Camp Butner UXO Data Inversion and Classification Using Advanced EMI Models

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1. REPORT DATE
NOV 2010

2. REPORT TYPE

3. DATES COVERED
00-00-2010 to 00-00-2010

4. TITLE AND SUBTITLE
Camp Butner UXO Data Inversion and Classification Using Advanced EMI Models

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Dartmouth College, Thayer School of Engineering, Cummings Hall 800, Hanover, NH, 03755

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at the 15th Annual Partners in Environmental Technology Technical Symposium & Workshop, 30 Nov – 2 Dec 2010, Washington, DC. Sponsored by SERDP and ESTCP.

14. ABSTRACT
Advanced (non-simple-dipole) EMI models inversion and classification performance is presented for the ESTCP Live-site UXO Discrimination Study at former Camp Butner, NC. The advanced models combine: (1) the joint diagonalization (JD) algorithm for estimating number of potential anomalies from the measured data without inversion, (2) the orthonormalized volume magnetic source (ONVMS) for representing targets? EMI responses and extracting targets? intrinsic parameters feature vector, and (3) the Gaussian Mixture algorithm and probability neural network, that utilizes the extracted discrimination features for classifying buried objects as targets of interest or not. Namely, the studies were conducted for the next generation sensor data: Time-domain Electromagnetic Multi-sensor Towed Array Detection System (TEMTADS) and Metal Mapper (MM) sensors? cued data sets collected at the Camp Bunter, live UXO site. These sensors provide the measured multi-static response (MSR) data matrix. Eigenvalues versus time, which are determined using the JD from the MSR data matrix provide information about the number of targets contributing to the signal and their initial classification features. Once the number of targets is known, then data are inverted and intrinsic parameters, such as the total ONVMS that is a function of target’s geometry and material composition, are determined for each potential target. These intrinsic parameters are grouped using the unsupervised Gaussian mixture approach. For each group an anomaly is identified and ground truth is requested. Once the requested ground truth data are obtained, then each of the groups is classified. In this presentation, the advanced EMI methods? data inversion, processing and discrimination scheme will be reviewed, and the classification results scored by the Institute for Defense Analyses (IDA) will be presented for both the TEMTADS and MM sensors Camp Butner, NC cued data sets.
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<th>17. LIMITATION OF ABSTRACT</th>
<th>18. NUMBER OF PAGES</th>
<th>19a. NAME OF RESPONSIBLE PERSON</th>
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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18
CAMP BUTNER UXO DATA INVERSION AND CLASSIFICATION USING ADVANCED EMI MODELS

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Outline

- Advanced EMI Models
  - Normalized Surface Magnetic Source (NSMS) Model
  - Orthonormalized Volume Magnetic Source (ONVMS) Model

- EMI Data Pre-processing and Inversion
  - Joint Diagonalization
  - Direct Search technique for Multi Targets

- Classification
  - Clustering
  - Library Matching
  - Results (IDA Score)

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

1. Data Collection
2. Data Inversion
3. Decision

**Forward Operator**

\[ d = F[p] \]

**Inverse Operator**

\[ p = F^{-1}[d] \]
Forward Models: NSMS

Normalized Surface Magnetic Source Model

- Extended dipole model
- 3D approach

Primary field induces eddy currents inside metallic objects

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

1. APG test site (214 anomalies)

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

2. SLO Live UXO site

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

The main challenges there were:
- Multiple overlapping targets
- Low signal to noise ratio
The ONMVS model divides the computational space into cells.

The key elements of the ONMVS are:

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

\[
H(r) = \sum_{i=1}^{N_v} \bar{\psi}_i(r) \cdot b_i,
\]

Where

\[
\int \left( \bar{\psi}_i^T \cdot \bar{\psi}_k \right) \, dv = \begin{cases} \bar{0}, & i \neq k \\ \bar{F}_i, & m = k \end{cases}
\]
These orthogonal functions are constructed using the scattered magnetic field’s Green function via Gram-Schmidt ortho-normalization process:

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

The modeled Magnetic field is fitted to measured data, and

The ONVMS:

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

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

\[
D(t_k) = V^T H_d(t_k) V, \quad k=1, 2, \ldots, n
\]
JD applied to CB-TEMTADS data:

The eigenvalues show targets features:

Two targets (105 mm HE and 105 mm HEAT), having same size, but different material properties have different time decaying eigenvalues
JD applied to CB-TEMTADS data:

eigenvalues for classification

TOIs have slow time decaying eigenvalues

37 mm projectiles with copper bands have distinguishable eigenvalues
JD applied to CB-TEMTADS data:

- eigenvalues versus time

Clutter items have fast time decaying eigenvalues.

TOIs have slow time decaying eigenvalues.

Clutter items have fast time decaying eigenvalues.
JD applied to CB-TEMTADS data:

eigenvalues for Multi targets

- Too many Targets

- eigenvalues versus time

Target 1

Target 2

- eigenvalues versus time
JD applied to CB-TEMTADS data:

Resolving small signal to noise ratio

The eigenvalues are small, but decay slowly in time, that means:
the anomaly is buried deep and it is a potential TOI.
CB-TEMTADS Data Classification Approach:

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

105 mm HE

105 mm HEAT

M48 Fuze

37 mm-1

37 mm-2
Camp Butner TEMTADS Classification results

Scored Results for the TEMTADS Cued Data Sets:

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

- All data sets were inverted as
  - One
  - Two
  - Three
  
  targets using the ONVMS.

- The effective polarazabilities were determined;

- Targets were clustered using the principal effective polarazabilities;
ONVMS applied to CB-Metal Mapper
Data: Anomaly #2504

Single source inversion

Multi targets inversion

37 mm: Library

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

Single source inversion

Multi targets inversion

37 mm: Library

Inverted parameters
Gaussian mixture model for MM-ONVMS clustering

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

\[ M_{zz}(t_1) \] and \[ M_{zz}(t_1)/M_{zz}(t_{30}) \] are used as discrimination features.
Camp Butner Metal Mapper Classification results

Scored Results for the Metal Mapper Cued Data Sets:

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

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