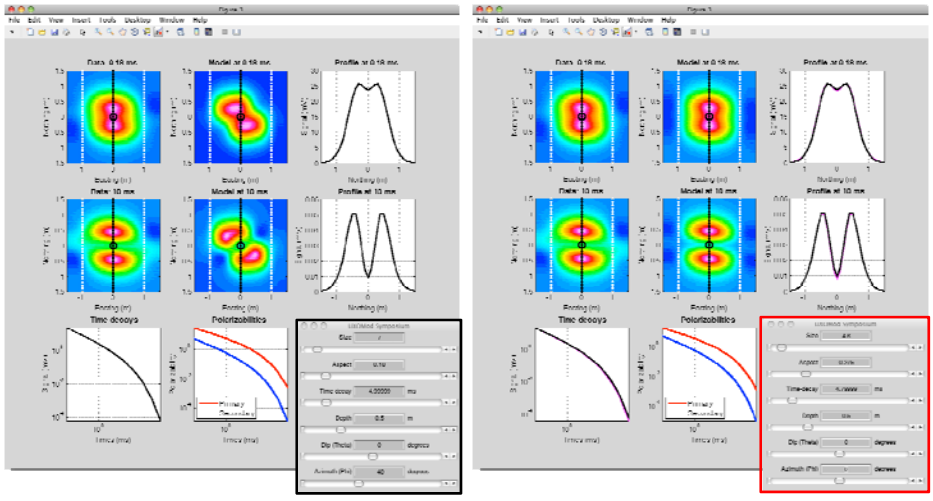
Effect of position errors
4 cm position error



Effect of data density

Original inversion model

Modified inversion model
Smaller and more symmetric



Summary

- EMI sensor data holds information about target's size, shape, thickness and material composition
- Polarizabilities along target's principal axis directions fully characterize EMI response
  - Basis for classification
- Target's principal axis polarizabilities are determined by mathematically inverting EMI data collected over target
  - Requires excitation of target and observation of response from many directions
  - Ability to constrain polarization tensor parameters depends on quality, density and diversity of collected data

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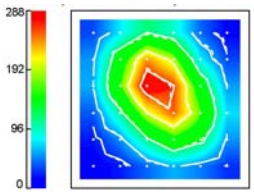
Stages in the Classification Process

1. Acquire EMI data over target



2. Invert data using dipole model and extract target features

Next Module

3. Classify target using decision rules applied to target features

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Classification with EM61 Data

Dr. Dean Keiswetter

ESTCP

Outline

- Classification Process
  - Methods
  - Product
  - Assessment
- EM61 Datasets
  - Elements of a database
  - Analysis environment & flow
  - Noise issues & problems
  - Data requirement summary
  - Example #1: Aberdeen Proving Ground
  - Example #1: San Luis Obispo
- Concluding comments

Classification Objective

We want…

(a) to **identify those anomalies that are definitely clutter (they cannot possibly be UXO)** at the site

(b) a principled process that results in a decision

This entire process is not magic…it must make sense, be physically inspired, and be documented

Advances in Classification - Classification with EM61 Data 3

How do we classify?

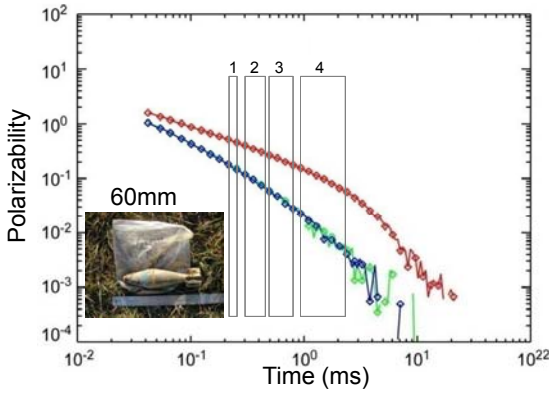
Visually, we use physical attributes such as size & shape

Because we cannot see buried objects, we must rely on attributes determined from geophysical data

Advances in Classification - Classification with EM61 Data 4

How do we classify?

The attributes that we use are based on the intrinsic polarizabilities or measured decay



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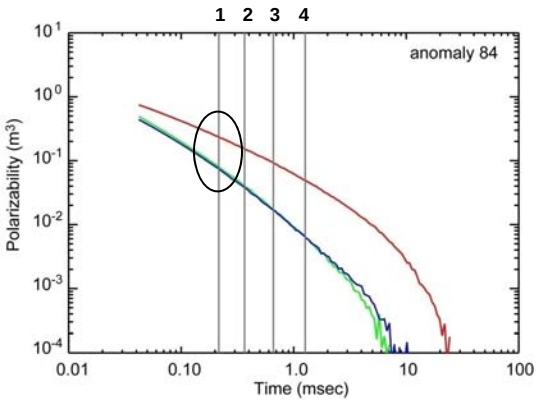
EM61 Target Attributes



Based on polarizabilities (βs) at the 4 EM61 time gates

Size attribute
Size $\propto \sqrt[3]{\Sigma\beta}$ (gate 1)

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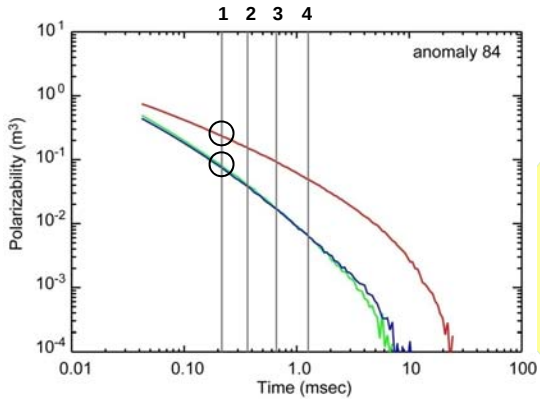
EM61 Target Attributes



Based on polarizabilities (βs) at the 4 EM61 time gates

Shape attributes

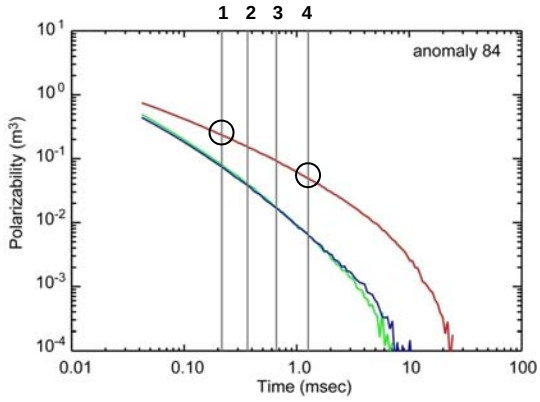
Symmetry = $(\beta_2-\beta_3)/\beta_1$

Aspect Ratio = $\frac{1}{2}(\beta_{2+}\beta_3)/\beta_1$

(usually gate 1)

Advances in Classification - Classification with EM61 Data 7

EM61 Target Attributes



Based on polarizabilities (βs) at the 4 EM61 time gates

Decay attribute

Decay = $\beta_1(4)/\beta_1(1)$

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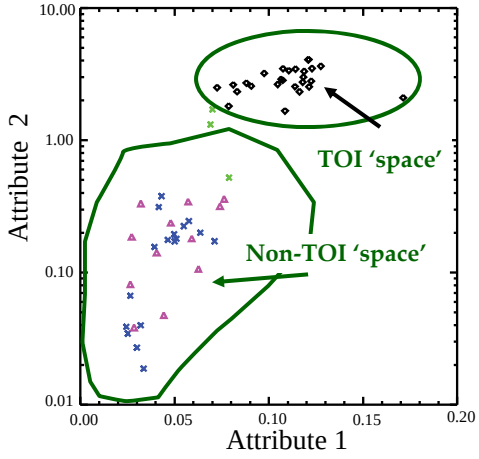
Classification Cartoon

Given attributes for a site with a single munitions item

General Process:

1) Visualize attributes
2) Obtain labels (e.g., ground truth information)
3) Establish boundaries – *this is the classification piece*

It can be this easy…if the features are separable



Remember the goal: identify anomalies that are not UXO

Advances in Classification - Classification with EM61 Data 9

EM61 Sensor & Data Collection

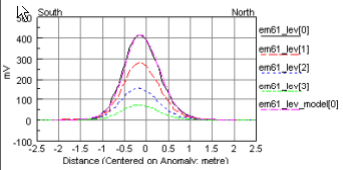
The work horse in the UXO EMI surveying industry…

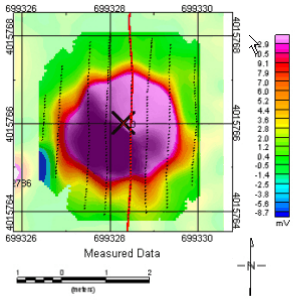
Designed and manufactured by Geonics Limited

- Produced since 1993
- Sold in 15 countries
- Number of sensors ~500

Advances in Classification - Classification with EM61 Data 10

Maps = EMI + GPS + Orientation





Spatial registration…

Sensor data…

Orientation data…

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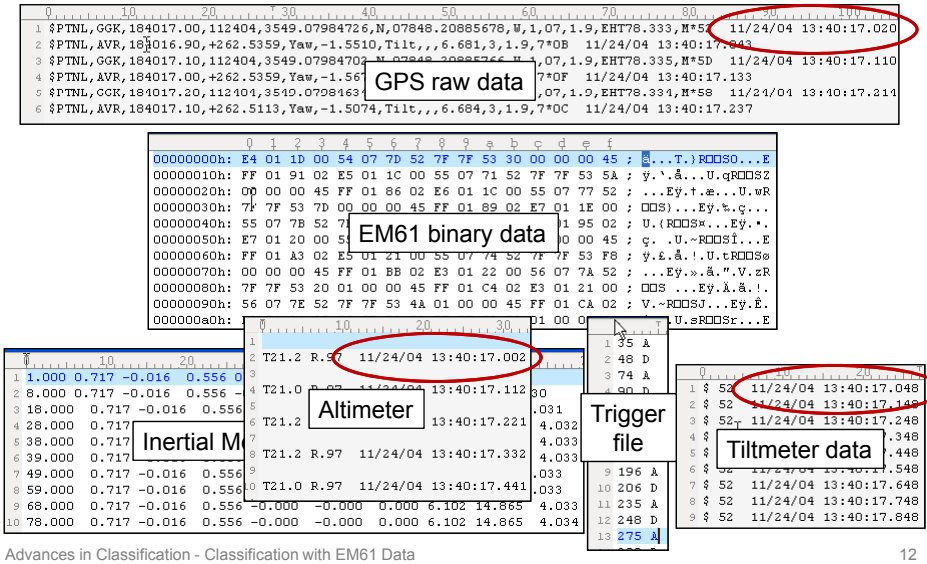
Geo-registered Data Inputs



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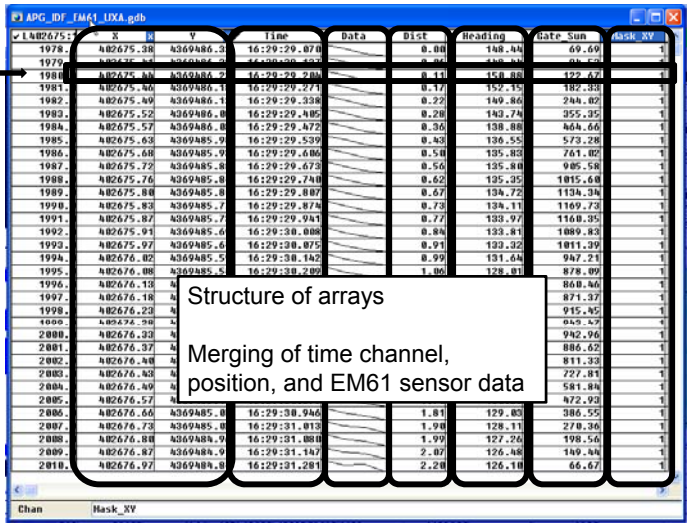
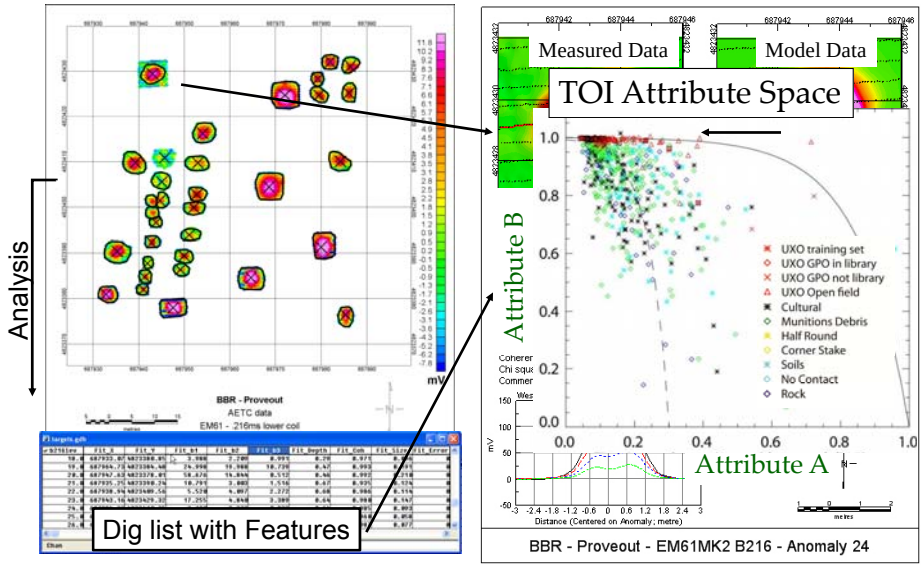
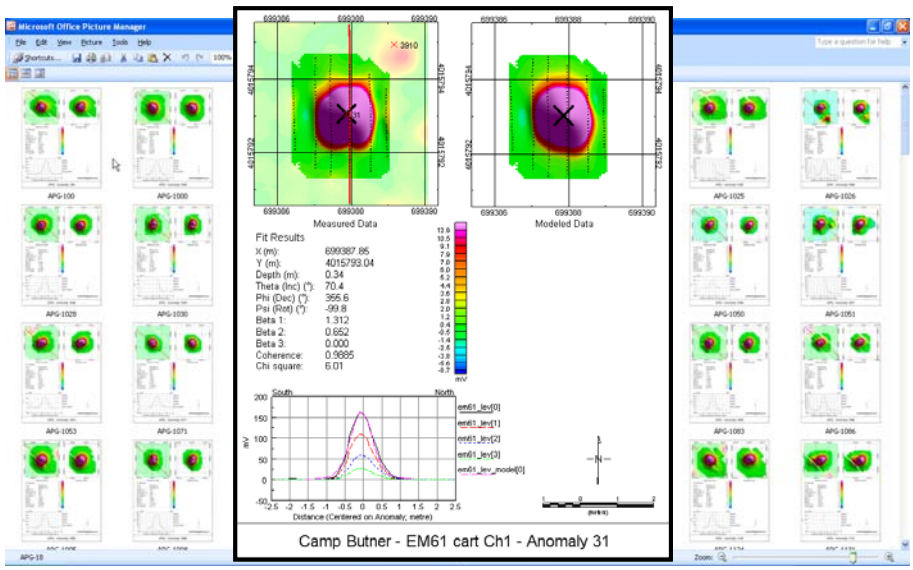
Georegistered Database



Process Overview



Documentation Goal



Prioritized Dig List

The Classification Product

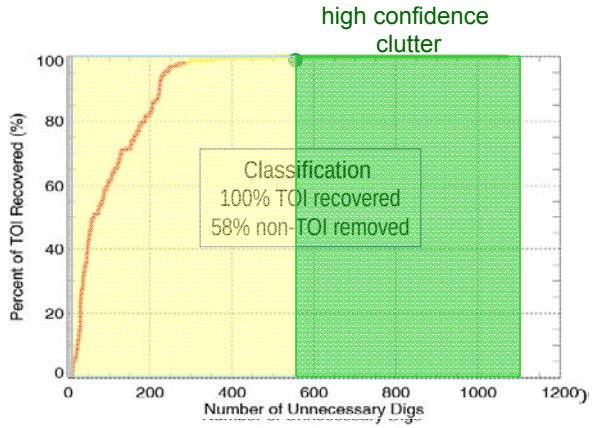
Rank based on the probability that the anomaly is clutter

	Target ID #	Rank	Category	Overlaps
Do not dig	438	1	Can Analyze: Likely Clutter	0
	23	2	Can Analyze: Likely Clutter	0
	5	3	Can Analyze: Likely Clutter	1
Dig Threshold →	694	...	Can Analyze: Cannot Decide	1
	4	...	Can Analyze: Cannot Decide	0
	305	...	Can Analyze: Cannot Decide	2
	303	...	Can Analyze: Cannot Decide	0
Dig	66	...	Can Analyze: Likely Munition	0
	56	...	Can Analyze: Likely Munition	0
	10	1313	Can Analyze: Likely Munition	0
	1300	NA	Cannot Analyze	2
	222	NA	Cannot Analyze	1
	37	NA	Cannot Analyze	0

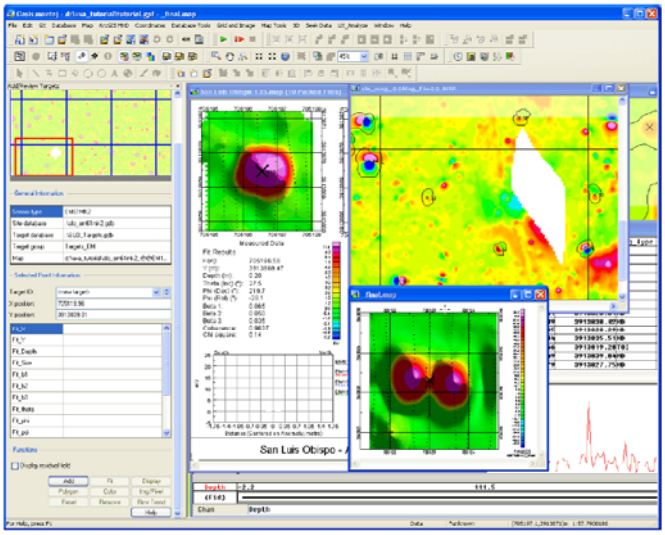
Once prioritized, establishing the dig threshold is critical

Performance Assessment

Receiver Operating Characteristic Curve
(only exists if all detected targets are removed)

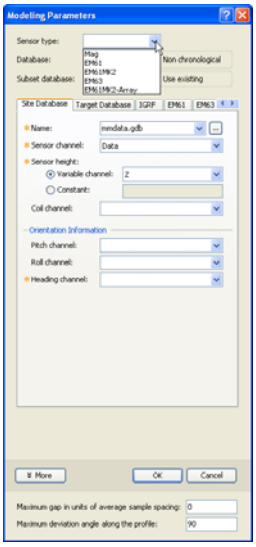


Data Analysis Environment



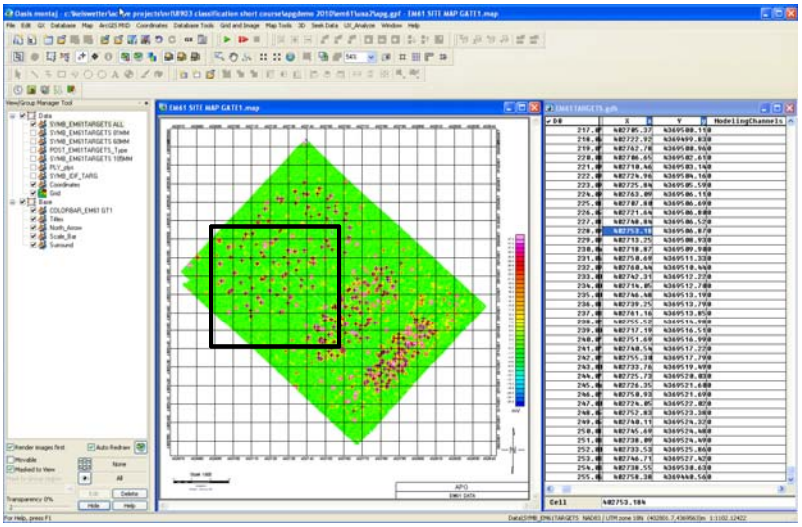
Oasis montaj
- High performance database
- Advanced data processing
- Dynamic linking (maps, data, profiles, etc.)
- Professional map production
- Audit trail

Reconnaissance Surveys (dynamic)

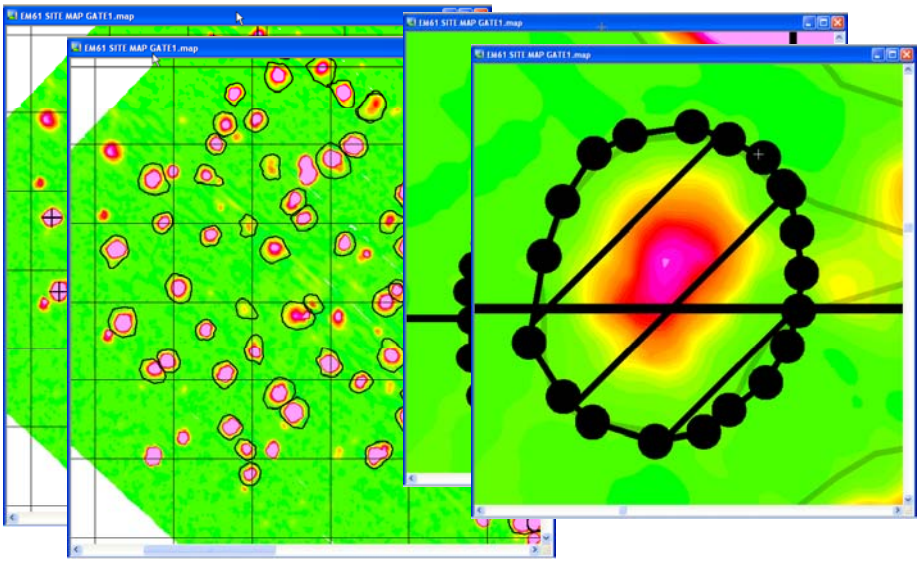


EM61 Data from APG

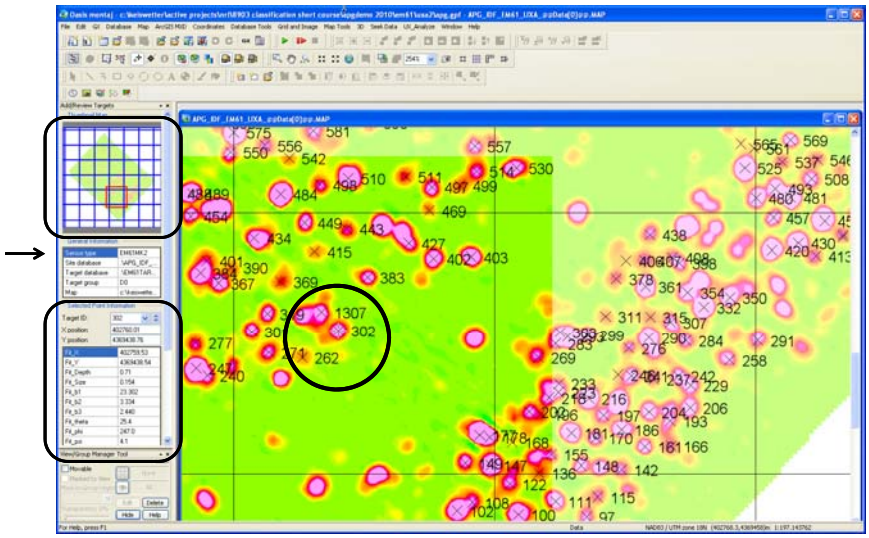
UXO
60mm
81mm
105mm



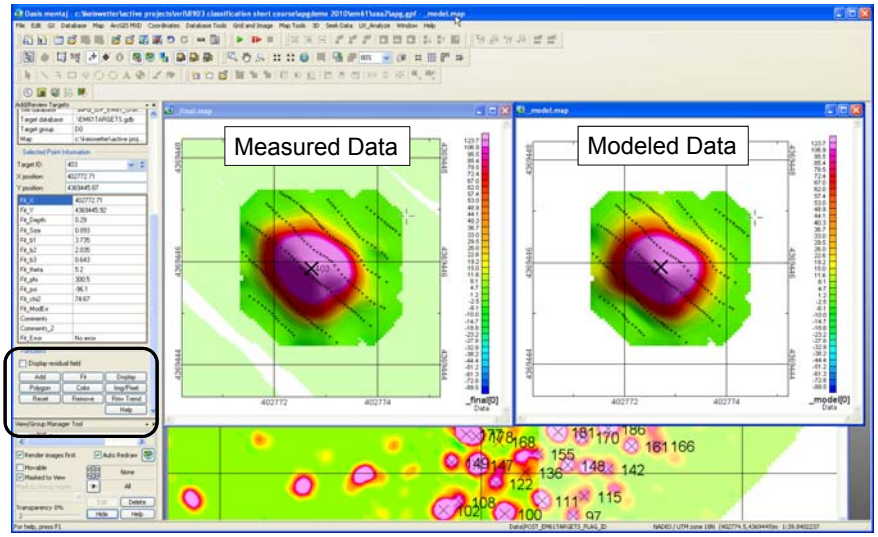
Isolating Each Anomaly



Interactive Modeling



Interactive Modeling



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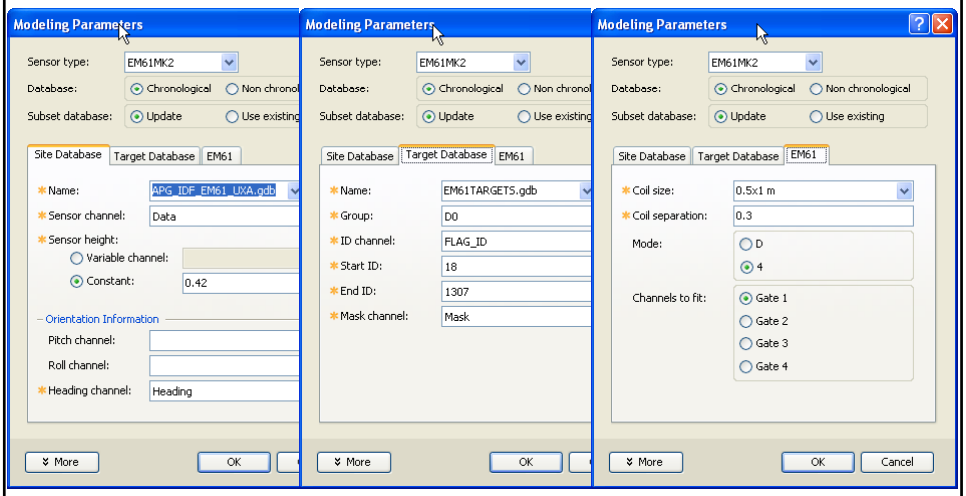
Batch Model



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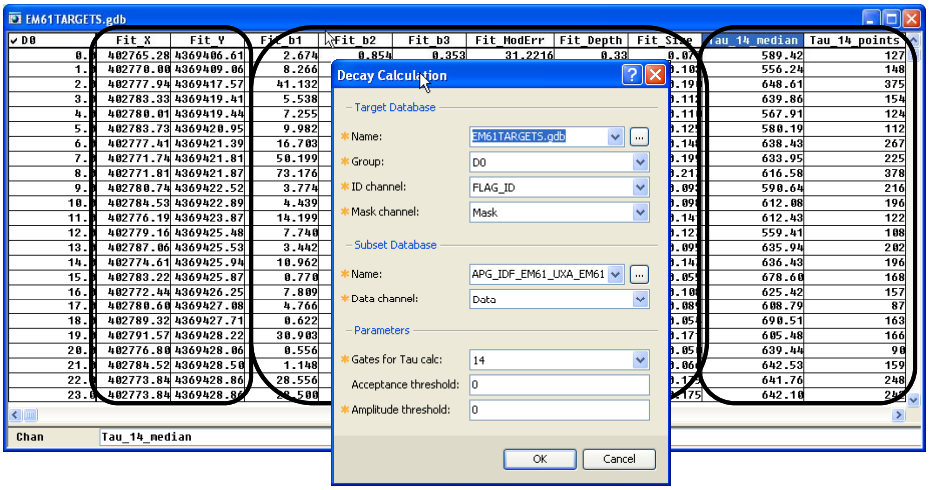
Target list with Attributes



EM61 Attribute Characteristics at APG

Three types of UXO: 60mm, 81mm, & 105mm

	60mm			81mm			105mm		
	median	mean	std dev	median	mean	std dev	median	mean	std dev
Intrinsic size	2	36	265	4	9	15	8	20	30
Model error	17	21	13	14	18	10	15	18	11
Decay rate	639	643	34	633	627	35	637	633	27

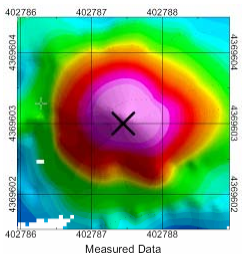
	60mm			81mm			105mm		
	median	mean	std dev	median	mean	std dev	median	mean	std dev
Intrinsic size	2	36	265	4	9	15	8	20	30
Model error	17	21	13	14	18	10	15	18	11
Decay rate	639	643	34	633	627	35	637	633	27

	60mm			81mm			105mm		
	median	mean	std dev	median	mean	std dev	median	mean	std dev
Intrinsic size	2	36	265	4	9	15	8	20	30
Model error	17	21	13	14	18	10	15	18	11
Decay rate	639	643	34	633	627	35	637	633	27

These intrinsic polarizabilities do not cluster…

For each Anomaly: Can we Classify based on Polarizations?

Measured

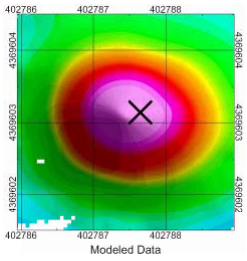


GOOD ENOUGH?

Fit Results

X (m):	402787.65
Y (m):	4369603.14
Depth (m):	0.85
Theta (Inc) (°):	-15.9
Phi (Dec) (°):	276.4
Psi (Rot) (°):	154.7
Beta 1:	1.628
Beta 2:	0.590
Beta 3:	0.928
Coherence:	0.981
Chi square:	0.2
Comments:	105mm M456 HEAT

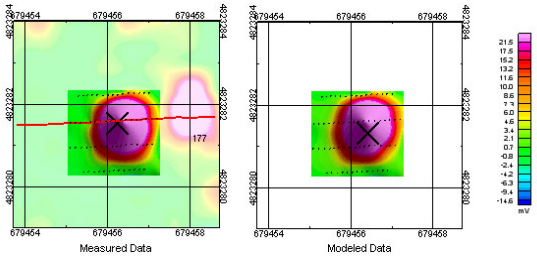
Model



Forward models suggest that a tremendous amount of information is contained in our model – but is the anomaly in question good enough?

Model Match Fit Quality

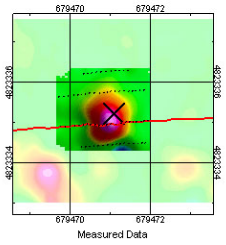
- Fit quality is determined by the mismatch between the data and dipole model fit to the data
  - ♦ Reflects ability of data quality to support inversion and estimation of target attributes for classification



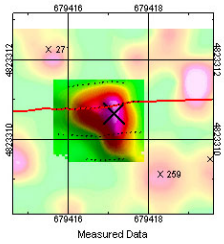
Well resolved anomaly with good dipole fit quality (5% fit error)

EM61 (gate 1) data over 2.75" rocket warhead at Badlands Bombing Range

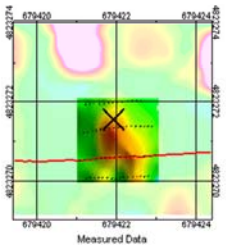
Parameter Extraction Issues



Line spacing does not provide adequate sampling of the intrinsic polarizabilities



Overlapping signals



Weak signal (low SNR)

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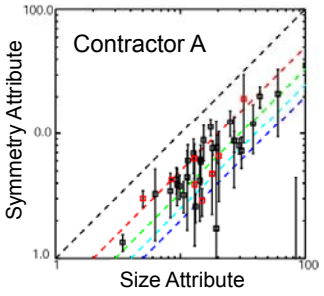
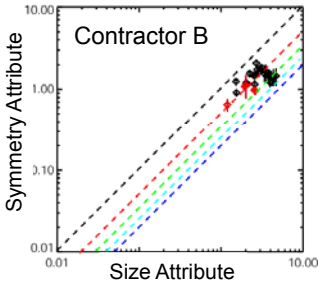
Survey Data Quality

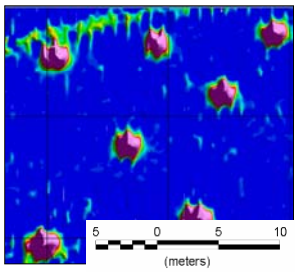
Good survey quality control is important for classification

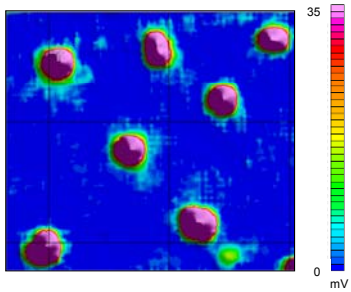
Same:
- site
- buried objects
- sensor

Different:
- signatures
- repeatability
- classification









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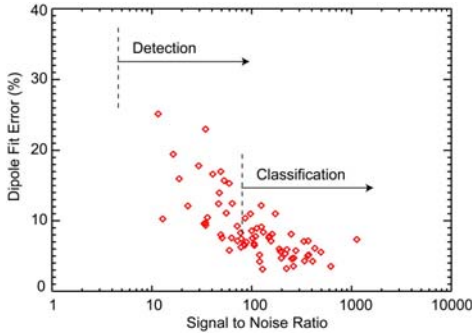
SNR Requirements

Reliable estimation of target attributes (polarizabilities) requires very high quality data with dipole fit error less than 5-10%

SNR approaching 100 is required for classification, compared to ~5 for detection



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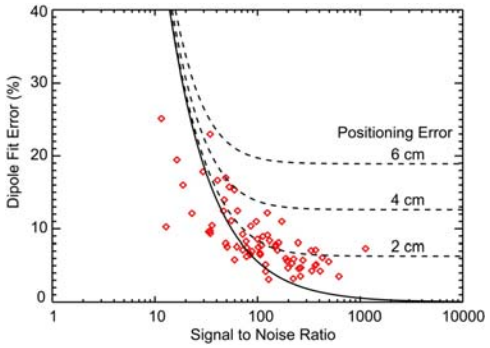
Positioning Errors

- Errors in recorded sensor locations corresponding to EM data can substantially increase dipole fit error
  - It is very hard to maintain survey geolocation at the accuracy level required to support reliable classification



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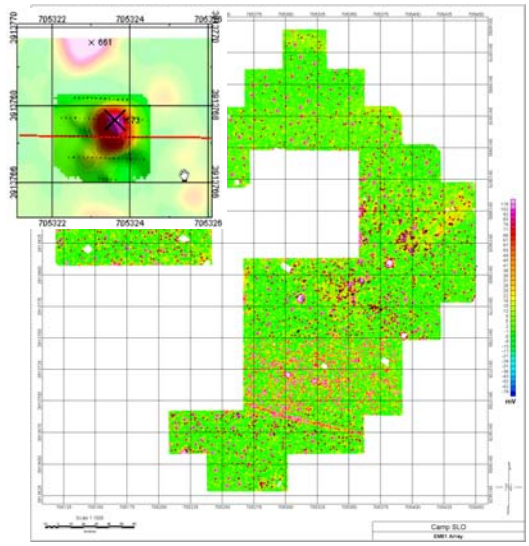
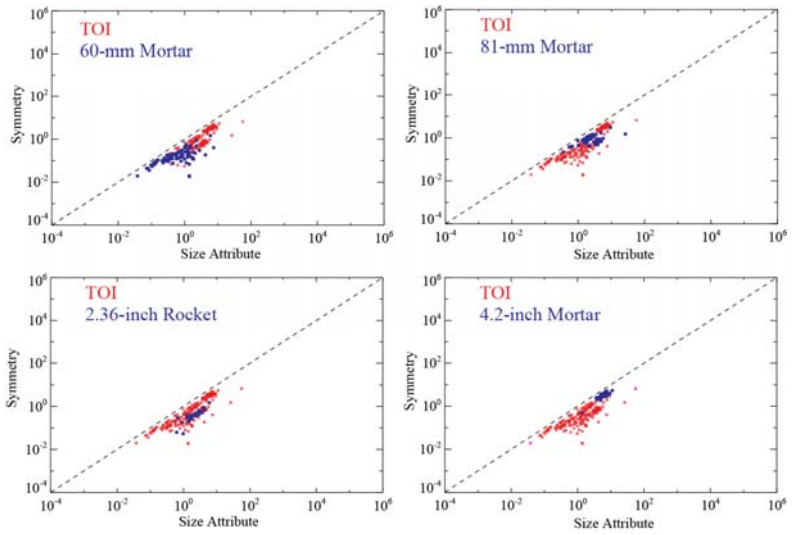
Data Requirement Summary

- Inversion requires accurately mapped survey data
  - ♦ Also requires sensor orientation and vertical position
- Data density and spatial extent must adequately sample the principal axis polarizabilities
- No overlapping signals
- SNR needed for classification > SNR needed to detect object

Camp SLO Demonstration



Attributes: size vs. symmetry



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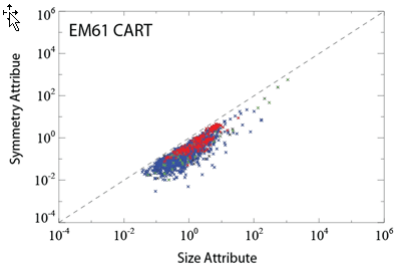
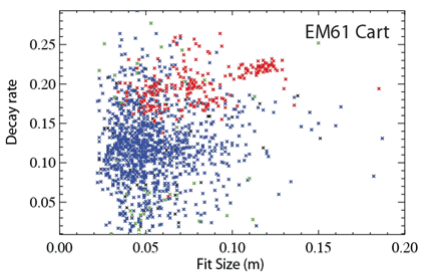
Attributes: UXO vs Clutter

size vs. symmetry



RED -- target of Interest
Blue -- munitions debris
Green -- cultural debris



size vs. decay

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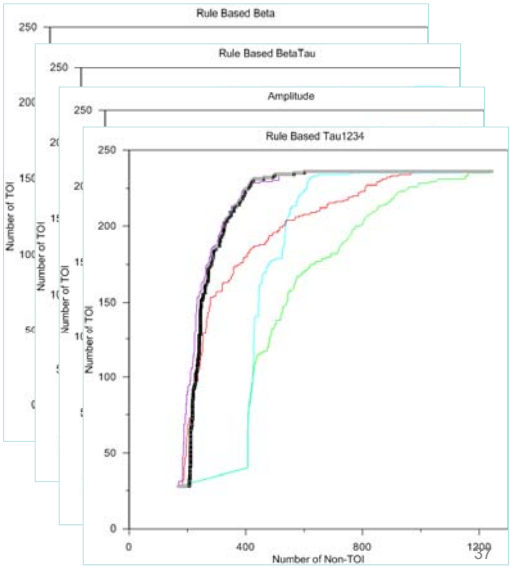
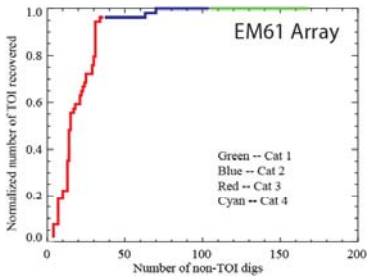
Classification Approaches…

- Intrinsic polarizations
- Intrinsic polarizations & Decay rate
- Amplitude
- Decay rate

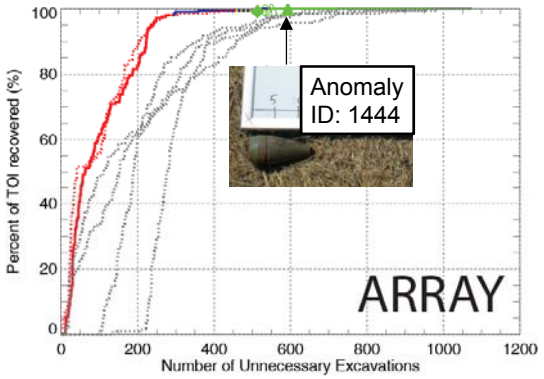


EM61 Cart Classification Performance

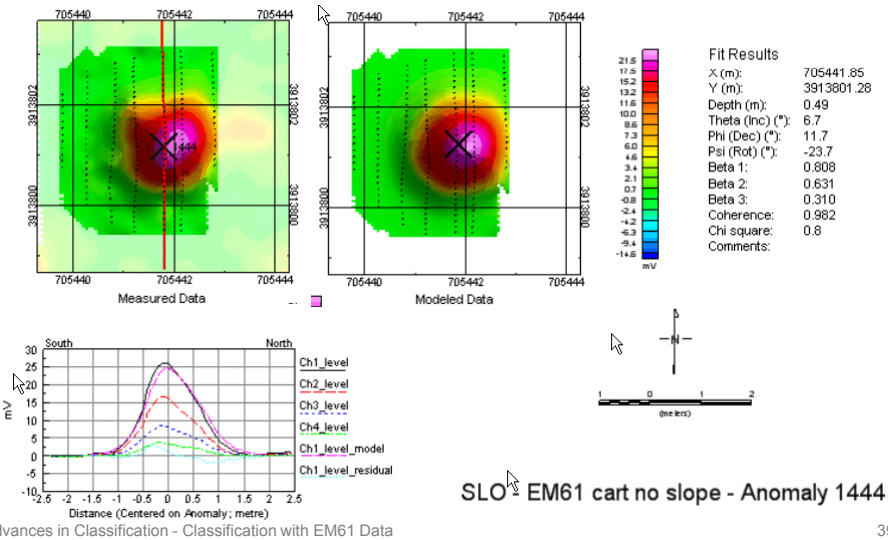
ROC based on Training Labels



False negative's stop dig point:
Analyst #1: none
Analyst #2: 1444

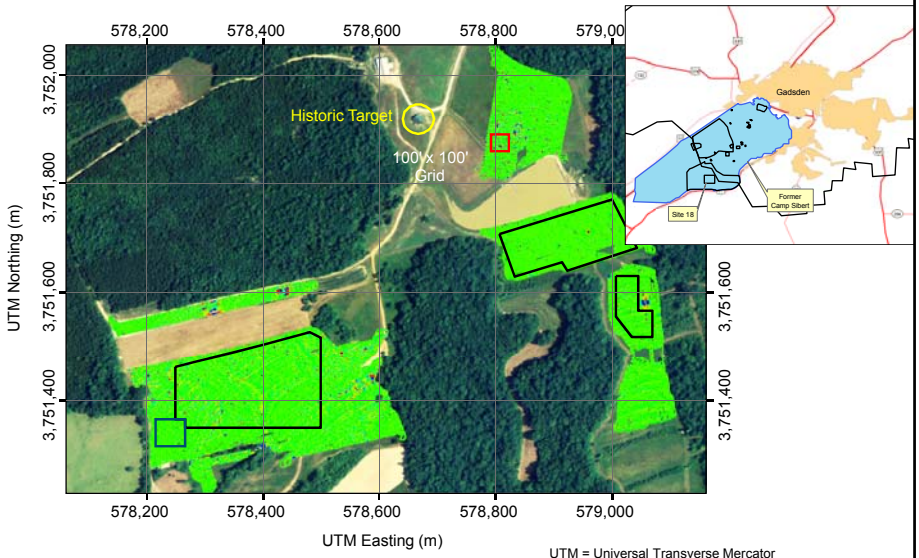


False Negative



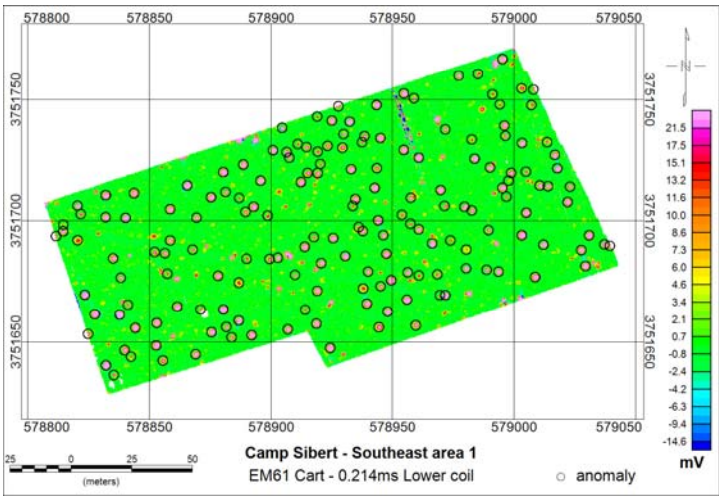
SLO EM61 cart no slope - Anomaly 1444

Camp Sibert, Alabama



UTM = Universal Transverse Mercator

EM61 Mk2 Data – Man Portable Cart



mV = milliVolt

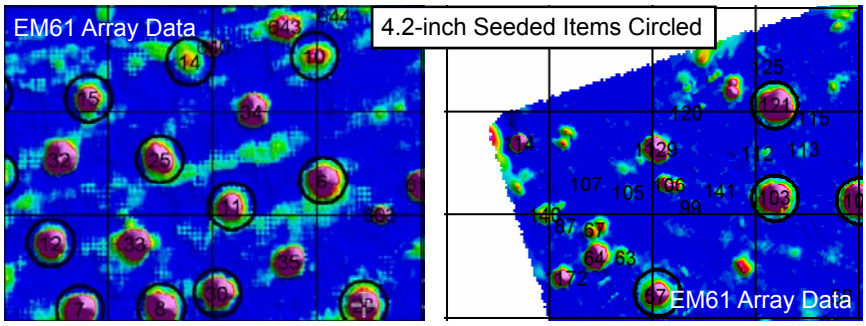
MTADS = Multi-sensor Towed Array Detection System
EM61 Mk2 sensors are products of Geonics Limited

Munitions and Clutter Classes

Data Analysis Objective

Discriminate 4.2-inch mortars from native clutter

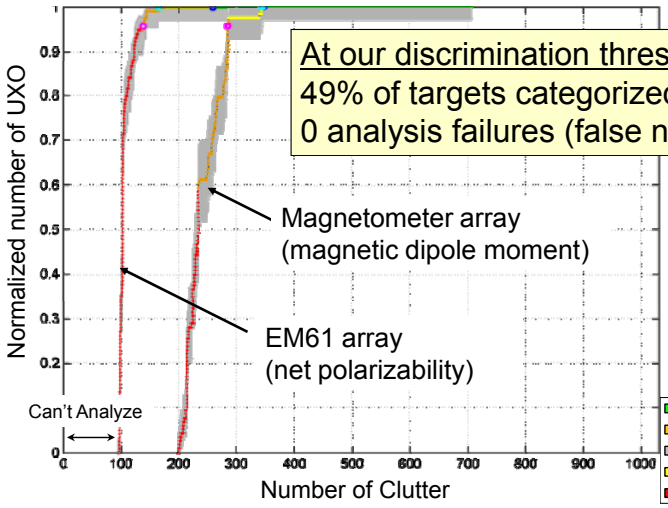
- Characterization (inversions)
- Classification (statistical classifier or canonical metrics)



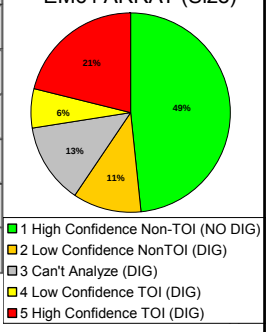
EM61 Mk2 Array Data Color Scale 0-50 milliVolts 10 meters grid lines

EM61 Mk2 sensors are products of Geonics Limited

Performance based on Size Estimates

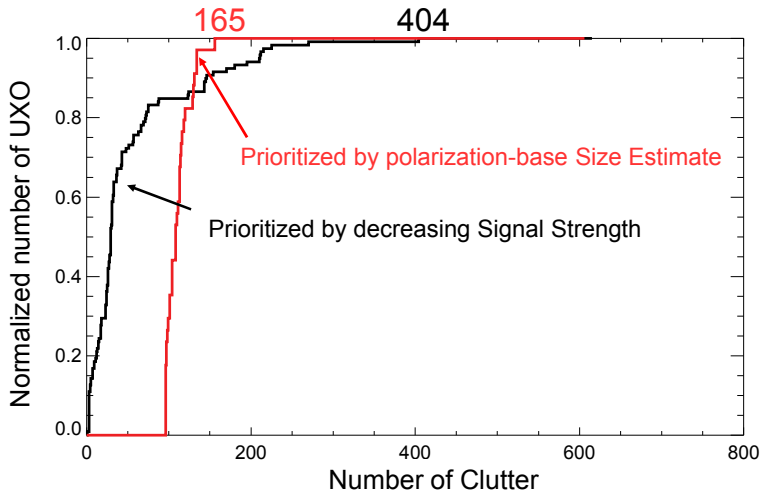


At our discrimination threshold
49% of targets categorized as Do Not Dig
0 analysis failures (false negative)



Performance Comparison

Signal Strength vs. Polarization-based Size



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Summary

Respectable classification results can be realized using EM61 data for some sites

Target size and decay rate were the best attributes for the Camp Sibert and Camp San Luis Obispo demonstrations

Classification performance is typically poor if target shape estimates are required from survey mode EM61 data

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Advanced EMI Sensors

Thomas Bell

ESTCP

Module Outline

- Limitations of conventional sensor technology
  - Basic design considerations for advanced sensors
- Advanced sensor systems
- Performance
  - Principal axis polarizabilities
  - Classification performance

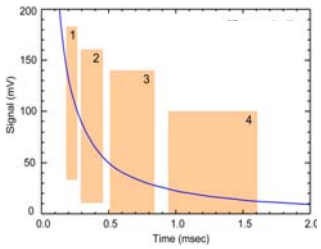
The Classification Problem

- Classification performance using conventional EMI sensor technology is limited by two primary factors
  - The eddy current decay cycle is not fully captured
  - Multi-cm positioning errors inherent to field survey work compromise the accuracy of dipole inversion and estimation of target attributes
- New UXO-specific technologies which avoid these problems are being developed and tested under SERDP and ESTCP

Conventional Sensor Technology

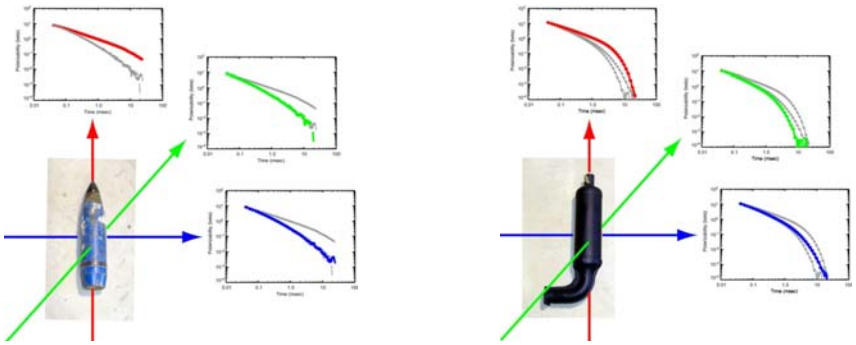
Geonics EM61 Mk2

- Industry standard for geophysical surveys in munitions response
  - Eddy current decay signal over four time gates centered at 216, 366, 660, and 1266 µsec
- Best UXO detection performance at 1994-96 Jefferson Proving Ground technology demonstrations
- Efforts to process survey data for shape-based target classification largely unsuccessful



Target Features from EM Data

- Intrinsic responses (polarizabilities) along target's principal axis directions fully characterize EMI signal
  - Requires illumination of target and observation of response from all directions



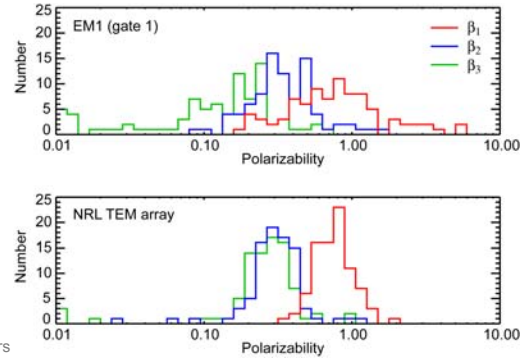
Target Features from EM Data

- Intrinsic responses (polarizabilities) along target's principal axis directions fully characterize EMI signal
  - Requires illumination of target and observation of response from all directions
  - Cannot be accurately determined from conventional survey quality EM data because of positioning uncertainty
  - Advanced sensors use fixed coil arrays for precise positioning of sensor readings to allow accurate calculation of principal axis polarizabilities

Camp SLO Example

- Significant overlap in primary and secondary polarizabilities from EM61 survey data compared to advanced sensors
  - Target size & shape attributes washed out
- Target size, symmetry and aspect ratio resolved with data from advanced sensors

60mm mortars – 2009 classification demo at Camp San Luis Obispo

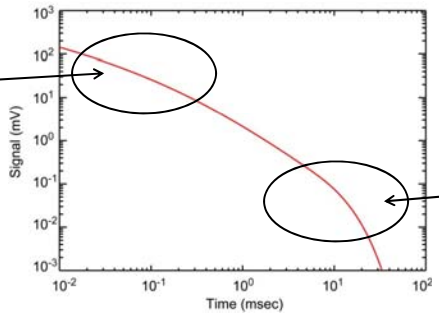


Target Features from EM Data

- Intrinsic responses (polarizabilities) along target's principal axis directions fully characterize EMI signal
  - Determined by physical properties of the target
  - Eddy current decay times from 10's of μsec to 10's of msec

Early time

Eddy currents at surface, object's size and shape determine the response.

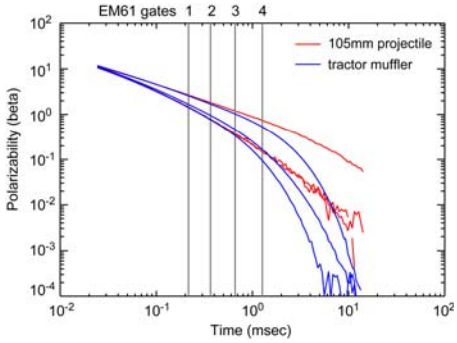


Late time

Eddy currents diffused through object, response is determined by wall thickness.

Eddy Current Signal Decay

- Intrinsic responses (polarizabilities) along target's principal axis directions fully characterize EMI signal
  - Determined by physical properties of the target
  - Objects with roughly comparable size and shape can have similar early time responses but different late time responses



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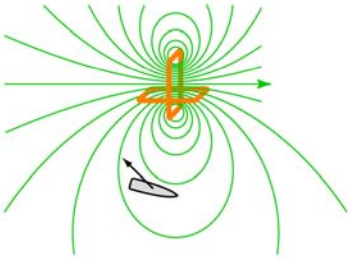
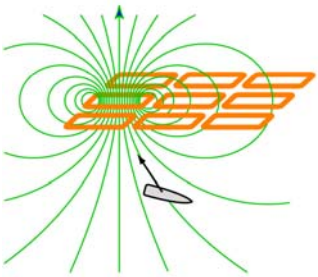
Advanced Sensor Configurations

Multi-axis sensors

Target directly underneath sees vertical primary field with vertical axis coil or horizontal field with horizontal axis coil.





Single axis arrays

Target directly underneath vertical axis coil sees vertical primary field, oblique fields for coils off to sides. Includes bi-static transmit/receive combinations.

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Survey vs. Cued ID Operation

- Classification using survey data from moving sensor arrays is challenging
  - Exciting target from different directions and observing response to late times takes time
  - Data density along survey lines suffers
- Most current systems use cued identification approach
  - Park sensor over previously flagged anomaly, collect data and move on to next anomaly
  - Several hundred targets per day possible

Advanced Sensor Systems

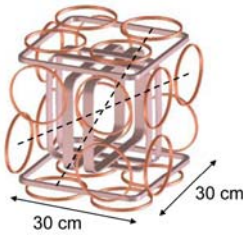
- Multi-axis sensor systems
  - BUD – Berkeley UXO Discriminator (Lawrence Berkeley Nat'l Lab)
  - MetalMapper (Geometrics, G&G Sciences, Snyder Geoscience)
  - ALLTEM (US Geological Survey)
  - EM63-3D Mk2 (Geonics)
- Single axis arrays
  - TEMTADS – Transient EM Towed Array Discrimination System (US Naval Research Lab, Nova Research, G&G Sciences, SAIC)
- Man-portable and handheld derivatives
  - Handheld BUD
  - Man-portable vector sensor (G&G, ERDC Hanover, Sky Research)
  - Man-portable and handheld TEMTADS

Berkeley UXO Discriminator (BUD)

- 3 orthogonal transmit coils (1 m square) – 8 receive coil pairs
  - 24 independent Tx/Rx measurements of transient response from 140 to 1400 μsec
- Survey mode (detection) or cued ID

Handheld BUD

- 3-axis transmit coils (30 cm square) – 10 receive coil pairs
  - Backpack electronics



Metal Mapper

- 3 orthogonal transmit coils, 7 multiaxis receive cubes
  - 69 Tx/Rx measurements of transient response
- Survey mode (detection) or cued ID
- Commercially available (Geometrics)

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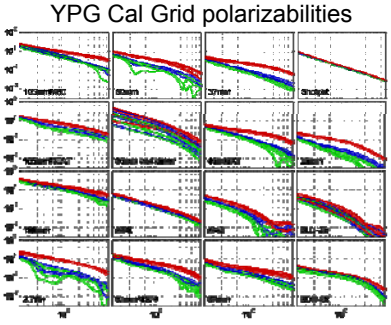
Man-Portable Vector (MPV) Sensor

- Metal Mapper technology
- Single axis transmit coil
  - 5 3-axis receive cubes
- Beacon positioning

YPG Cal Grid polarizabilities



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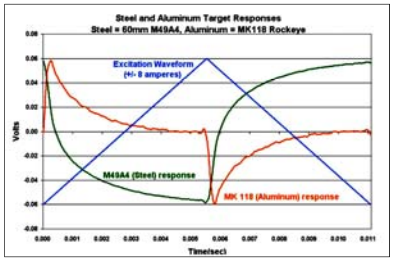
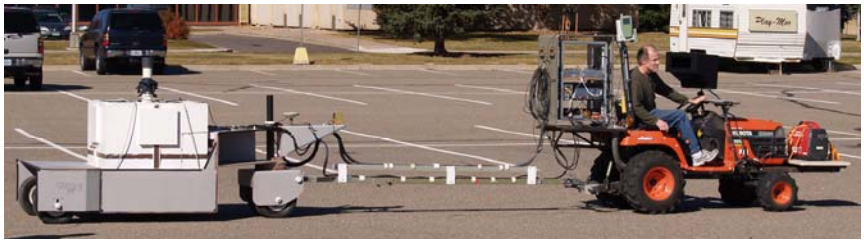
ALLTEM

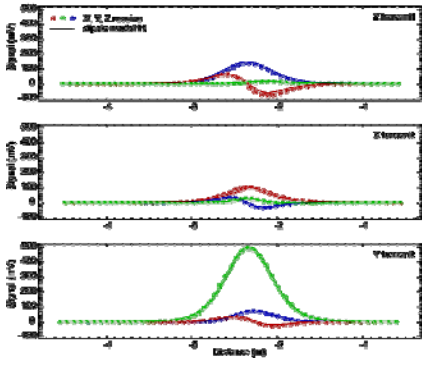
- CW traingular waveform switched between three orthogonal transmit coils
- 19 receiver coil configurations
- Survey mode operation for detection and classification





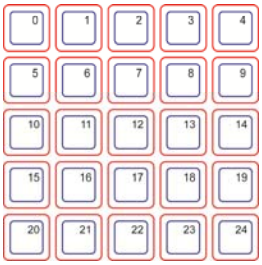
EM63-3D Mk2

- Three orthogonal transmit coils with multi-axis receive
- Survey mode detection/classification
  - Decay to 25 msec at 7.5 Hz base period, 7.3 msec at 30 Hz
- Commercially available (Geonics)



NRL TEM Array

- Transient EM Towed Array Discrimination System (TEMTADS)
- 2D array of 25 time domain EMI sensors, decay times from 0.04 to 25 msec
  - 325 unique transmit/receive combinations
  - Cued ID

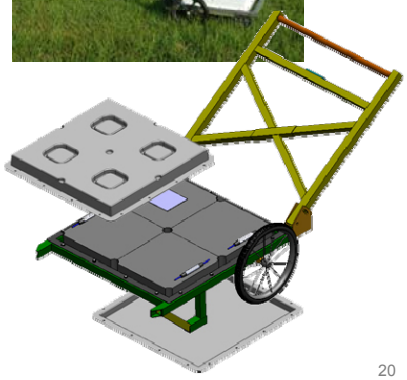


Advances in Classification - Advanced EMI Sensors 19

Man-Portable Array

- 2x2 element cart-mounted array
  - Backpack electronics
  - iPAQ controlled data logger

2009 prototype at Remington Woods



Advances in Classification - Advanced EMI Sensors 20

Handheld Sensor

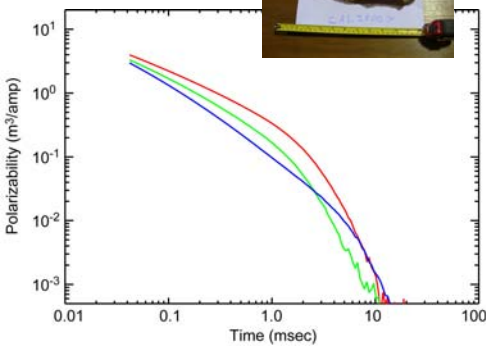
- Man-portable electronics and DAQ package
- Cued ID using grid template over target
  - IMU positioning in future

Advances in Classification - Advanced EMI Sensors 21

Principal Axis Polarizabilities

- Full 5x5 array

APG Cal Grid
D1 clutter

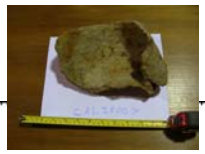


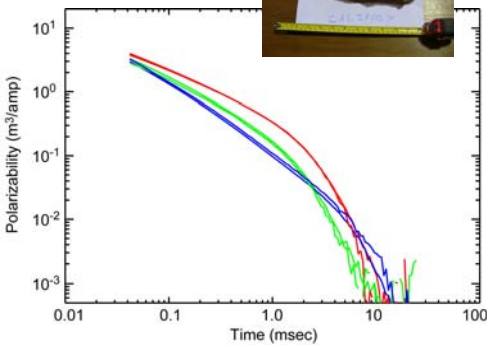
Advances in Classification - Advanced EMI Sensors 22

Principal Axis Polarizabilities

- Full 5x5 array
- 2x2 man-portable

APG Cal Grid
D1 clutter

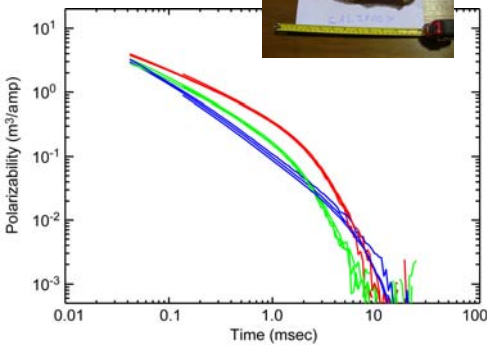




Principal Axis Polarizabilities

- Full 5x5 array
- 2x2 man-portable
- Handheld sensor

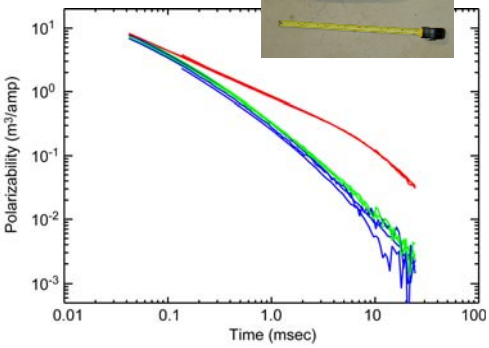
APG Cal Grid
D1 clutter



Principal Axis Polarizabilities

- Full 5x5 array
- 2x2 man-portable
- Handheld sensor

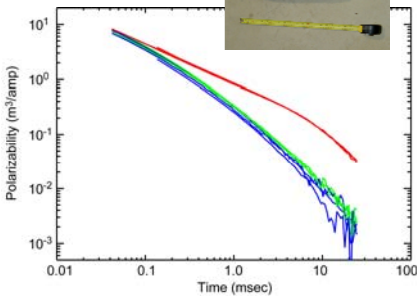
APG Cal Grid
K6 105 mm



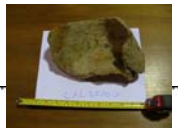
Advances in Classification - Advanced EMI Sensors 25

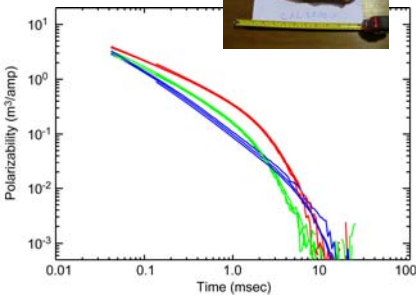
Polarizabilities → Classification

APG Cal Grid
K6 105 mm



APG Cal Grid
D1 clutter



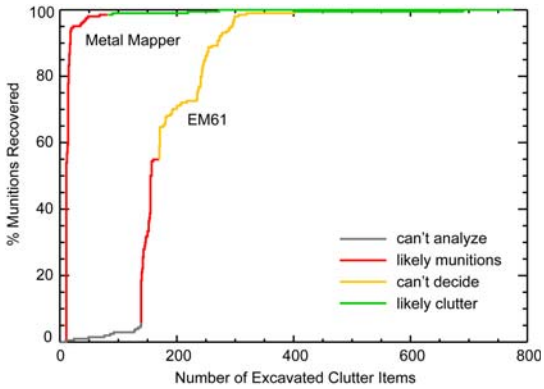


Advances in Classification - Advanced EMI Sensors 26

Classification Performance

Metal Mapper cued ID vs. EM61 survey

- Camp San Luis Obispo Classification Demonstration
- Common targets (204 munitions, 776 clutter items)



Advances in Classification - Advanced EMI Sensors 27

Summary

- Classification performance using conventional EMI sensor technology is limited by two primary factors
  - The eddy current decay cycle is not fully captured
  - Multi-cm positioning errors inherent to field survey work compromise the accuracy of dipole inversion and estimation of target attributes
- New UXO-specific technologies which avoid these problems are being developed and tested under SERDP and ESTCP
  - Results from technology demonstrations are very encouraging
    - Aberdeen & Yuma Proving Ground Standardized Test Sites
    - Former Camp Sibert, Camp San Luis Obispo, Camp Butner live site classification demonstrations

Advances in Classification - Advanced EMI Sensors 28

Classification with Advanced EMI Sensor Data

Dr. Dean Keiswetter

ESTCP

Outline

- *Review*
- Data analysis environment / processing overview
- Classification
  - Approach and features
  - Aberdeen Proving Ground
  - San Luis Obispo
- Multiple source situations
- Closing comments

Review: Factors Affecting Classification Performance with EM61 data

- Limited capability for target classification in survey mode
  - Analog smoothing distorts signal shape
  - Limited decay time coverage
  - Centimeter-level sensor positioning uncertainty degrades target parameter estimates
- Towed arrays have limited target illumination with transmitters operated simultaneously

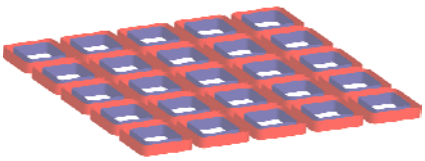
Advances in Classification - Classification with Advanced Sensors 3

Review: EMI Sensors designed for Classification

In order to observe the complete EM response pattern the object must be excited and measured from all directions

The new EMI technologies accomplish this with multi-axis coil sensors or single axis coil arrays

Multi-axis coil array



Single axis planar array

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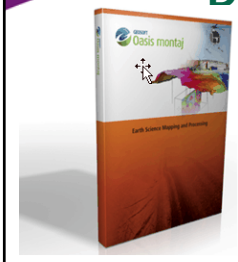
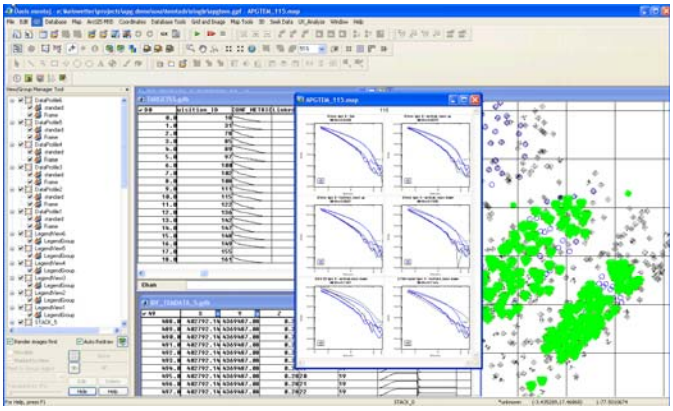
Review: Two vehicle-towed EMI sensors

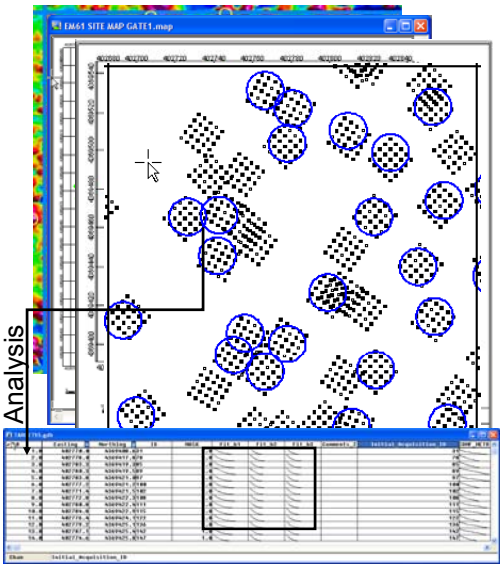
Data Analysis Environment



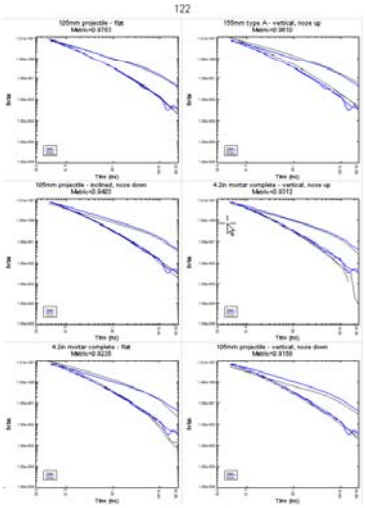


Oasis montaj
- High performance database
- Advanced data processing
- Dynamic linking (maps, data, profiles, etc.)
- Professional map production
- Audit trail

Analysis Flow



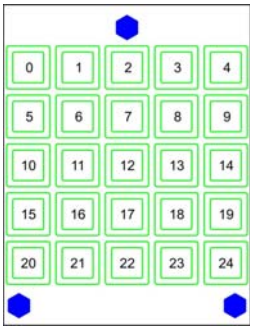
Intrinsic Polarizabilities

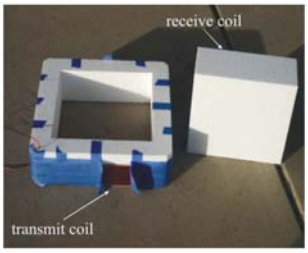


Advances in Classification - Classification with Advanced Sensors 7

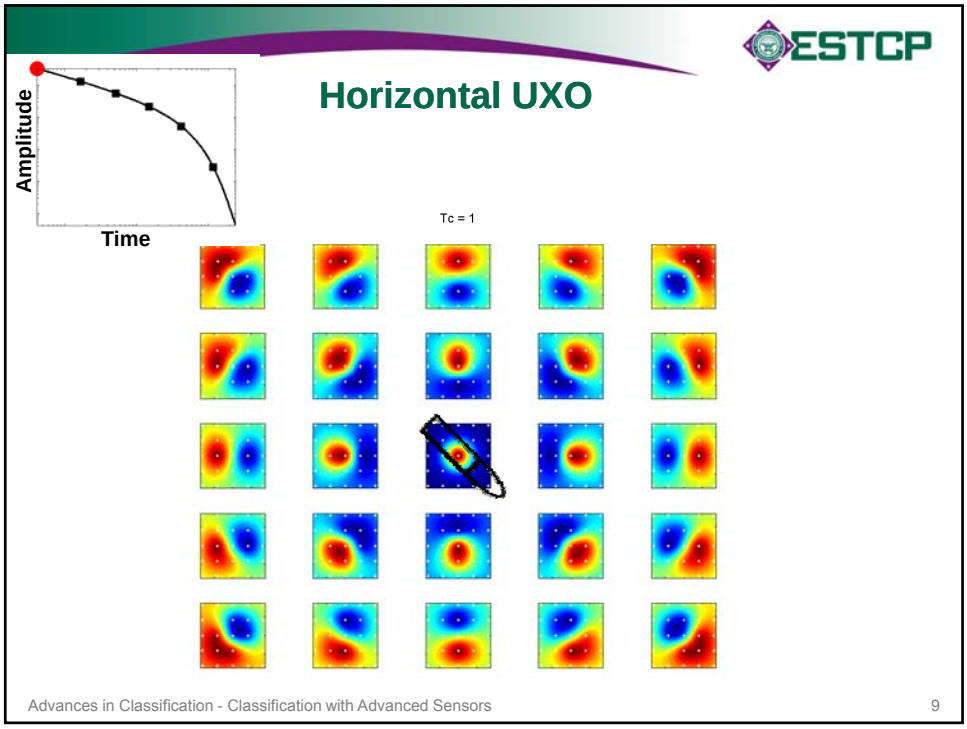
TEMTADS

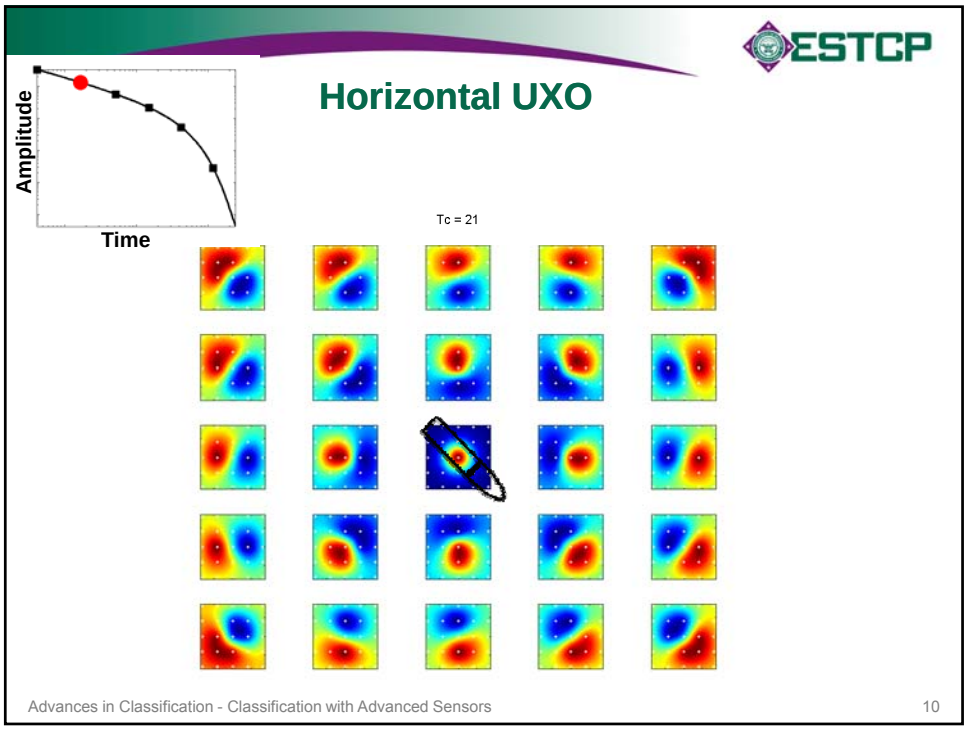
- 25 transmitters/25 receivers
  - ♦ Park over location estimated by previous survey
  - ♦ Fire transmitter 1, record on all 25 receivers
  - ♦ Fire transmitter 2, record on all receivers
  - ♦ and so on …





Advances in Classification - Classification with Advanced Sensors 8


ESTCP
Horizontal UXO
Amplitude
Time
Tc = 1
Advances in Classification - Classification with Advanced Sensors
9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Advances in Classification - Classification with Advanced Sensors
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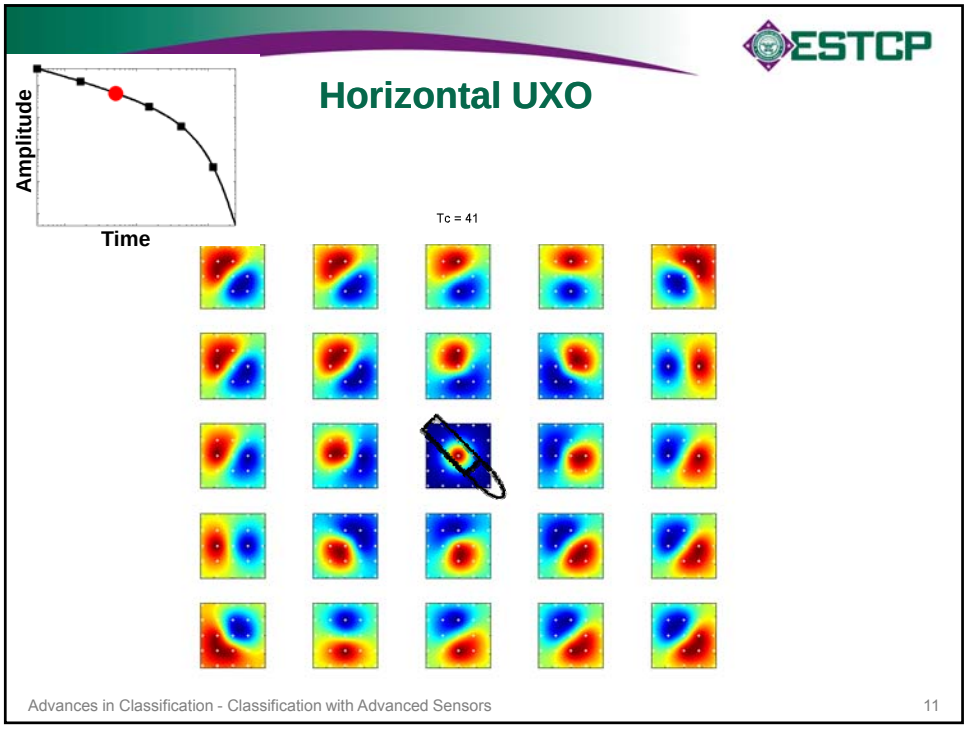
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Advances in Classification - Classification with Advanced Sensors
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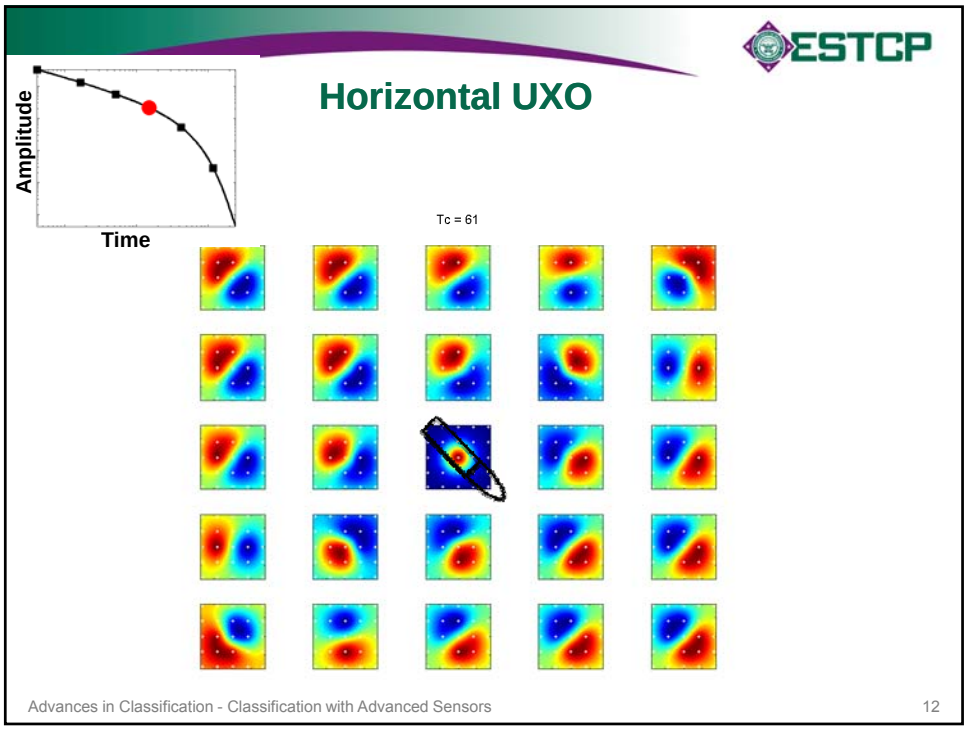
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Amplitude
Time
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Advances in Classification - Classification with Advanced Sensors
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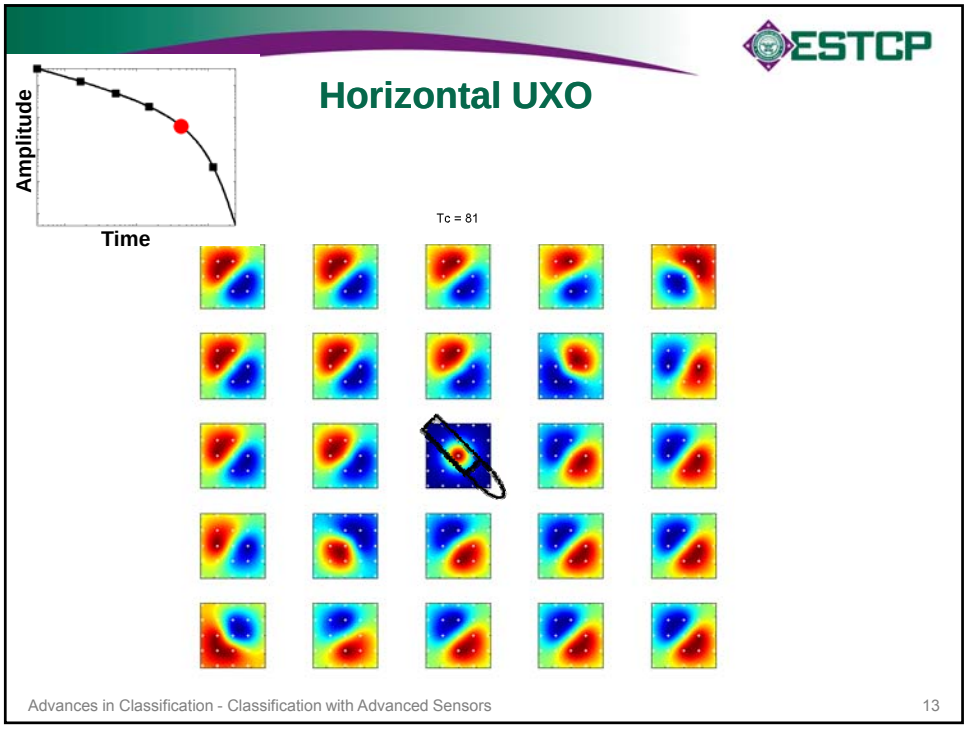
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Amplitude
Time
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Advances in Classification - Classification with Advanced Sensors
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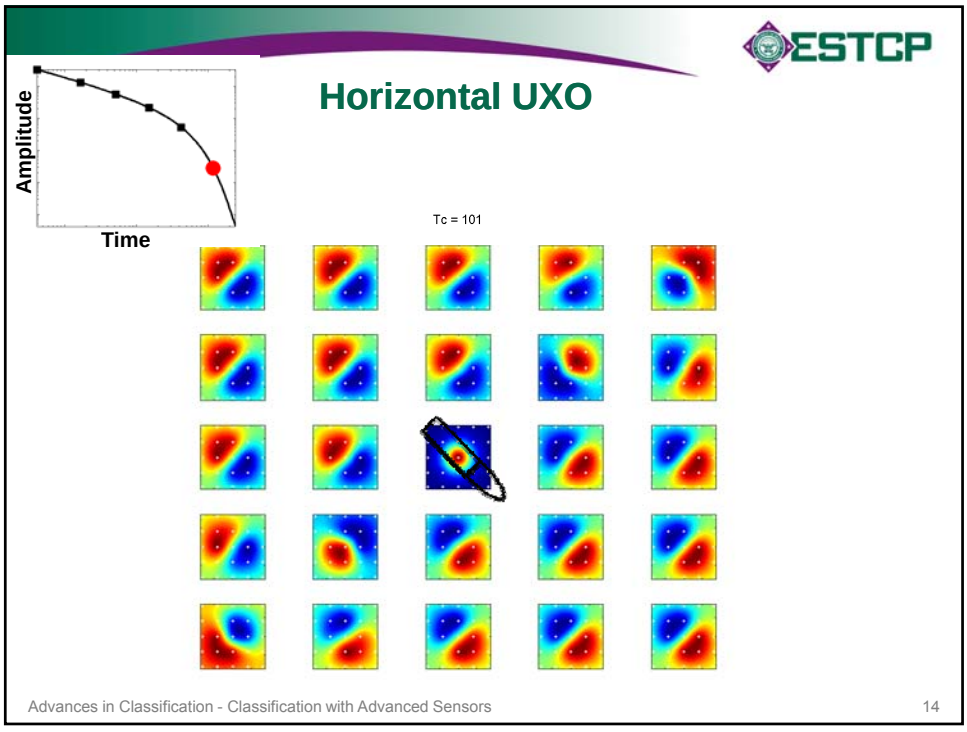
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Amplitude
Time
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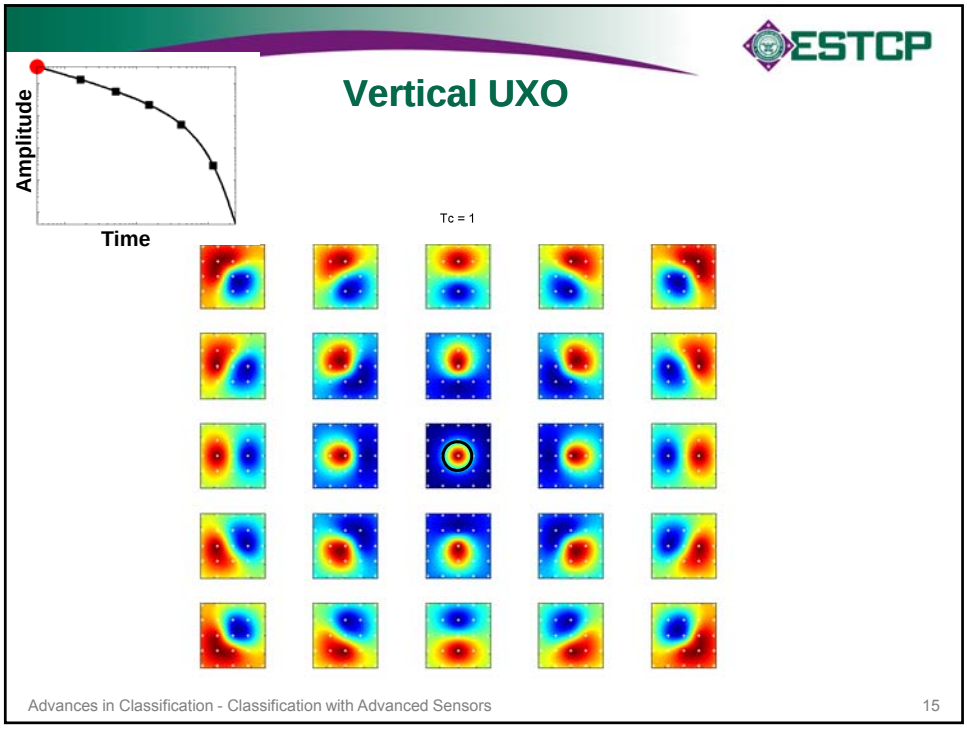
Advances in Classification - Classification with Advanced Sensors
14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Amplitude
Time
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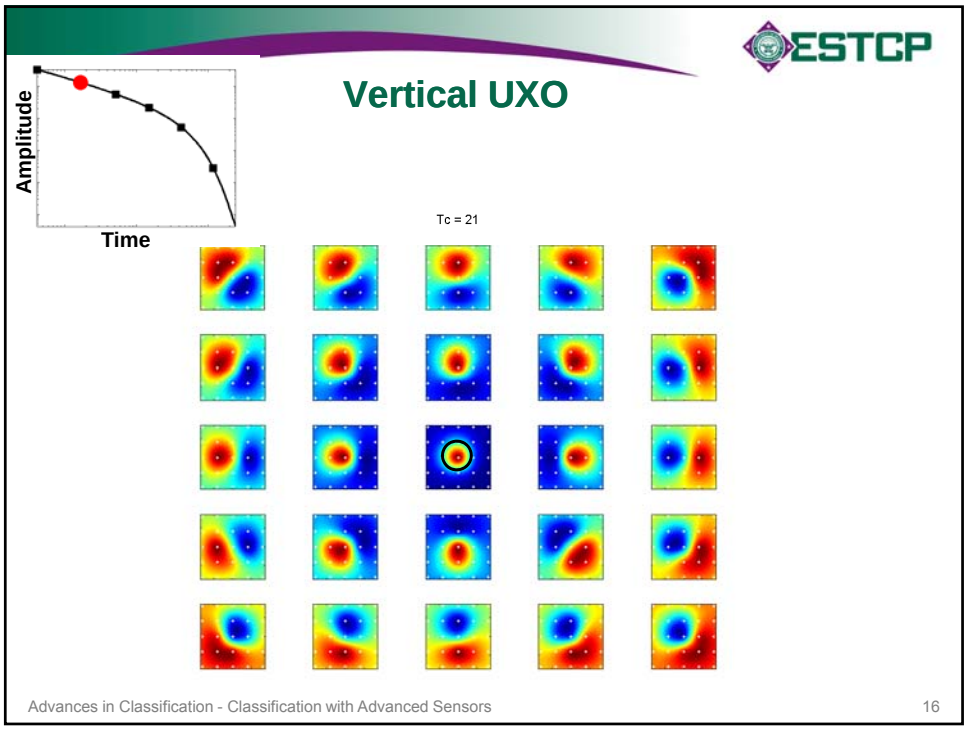
Advances in Classification - Classification with Advanced Sensors
15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Vertical UXO
Amplitude
Time
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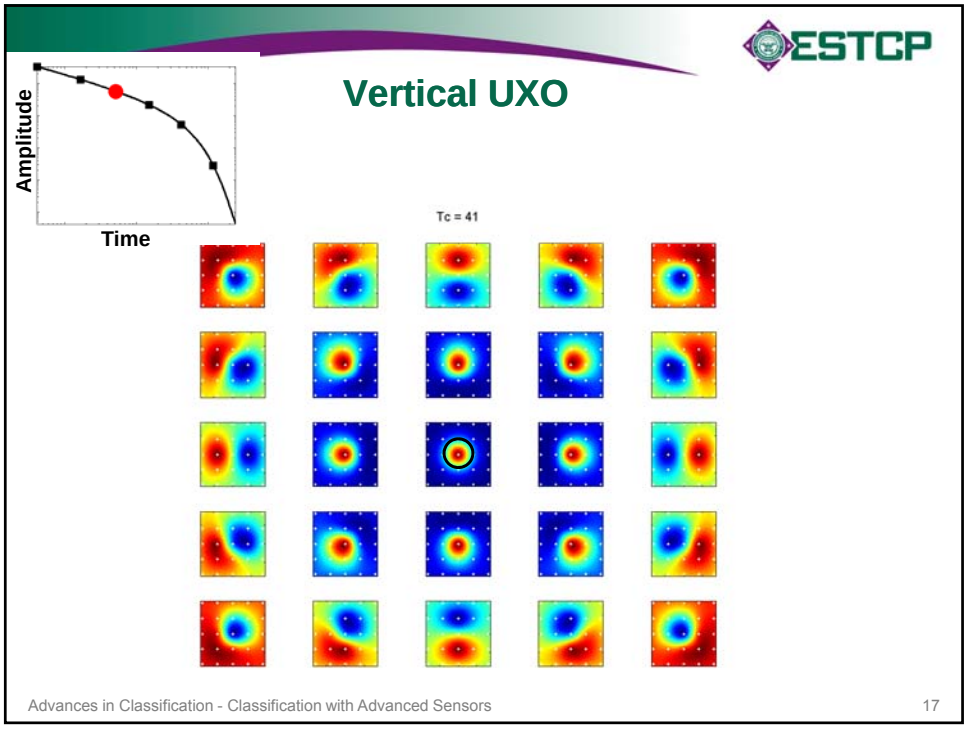
Advances in Classification - Classification with Advanced Sensors
16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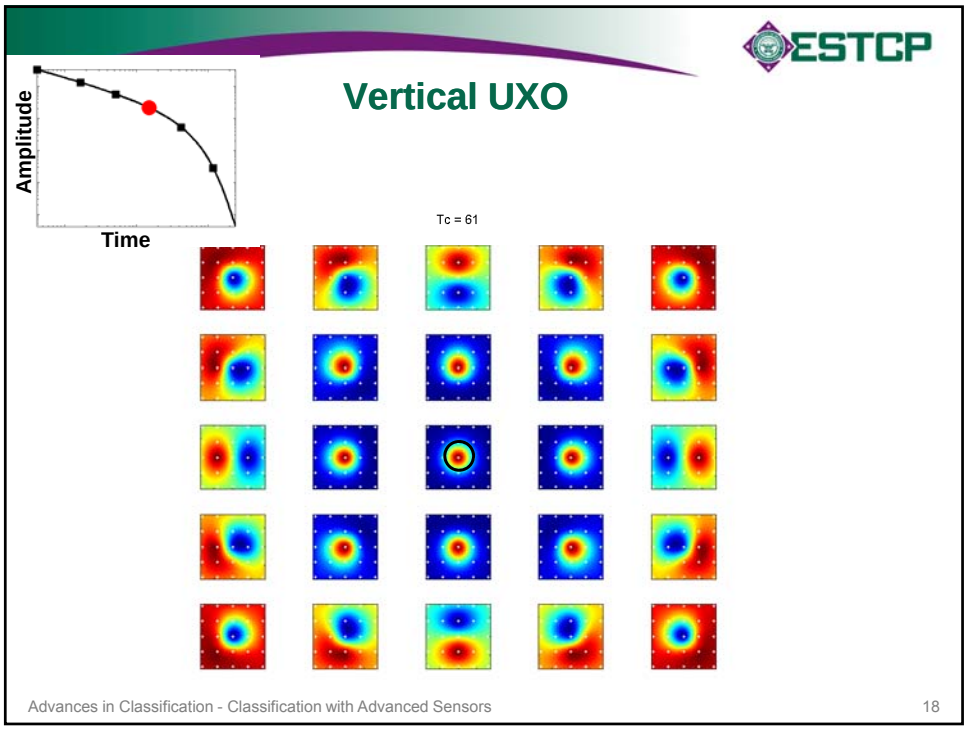
Vertical UXO
Amplitude
Time
Tc = 41
Advances in Classification - Classification with Advanced Sensors
17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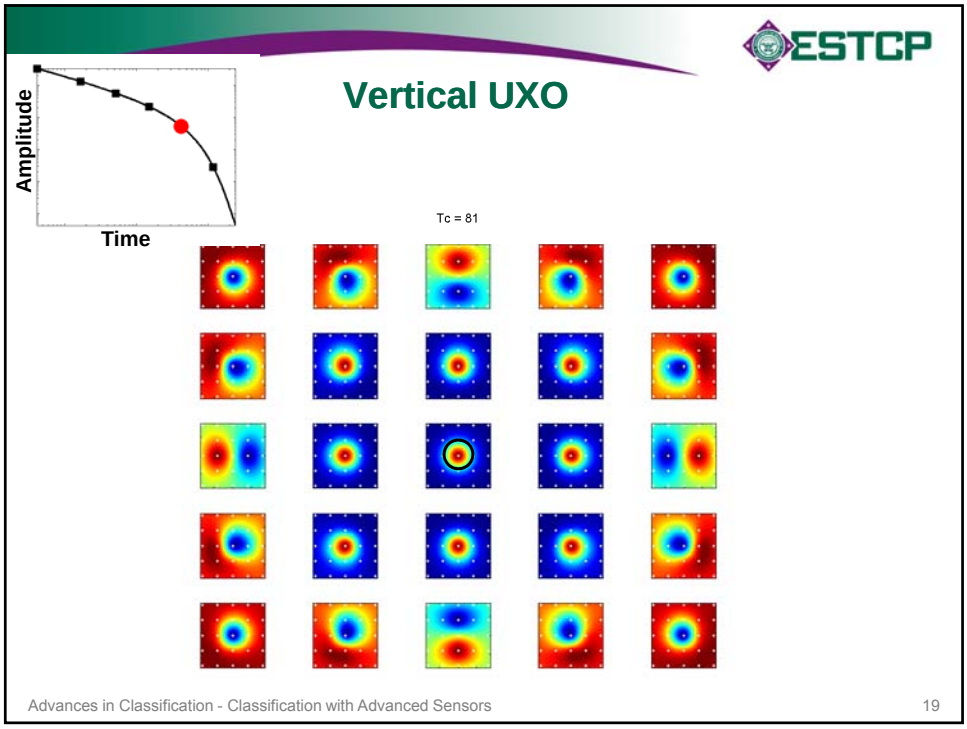
Vertical UXO
Amplitude
Time
Tc = 61
Advances in Classification - Classification with Advanced Sensors
18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Amplitude
Time
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Advances in Classification - Classification with Advanced Sensors
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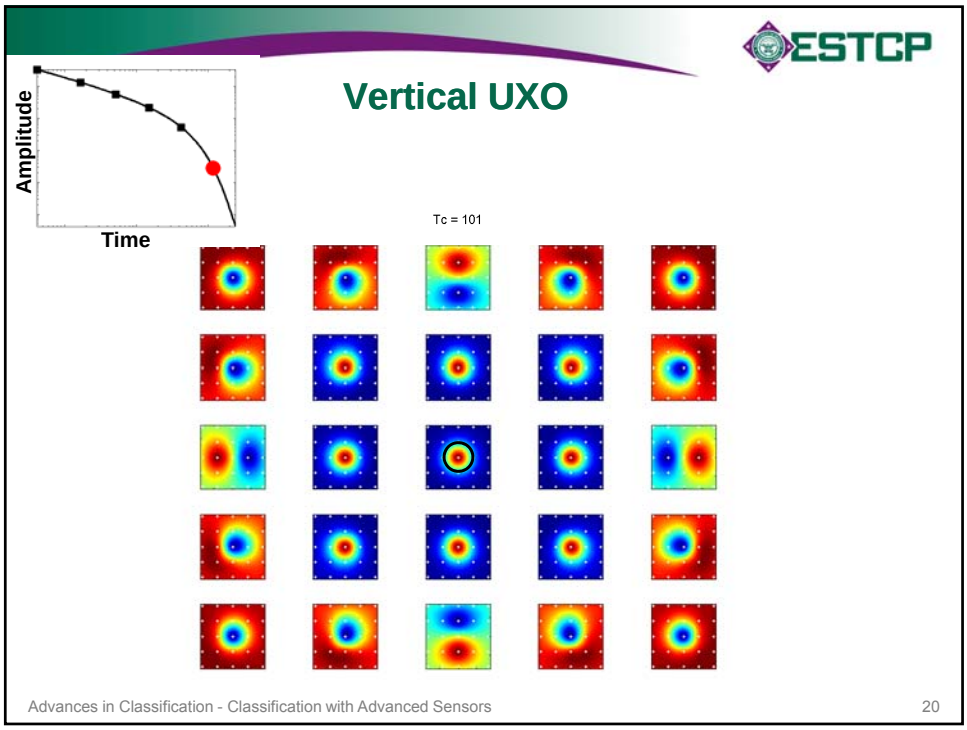
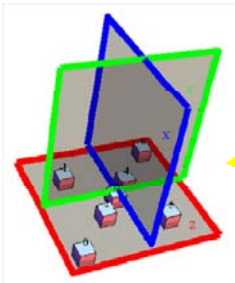
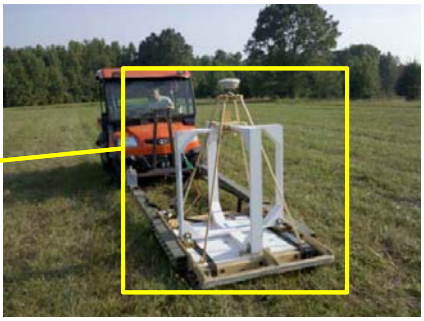

ESTCP
Vertical UXO
Amplitude
Time
Tc = 101
Advances in Classification - Classification with Advanced Sensors
20

MetalMapper

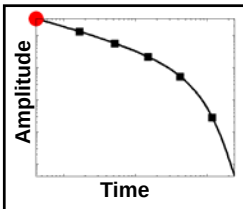
- 3 orthogonal transmitters & 7 three-axis receivers
  - ♦ Park over location estimated by previous survey
  - ♦ Fire transmitter 1, record on all 21 receivers
  - ♦ Fire transmitter 2, record on all receivers
  - ♦ Fire transmitter 3, record on all receivers

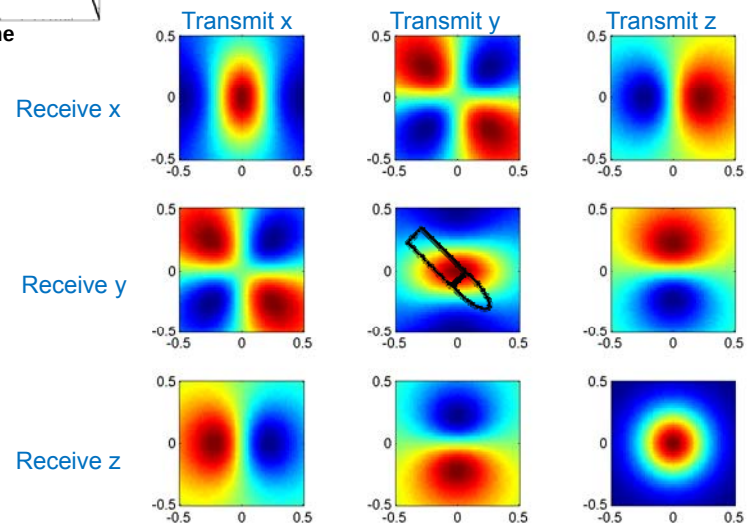




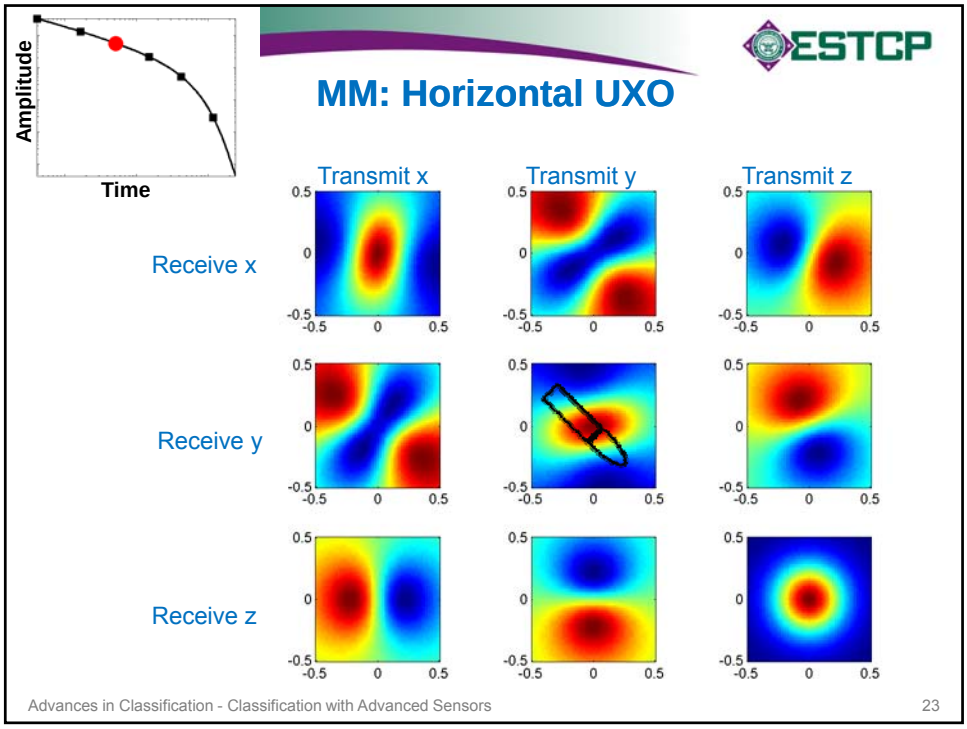
Advances in Classification - Classification with Advanced Sensors 21

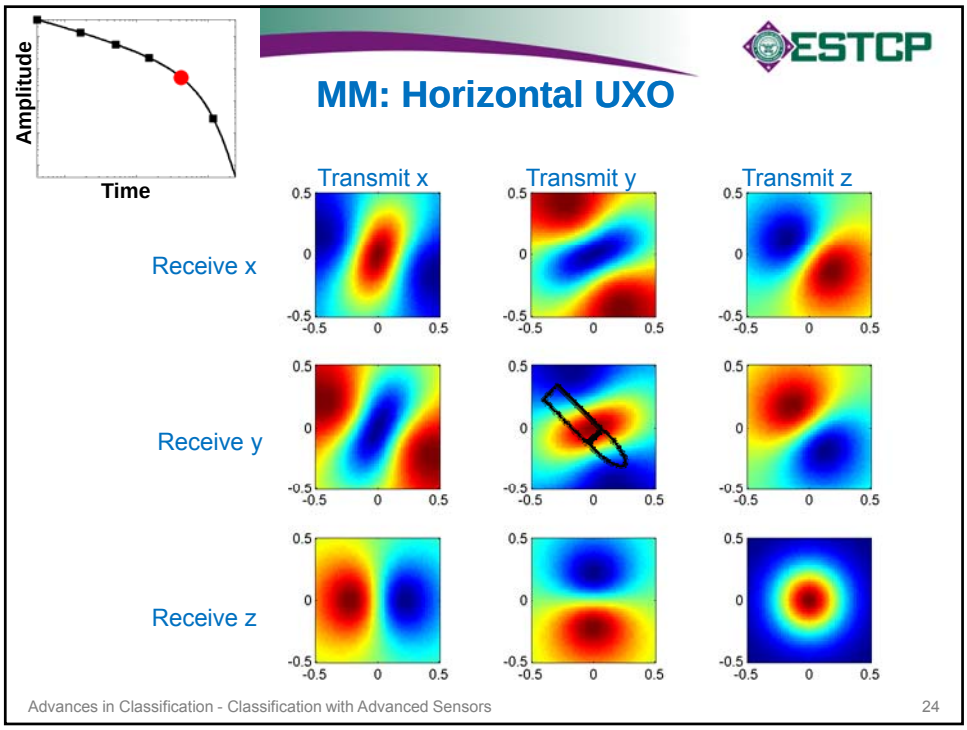
MM: Horizontal UXO



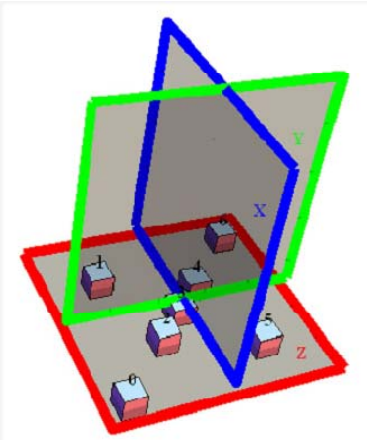


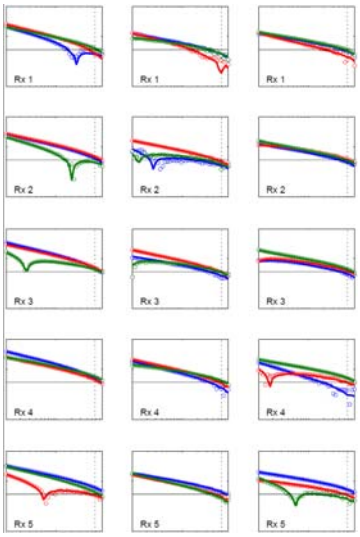
Advances in Classification - Classification with Advanced Sensors 22


Amplitude
Time
MM: Horizontal UXO
ESTCP
Transmit x
Transmit y
Transmit z
Receive x
Receive y
Receive z
Advances in Classification - Classification with Advanced Sensors
23


Amplitude
Time
MM: Horizontal UXO
ESTCP
Transmit x
Transmit y
Transmit z
Receive x
Receive y
Receive z
Advances in Classification - Classification with Advanced Sensors
24

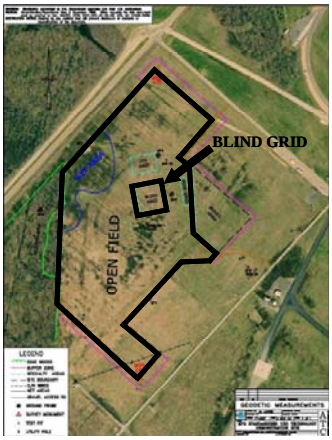
Example MetalMapper fit

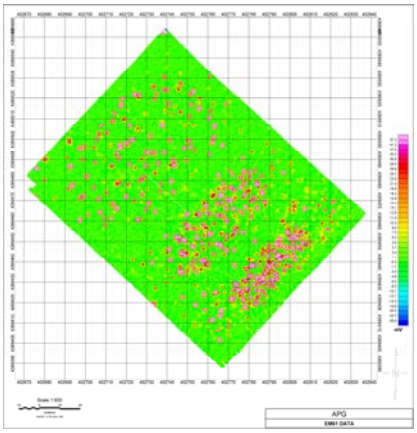




Advances in Classification - Classification with Advanced Sensors 25

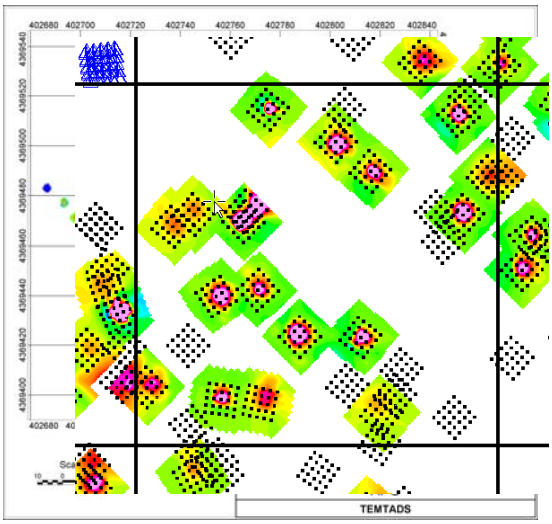
Aberdeen Proving Ground Classification Example

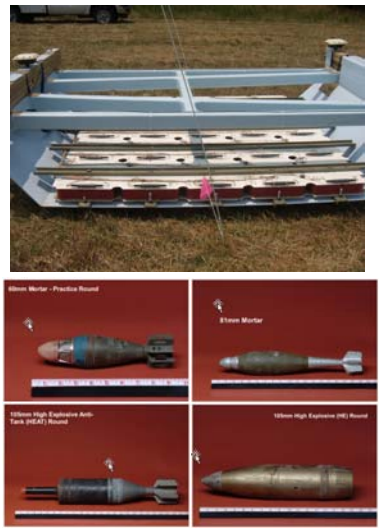




Advances in Classification - Classification with Advanced Sensors 26

APG TEMTADS Data

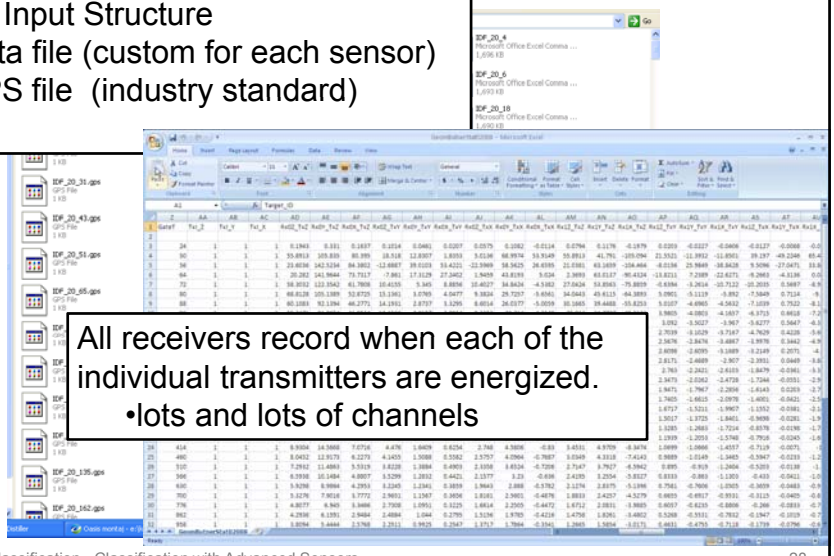




Advances in Classification - Classification with Advanced Sensors 27

Input Data Files

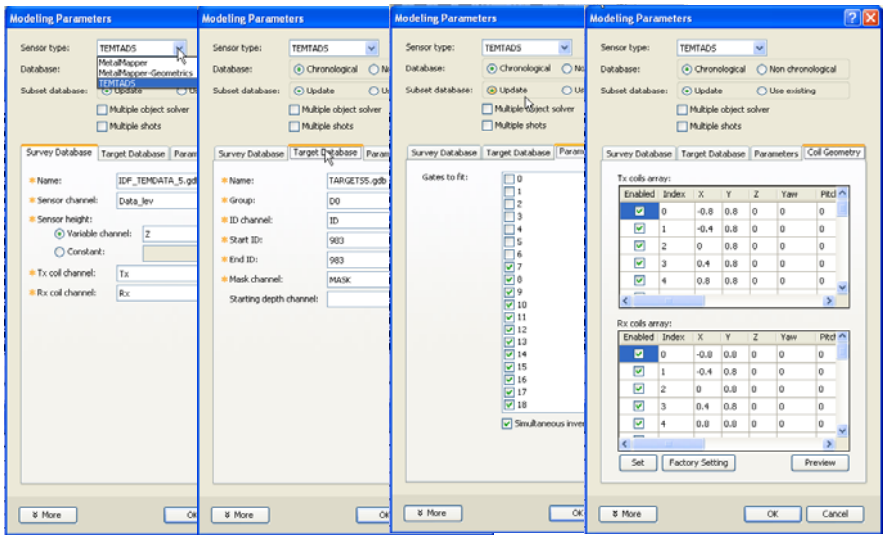
Simple Input Structure
- Data file (custom for each sensor)
- GPS file (industry standard)



All receivers record when each of the individual transmitters are energized.
- lots and lots of channels

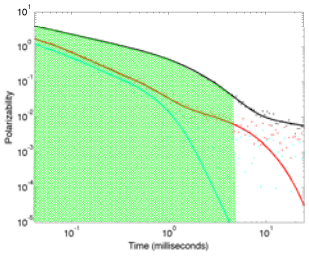
Advances in Classification - Classification with Advanced Sensors 28

Analysis Interface

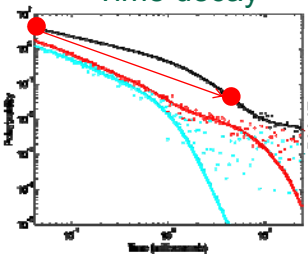


Features for discrimination

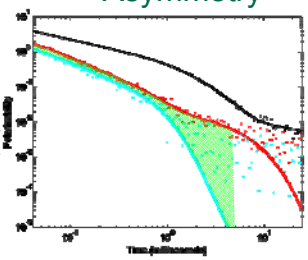
Size



Time decay



Asymmetry



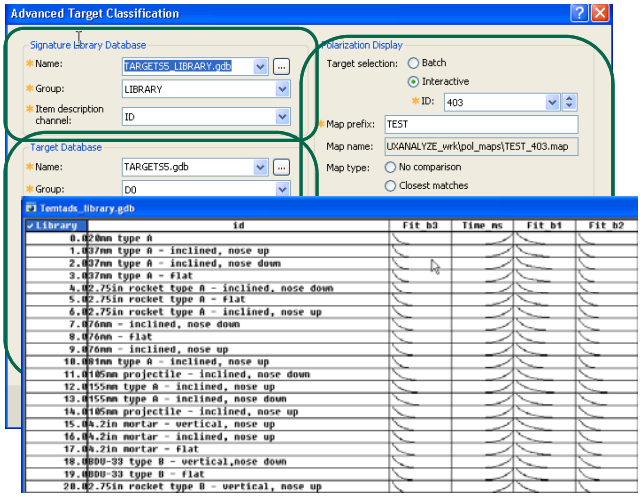
Classification

Statistical classification
- •Size
- •Time-decay
- •Shape
- •Asymmetry

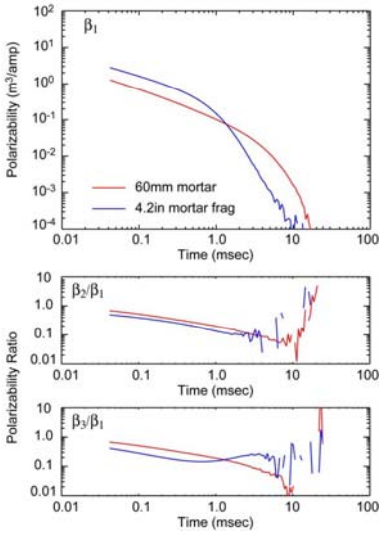
Library based classification

Template matching

"Expert" identification



Classification using a rule-based approach

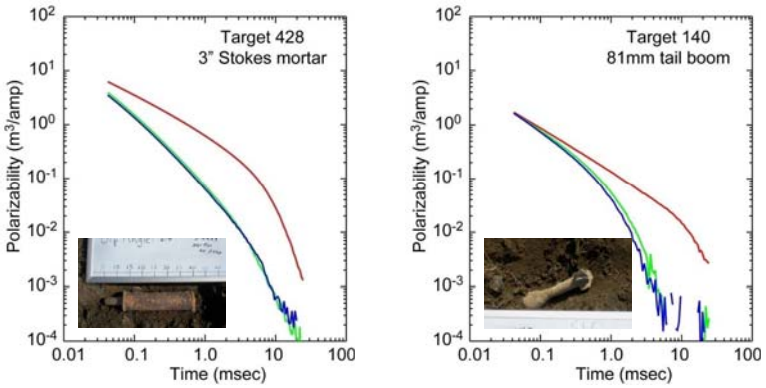


- "Library match" metric, compares
  1. Primary polarizability (β_1)
  2. Ratio secondary to primary (β_2/β_1)
  3. Ratio tertiary to primary (β_3/β_1)

  for targets of interest
- 3-criteria (β_1; β_2; β_3)
- 2-criteria (β_1; β_2)
  - ♦ Robust to β_3 for weak signals
- Decision boundary chosen to accommodate training data

Axial Symmetry

- Targets with axially symmetric response that do not match known munitions included in “can’t decide”
  - ♦ Hedge against unexpected munitions (e.g. 3” Stokes mortar)



Can’t Analyze & Can’t Decide

Can’t Analyze

Lack of data due to a sensor-specific data gap
Inversion fails to converge
Inversion produces unphysical parameters (depths >2m or negative polarizabilities)

Can’t Decide

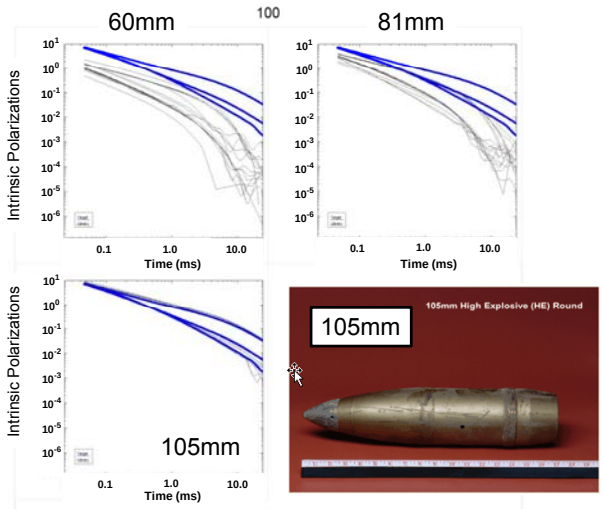
Low SNR
Multiple sources suspected (overlapping signatures)
Axially symmetric* (but does not match library)
Buffer zone*

*TEMTADS & MetalMapper

Stable Polarizations: the Key to classification

Blue → Unknown

Grey → Library from APG



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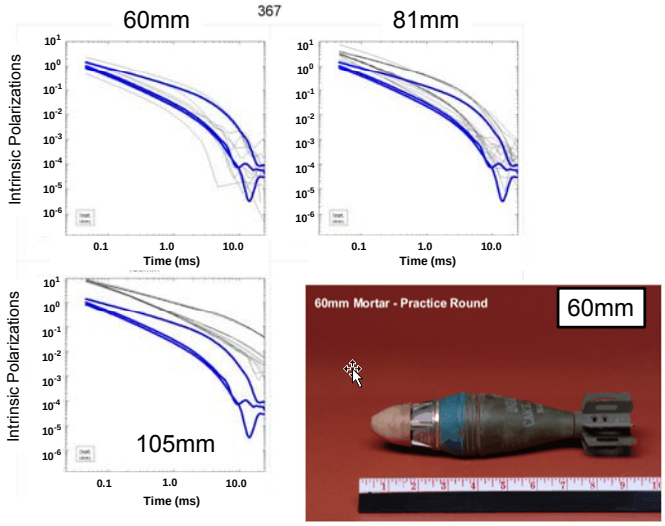
Stable Polarizations: the Key to classification

Blue → Unknown

Grey → Library from AP



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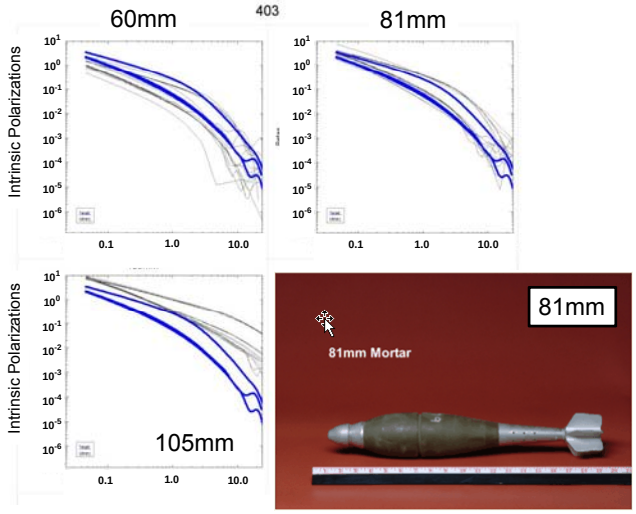
Stable Polarizations: the Key to classification

Blue → Unknown

Grey → Library from APG



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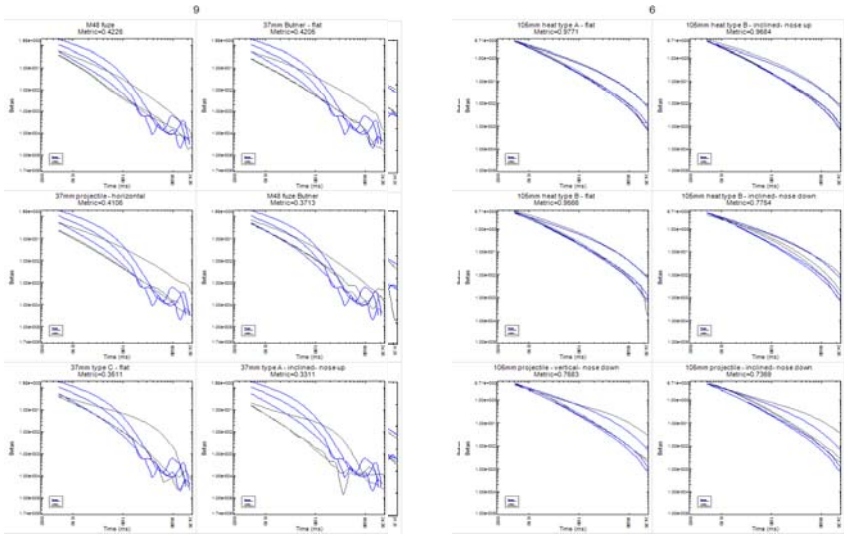
Polarization Comparisons



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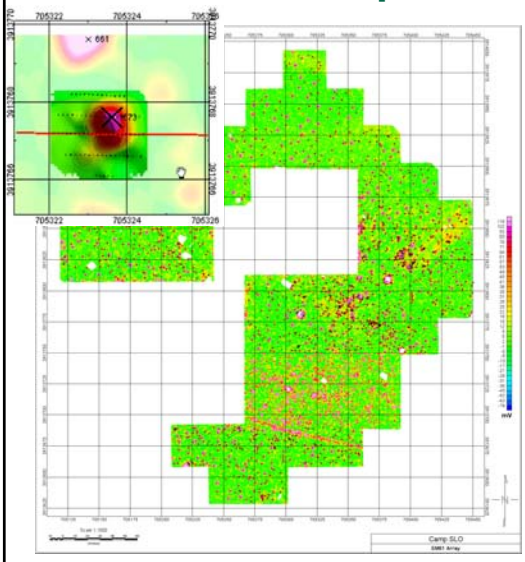
San Luis Obispo Classification Project



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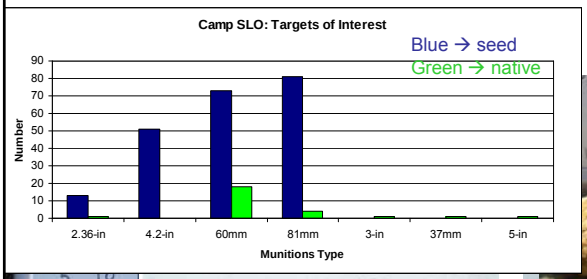
Targets of Interest (TOI)



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non Targets of Interest…

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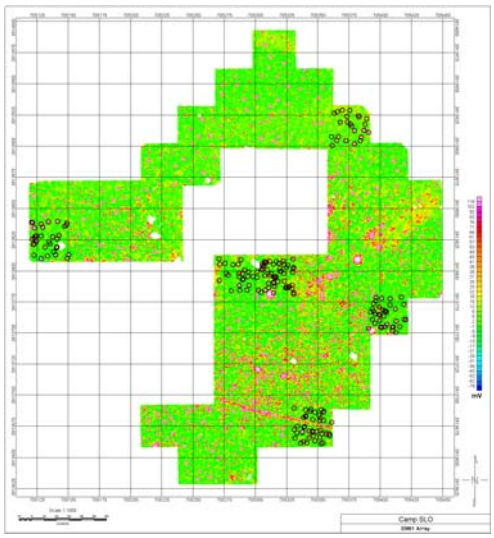
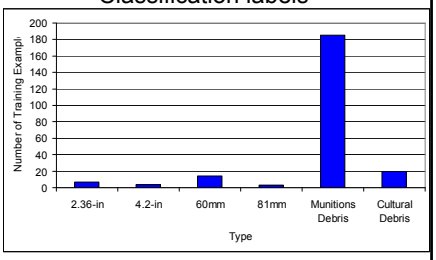
Training Labels



Calibration Line & Pit (on site): 60mm, 81mm, 2.36-in rocket, and 4.2-in rocket

Survey data: 233 anomalies excavated for training purposes

Classification labels



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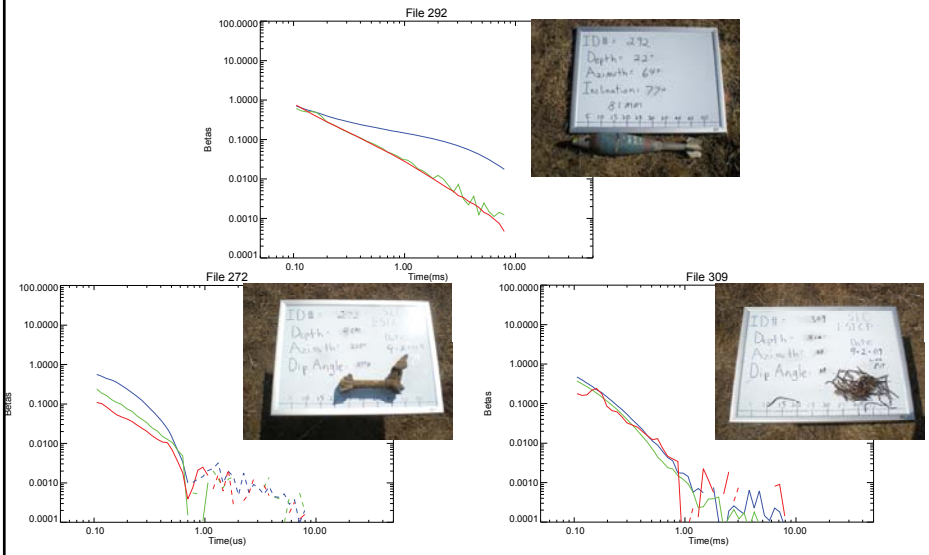
MetalMapper Polarizations



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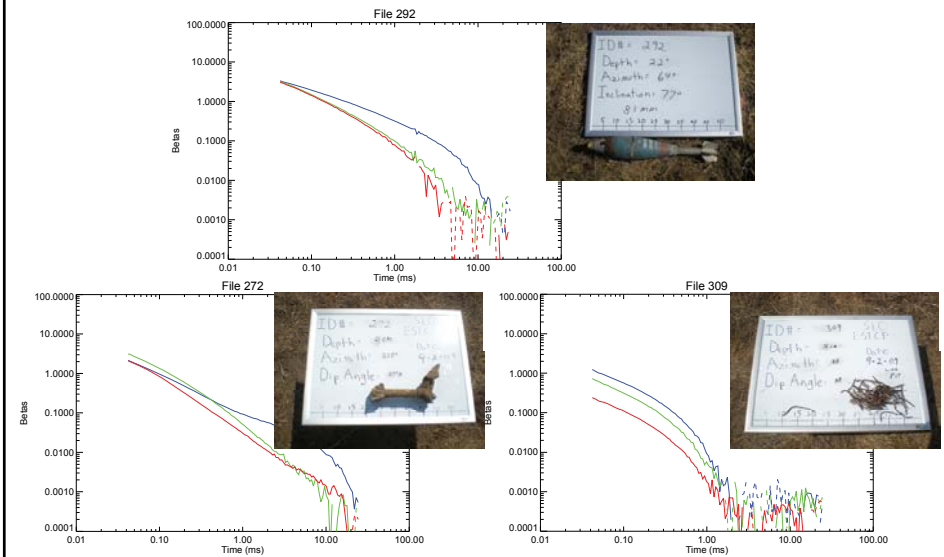
TEMTADS Polarizations



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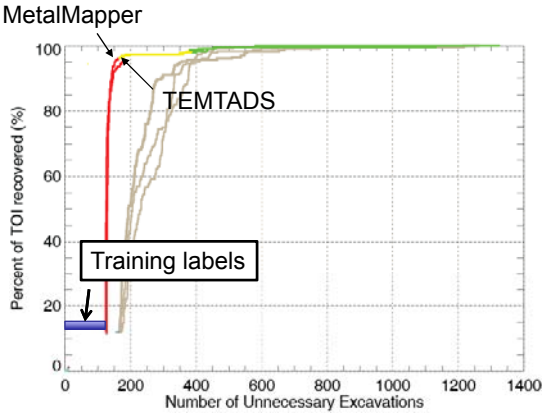
Excellent Classification with Both EMI Systems



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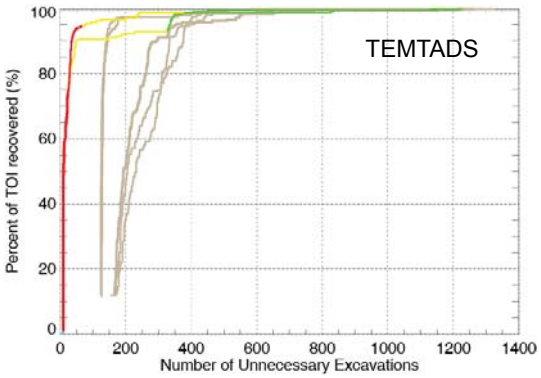
Exploring the Value of Training Labels

- No on-site training
- Assume knowledge of TOI munitions type
- Utilize prior polarization library

# UXO	# Digs
50	50
100	100
183	200
216	250
221	300
11	The Rest



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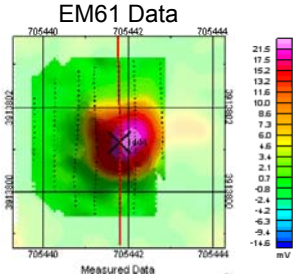
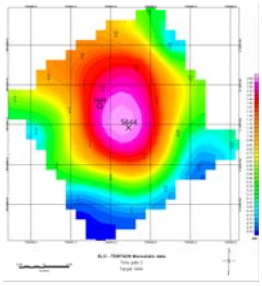
Anomaly Misclassified Using EM61 Data Was Correctly Typed

EM61 Data



TEMTADS Data



MASTER ID	DECISION STATISTIC	Rank	Category	Overlaps	Type	Easting (m)	Northing (m)	Depth (m)	Azimuth
1444	0.0233	1152	3	0	60mm	705441.6	3913801.47	0.282	46.33
413	0.0231	1153	3	0	2.36in	705275.41	3913921.9	0.326	137.07
448	0.0227	1154	3	0	2.36in	705281.8	3913666.61	0.28	7.53
60	0.0226	1155	3	0	60mm	705157.46	3913820.49	0.302	222.83

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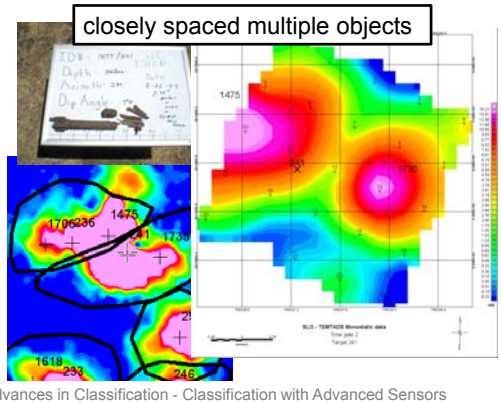
Implementation Challenges

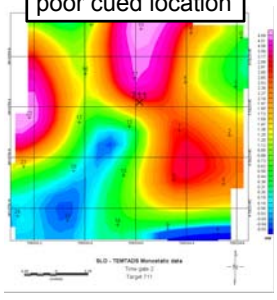
Challenges include:

a. multiple objects within the sensors view
b. incorrect cued locations
c. poor or incomplete ground truth information

closely spaced multiple objects



poor cued location



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Non-Inversion Approaches

Non-traditional approaches are being pursued by a number of research firms.

Objective(s) include:

- Detect and classify using survey data
- Increase speed of calculations
- Decrease noise sensitivity
- Require fewer measurement systems (such as geolocation)
- Reduce data demands

Key: Intelligent use of the output from multi-axis loop sensors

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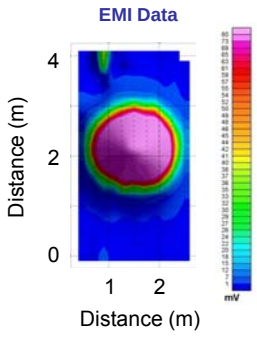
Multiple Source Situations

The munitions debris on the left was 5cm below the surface and 21cm above a 60mm projectile

The measured anomaly on the right, however, provides little to no evidence that multiple targets are present



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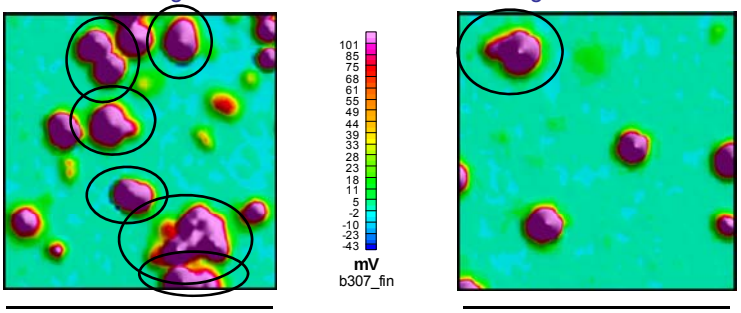
Multiple Source Situations

Complex anomalies are not uncommon…

Electromagnetic Data from Aberdeen Proving Ground

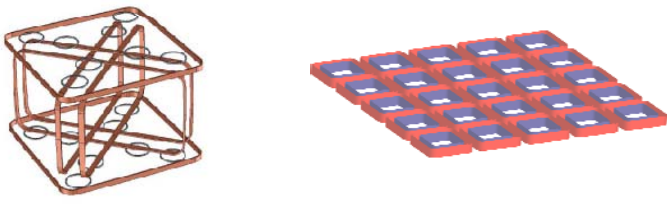


EMI Arrays

Because of these the EMI sensor advancements

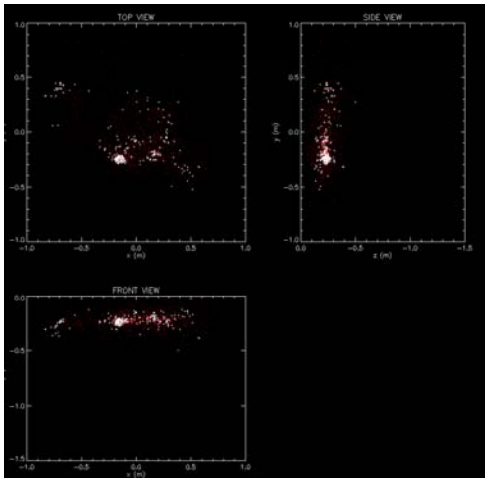
- multiple Tx and Rx pairs,
- rigid construction and
- broadband digital electronics

we can now attack multi-source scenarios…



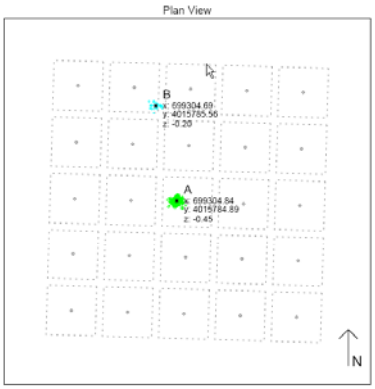
Multi-source Solver (MM-1662)

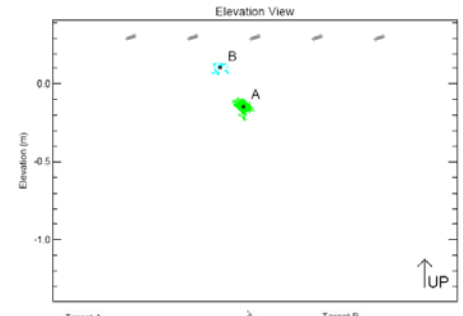
1. Determine number and location of sources contributing to measured data
2. Form clusters
3. Perform multi-source simultaneous inversion
4. Classify based on inverted intrinsic polarizabilities

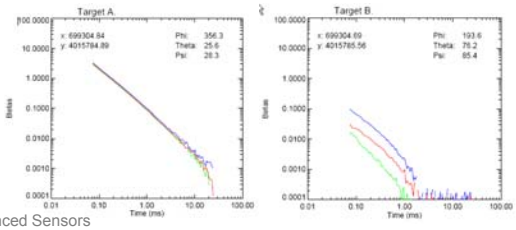


Solver Documentation (*.pdf)

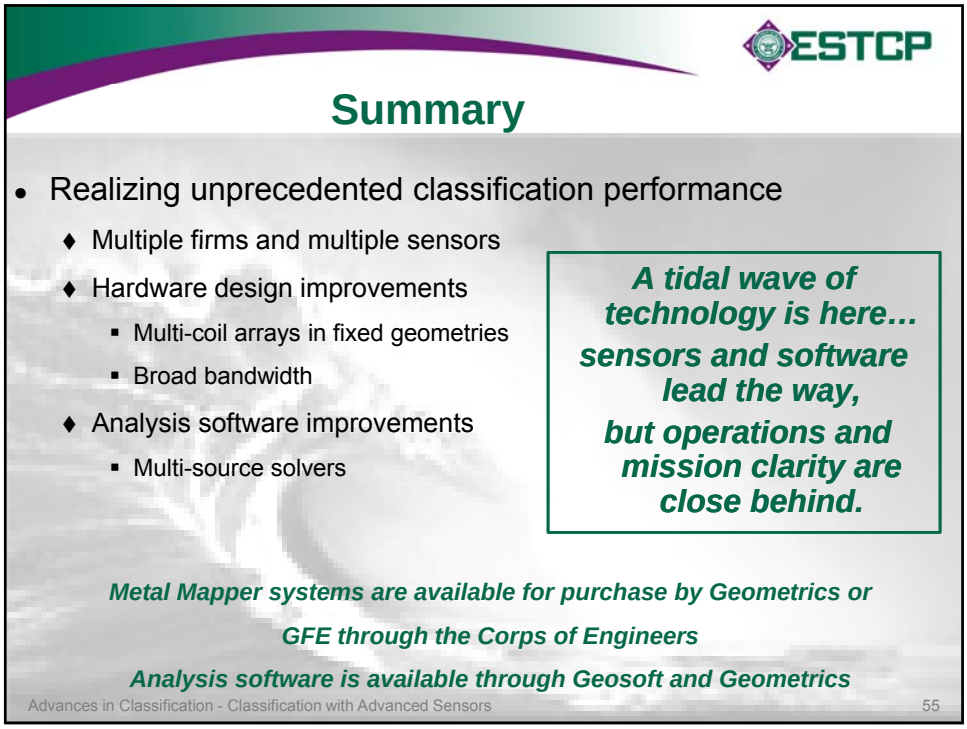
1001
NRL TEM array
Number of targets: 2







Archive Documentation for each anomaly processed


ESTCP
Summary
• Realizing unprecedented classification performance
♦ Multiple firms and multiple sensors
♦ Hardware design improvements
▪ Multi-coil arrays in fixed geometries
▪ Broad bandwidth
♦ Analysis software improvements
▪ Multi-source solvers
A tidal wave of technology is here…
sensors and software lead the way,
but operations and mission clarity are close behind.
Metal Mapper systems are available for purchase by Geometrics or GFE through the Corps of Engineers
Analysis software is available through Geosoft and Geometrics
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Concluding Thoughts

Herb Nelson

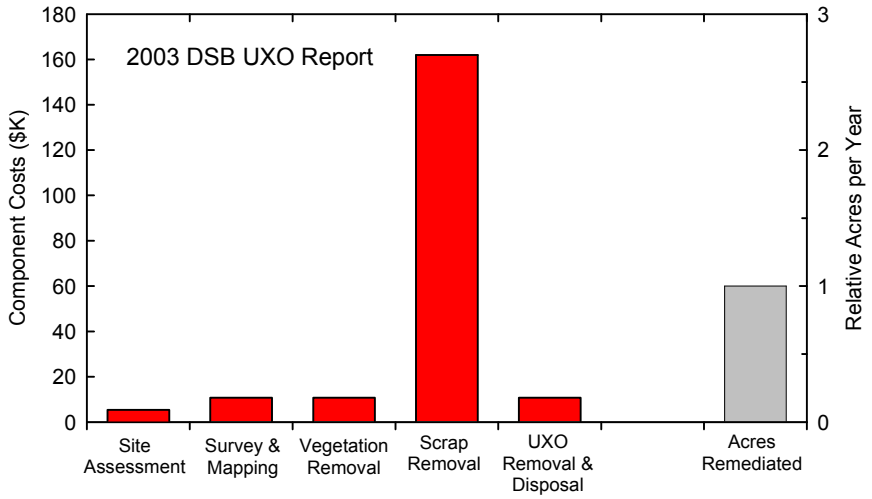
ESTCP

Objective of the Course

Provide an update on the sensors, methods, and status of the classification of military munitions using geophysical methods

- Advanced processing of data collected with existing commercial instruments
- Significant improvements possible using advanced EMI sensors

Breakdown of $200M FUDS MMRP



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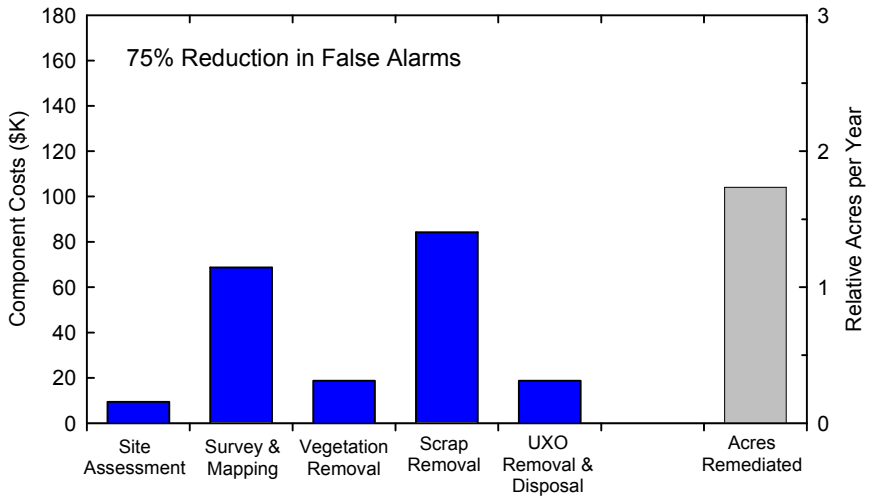
Breakdown of $200M FUDS MMRP



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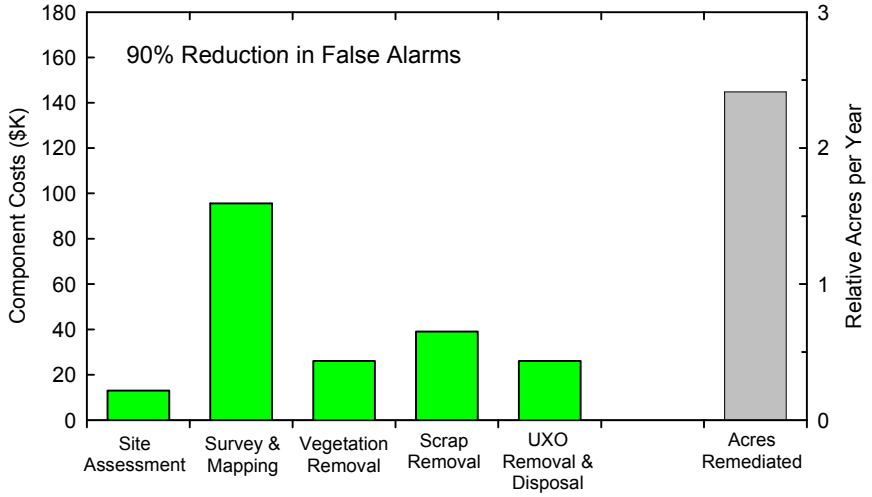
Breakdown of $200M FUDS MMRP



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Implementation Approaches

- Hazard-based dig decision
  - ♦ High confidence non-hazardous anomalies remain in the ground
  - ♦ Remaining anomalies are dug
- Hazard-based dig protocol
  - ♦ High confidence non-hazardous anomalies dug with one UXO tech supervising a team of lower-cost diggers
  - ♦ Remaining anomalies are dug with usual procedures (UXO personnel and safety equipment)

Approach would be site dependant and determined by the site team

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Acceptance

- Requires transparent process involving explicit, documented classification
- Continued collaboration with stakeholders- Advisory Group and beyond
- Need to start thinking about things like QC methods

Joint Web Site

SERDP DOD • EPA • DOE | ESTCP

Meeting DoD's Environmental Challenges

- SERDP & ESTCP Information at One Location
  - ♦ Easy access to all information
    - ▪ Funding opportunities
    - ▪ Investigator resources
    - ▪ Research results
  - ♦ Highlights program areas and initiatives
  - ♦ Platform for technology transfer: Tools and Training

serdp-estcp.org