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14. ABSTRACT
This report covers the use of the standard EMI inversion algorithm as a detection filter. The basic concept is to grid the survey filter into a regular grid of hypothesized locations. A window of data is taken about each location and a simple linear inversion applied. The filter output is the squared correlation of the inverted model and data from the fit at each grid location. The best fits to data occur at target locations and the filter output peaks there. Issues in implementing the filter on advanced EMI survey data are explored. Results from applying the detection filter to several Live Site Demonstrations are covered. Overall, the detection filter output can be predicted for a given target-of-interest to a specified depth along with the filter background noise. The filter exploits all channels of data from the EMI sensors and results in a higher SNR output than simple consideration of signal amplitude. It was observed that the filter depth setting could be used to de-emphasis small surface clutter in the target selection process, but still select all TOI. Given the filter peak locations, inversion can be performed on data windows centered at each. In data sets with high target densities, it was found to be useful to apply N-dipole inversions at the filter peaks as well. The inverted polarizations were found to match those found from cued data collected with the same sensor.

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<tbody>
<tr>
<td>EMI</td>
<td>Electromagnetic Induction</td>
</tr>
<tr>
<td>ESTCP</td>
<td>Environmental Security Technology Certification Program</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>IDL</td>
<td>Interactive Data Language</td>
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<tr>
<td>IMU</td>
<td>Inertial Measurement Unit</td>
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<tr>
<td>ISO</td>
<td>Industry Standard Object (one of several standardized pipe sections)</td>
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<td>RMS</td>
<td>Root-Mean-Square (as in standard deviation of a random variable)</td>
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<td>Ri, Rj,…</td>
<td>Receive channel i, j, etc.</td>
</tr>
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<td>Rx</td>
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<td>SERDP</td>
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<td>SNR</td>
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<td>SWPG</td>
<td>Southwestern Proving Ground</td>
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<tr>
<td>TEMTADS</td>
<td>Transient Electromagnetic Towed Array Detection System</td>
</tr>
<tr>
<td>TOI</td>
<td>Target of Interest</td>
</tr>
<tr>
<td>Ti, Tj,…</td>
<td>Transmit channel i, j, etc.</td>
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<td>Tx</td>
<td>Transmit</td>
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<td>UXO</td>
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Keywords

Munitions Response
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Abstract

The original aim of this project was to consider ways to measure and exploit the complete EMI response including an item’s bulk magnetization to better identify objects as UXO or clutter. As explained later, the project was re-directed to look into better ways of processing the survey data being collected by the newly developed advanced EMI sensors to intelligently select possible target locations.

Several approaches were considered, but the bulk of this report covers the use of the standard EMI inversion algorithm as a detection filter. The basic concept is to grid the survey filter into a regular grid of hypothesized locations. A window of data is taken about each location and a simple linear inversion applied. The filter output is the squared correlation of the inverted model and data from the fit at each grid location. The best fits to data occur at target locations and the filter output peaks there. Issues in implementing the filter on advanced EMI survey data are explored. Results from applying the detection filter to several Live Site Demonstrations are covered.

Overall, the detection filter output can be predicted for a given target-of-interest to a specified depth along with the filter background noise. The filter exploits all channels of data from the EMI sensors and results in a higher SNR output than simple consideration of signal amplitude. It was observed that the filter depth setting could be used to de-emphasis small surface clutter in the target selection process, but still select all TOI. Given the filter peak locations, inversions can be performed on data windows centered at each. In data sets with high target densities, it was found to be useful to apply N-dipole inversions at the filter peaks as well. The inverted polarizations were found to match those found from cued data collected with the same sensor.
Objective

The objective of the Strategic Environmental Research and Development (SERDP) Statement of Need under which the proposal for this project was submitted was to develop sensors, signal processing methodologies, sensor platforms, systems, supporting technologies, or remediation technologies or to conduct phenomenology studies to address the diverse challenges associated with the cleanup of Department of Defense munitions-contaminated terrestrial sites, i.e. sites contaminated with unexploded ordnance (UXO), discarded military munitions and related items.

The specific objective of the proposed research was to develop improved capabilities for classifying buried objects as UXO or clutter that exploit all of the information available in the electromagnetic induction (EMI) response of the object. As noted in the Background section below, the project addressed both sensor-related and processing-related improvements. The sensor-related work was documented in a pair of interim reports [1, 2]. This report documents the results of our processing-related work.
Background

The Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) have developed and tested several advanced electromagnetic induction (EMI) sensor arrays for classifying buried objects as either munitions (and other targets of interest) or clutter. These sensor arrays excite the target and measure its response over a diverse range of orientations, producing enough information to calculate the target’s intrinsic EMI response coefficients which can then be used to identify the target. Most of the demonstration and validation testing has focused on cued identification. In cued identification the array is positioned over a previously detected target and a set of readings are taken which are then used to classify the target.

Conventional EMI sensors such as the Geonics EM61 and the newly developed SERDP/ESTCP sensors for target classification measure the eddy current response of the target. This is only part of a target's complete EMI response, which also includes bulk magnetization effects. Accessing the bulk magnetization response requires primary field cancellation. Originally this project was designed to address two questions:

1. Is the information in the additional (magnetization) response that is not measured by current sensors likely to improve classification performance, and
2. Is it possible to build an instrument that can reliably access this information?

Results of our investigations into these two questions were published as interim reports [1, 2]. Following the Spring 2012 Munitions Response Program Area In-Progress Review the SERDP Program Office concluded that the potential classification performance improvement did not justify the technical risk and cost in developing a new EMI system capable of measuring the bulk magnetization response and in November 2012 the project was re-directed to develop intelligent procedures for selecting targets from survey data collected with advanced EMI sensor arrays. Traditionally, target detection had relied on geophysical surveys using the Geonics EM61. The new EMI sensor arrays can also be operated in a dynamic mode to collect geophysical survey data. They collect much richer data sets than the EM61 and intelligent procedures for selecting targets which fully exploit the data should result in improved detection performance.
Materials and Methods

EMI Sensors

EMI sensors excite eddy currents in the target and then observe how they decay. The size and shape of the target determine how the response varies with the direction of the exciting field and the directional sensitivities of the receiver elements. The EM61 uses a single pair of vertically directed transmit and receive (Tx/Rx) coils, and measures the eddy current signal at four times during the decay (0.216, 0.366, 0.660 and 1.266 ms).

There are two SERDP/ESTCP-developed advanced EMI systems in routine use today. The man-portable adjunct Transient Electromagnetic Towed Array Detection System (TEMTADS) [3] comprises a cart mounted 2x2 array of EMI sensors using 48 Tx/Rx combinations to measure the response of the target over a wide range of different excitation and observation direction combinations. The number and spacing of decay times sampled by the array is programmable – nineteen time gates ranging from 0.0.025 ms to 2.5 ms were used for the recent Camp Spencer demonstration. The other advanced sensor system currently in use, the MetalMapper [4] can measure the response for 63 Tx/Rx combinations, although only 21 are currently used in the dynamic or search mode. At Camp Spencer it sampled at the same time gates as the 2x2. Our goal here is to determine how to process these data to achieve the best possible detection performance while keeping the computational cost and complexity under control.

Signal-Based Target Detection

With the EM61 anomaly selection is straightforward: chose one of the four time gates, map out the survey data and then identify the spots where the signal exceeds some threshold. The proper threshold setting depends on the minimum signal that is expected from targets of interest and the noise level at the site. Typically the detection threshold is set by the predicted weakest possible peak signal from a target of interest (TOI) at its greatest expected depth. This signal level is calculated using the standard dipole polarization response model and the measured polarizations of the TOI [5]. Reliable detection requires signals that are perhaps five or six times the root-mean-square (RMS) noise level.

A similar approach can be used with the advanced sensors. Figure 1 compares the expected signal from a 60 mm mortar to the root-mean-square (RMS) noise for the 2x2 TEMTADS as a function of decay time. The upper plot shows the signal (in blue) from a single monostatic Tx/Rx pair (z-axis) with the mortar oriented horizontally and directly under the center of the array at a depth of 75 cm below the ground surface (the array is 20 cm above the ground surface). It is calculated using the 2x2 forward model with polarizabilities determined by inverting 2x2 data for a 60 mm mortar. The four noise curves (in red) are the standard deviation of the four monostatic sensor combinations for 12.5 s (~9 m) of survey data collected with the 2x2 in a clean, target-free area at the Naval Research Laboratory’s Blossom Point test field. The lower plot shows the ratio of the signal to the noise as a function of decay time. Since we typically need
a signal to noise ratio of at least five to reliably detect a target in this sort of scenario, 60 mm mortars buried 75 cm would be on the lower edge of detection. Deeper 60 mm mortars would be under an SNR of five and would not be consistently detected using raw, unprocessed monostatic 2x2 survey data at this site.

Figure 1. Monostatic 2x2 TEM signal and noise for a 75 cm deep 60 mm mortar at Blossom Point.

Figure 2 shows 2x2 TEMTADS minimum target signal vs. depth response curves at one particular point in the decay curve (0.137ms). The plot on the left is for a 60mm mortar and the plot on the right is for a medium-sized “Industry Standard Object” or ISO pipe section sometimes used as a seed item at munitions response sites [6]. Symbols correspond to measured response values at various depths and target orientations. Horizontal (flat) target orientations typically produce the smallest sensor response. The solid line is the calculated minimum response vs. depth for the target, with dotted lines corresponding to ±2 standard deviations of the noise about the expected minimum response. The horizontal dashed line is five times the RMS noise. The data were collected at the Blossom Point test site. Such curves aid in setting sensible detection thresholds for anomaly selection.
Figure 2. 2x2 TEMTADS minimum target signal vs. depth response curves for a 60mm mortar (left) and a medium-sized “Industry Standard Object” or ISO pipe section sometimes used as a seed item at munitions response sites.

Figure 3 shows EM61 and 2x2 TEMTADS data collected along a line over a set of 60 mm mortars at Blossom Point. The TEMTADS data represents the monostatic Z-response from receiver cube #1 in transmitter #1. While not optimal in SNR, the 2x2 data is from the time gate at 0.335 ms to compare the two sensors at roughly equal gates. There are four groups of three targets buried at 75 cm (spaced 6 m apart in the first 18 m of the survey track), 100 cm (18-36 m down track), 25 cm (36-54 m down track) and 50 cm (54-72 m down track). The targets at 75 cm depth are clearly visible in the EM61 data (top plot). Slight hummocks are barely discernable in the noise for the 2x2 monostatic data above the 75 cm deep mortars (middle plot). This is clearly consistent with the measured and calculated target response vis-à-vis the noise.

Figure 3. EM61 and 2x2 TEMTADS data over the 60 mm mortar line at Blossom Point.
Anomaly detection with the man-portable TEMTADS system using conventional (peak-picking using mapped monostatic Z-Z data) processing was tested as part of the Spencer Range demonstration [7]. Anomalies were picked from mapped data. The mapped data from the demonstration area are shown in Figure 4. EM61 (gate 2) data are shown on the left and the monostatic response from each TEMTADS sensor at the tenth usable time gate (1.024 ms) is shown on the right. As this was the first outing of the system in dynamic mode, a data analyst made each anomaly selection rather than an automated peak picker routine. The anomaly detection criteria were based on physical models of the system’s response to the expected TOI.

The ESTCP Demonstration Plan [8] had set as an objective detecting 37mm projectiles to a burial depth of 34 cm. To establish a detection threshold for this objective with the man-portable 2x2 system operating in dynamic survey mode, a series of forward model cases were run using the polarizabilities of known 37mm projectiles and actual, measured survey track positions from our test field. In dynamic survey mode, the earliest usable time gates are in the 0.1 to 0.2 ms range. Therefore, the first time gate considered in the forward model cases was 0.135 ms. The weakest responses are from 37mm projectiles oriented horizontally.

Figure 4. Located and leveled EM61 (left) and TEMTADS dynamic data (right) for the Dynamic Area at the former Spencer Artillery Range, TN.
A forward model was run with a fixed object depth of 34 cm, but over a range of object/survey track separations and a range of object azimuth orientations. The results indicated that the expected peak signals for the 37mm projectile are found within the range of 1.6 to 2.1 mV/A at 0.135 ms. Based on these modeling results, a pre-demonstration, conservative detection level of 1.0 mV/A was selected for the TEMTADS man-portable system dynamic survey.

EM61 and man-portable TEMTADS signal levels for all of the anomalies (targets of interest and clutter) are compared in Figure 5. The corresponding detection threshold levels for a 37mm projectile buried 34 cm deep are shown in the figure. Both systems detect all of the TOI, but many clutter items are picked by only one of the systems. In this environment (as opposed to the Blossom Point test site) the EM61 typically misses more of the targets with weak 2x2 signals than vice-versa because the TEMTADS array has a higher resolution than the EM61 and can resolve signals from multiple targets which are smeared out by the EM61.

![Figure 5. EM61 and 2x2 signal levels for anomalies in the Spencer demonstration area.](image)

The monostatic response clearly does not use all of the data collected by the 2x2 TEMTADS. We also looked at combining all of the available data using a singular value decomposition (SVD) approach [9] to adaptively determine the linear combination of channels producing the strongest response. Results for the Blossom Point 60mm line are shown in Figure 6. There does not appear to be much, if any improvement over the monostatic response.
Figure 6. SVD filtered 2x2 response along the Blossom Point 60mm line.

Since we are looking specifically for compact metal objects, we reasoned that perhaps a better approach would be to make use of the dipole response model [10], which searches out the combination of channels which best corresponds to the response due to a compact metal object. If the measured data in a particular area can be well fit by the model then there is probably an object there. If the measurement does not fit the model, the location is empty. With sufficient computational power, one could consider just fitting the model to every location in the survey field. We have taken a simpler approach that applies the model as a detection filter to a small window of data that is moved over the survey field. When the window is centered over an object, the filter response peaks. Such a filter should produce a response map which is a truer representation of the anomalies due to buried metallic object.

The basic idea of the detection filter is covered below, along with a discussion of the issues in implementing the filter with advanced EMI sensors. First, however, we review the basic dipole response model.

**Dipole Response Model**

In the standard dipole response model, we represent the target response by an induced dipole moment $m(t)$ which is proportional to the primary field $H_0$ at the target location. The proportionality factor is the target’s magnetic polarizability tensor $B(t)$. The elements $B_{ij}$ of $B$ form a $3 \times 3$ array of dipole moment components in the $i$ coordinate directions induced by excitation in the $j$ coordinate directions such that

$$m_x(t) = B_{xx}(t)H_{0x} + B_{xy}(t)H_{0y} + B_{xz}(t)H_{0z},$$
$$m_y(t) = B_{yx}(t)H_{0x} + B_{yy}(t)H_{0y} + B_{yz}(t)H_{0z},$$
$$m_z(t) = B_{zx}(t)H_{0x} + B_{zy}(t)H_{0y} + B_{zz}(t)H_{0z}.$$

Receive coils measure the signal from the induced dipole field. The sensitivity to the induced dipole components mimics the field that would be produced by currents flowing through the receive coil. Both the primary field and the receive coil response are calculated as Biot-Savart integrals around the coils. Writing $T$ for the field of the transmit coil and $R$ for the pseudofield of
the receive coil (including receiver gain factors), the signal from the transmit/receive coil pair is then simply

$$S = \mathbf{R} \cdot \mathbf{B}.$$

\(\mathbf{B}\) is a second rank tensor that depends on the size, shape and material properties of the target, as well as its orientation relative to the x, y, z coordinate directions. The target orientation relative to the x, y, z coordinate axes is specified by a set of roll, pitch and yaw angles \(\psi, \theta\) and \(\phi\). If the coordinate system is rotated by the angles \(\psi, \theta\) and \(\phi\) into alignment with the principal axes of the target, then the off diagonal elements of \(\mathbf{B}\) go to to zero \((B_{ij} = 0 \text{ for } i \neq j)\), and the diagonal elements correspond to the eigenvalues \(\beta_i\) of \(\mathbf{B}\). These are referred to as the target’s principal axis polarizabilities.

Using the dipole response model we can calculate the polarizability from EMI data collected over a target [10]. The target is classified as munitions (or other target of interest) or clutter depending on whether its polarizability is more munitions-like or clutter-like. Conventional dipole inversion uses an iterative search procedure to determine the dipole response model parameters which produce the closest match between the model and the measured response. The inversion algorithm can be split into two parts: a non-linear search for object location and a linear inversion for the polarization tensor in the earth frame [11]. The eigenvalues of this tensor give the three body-axis polarizations of the target and the eigenvectors give the body-axis orientation angles.

**Detection Filter**

To apply this inversion algorithm to a detection filter, the survey region is divided into a regular grid of potential object locations. Data about the current filter point is linearly inverted using the filter location for the model location parameters. The linear inversion is reasonably fast. The model and measured data are compared to give the filter output. While there are a variety of “goodness-of-fit” quantities, the coherence (squared correlation coefficient) between model and data was found to be an effective detection filter output. It provides a straightforward value between zero for poor match and not a likely object location and one for a perfect model-data match and a likely object location. While calculated as part of the process, the polarization tensor is not generally kept, only the filter output.

Figure 7 shows what happens when a dipole filter tuned to 75 cm deep targets is run over the 2x2 data from the Blossom Point 60mm line. The filter output is the squared correlation between the full multi-axis, multi-static 2x2 data set over a 16 point window and a dipole model fit to those data. When the data are processed this way we take advantage of the available signal excess in all of the 48 data channels and all of the time gates, and the 75 cm deep mortar signals become clearly visible. Tuning the filter to one meter does not bring out the mortars at that depth. At 100 cm the signal levels are only about 20% of the levels for the 75 cm mortars, and there is little or no signal excess remaining in any of the data channels.
A weakness of the standard approach to anomaly selection is that the peak EMI signal is not always at the object location. Elongated objects such as unexploded ordnance (UXO) have a stronger polarization on their long axis and horizontal UXO can produce double peaked responses with the object located between the two peaks. Using a dipole response filter with the advanced sensor systems solves this problem because the response peaks specifically at the locations of compact metal objects. Figure 8 compares EM61, 2x2 TEMTADS and MetalMapper signal levels and detection filter outputs for a pair of anomalies at the Spencer Range. Ground truth target locations are indicated by the blue diamonds. The detection filter does a better job of resolving anomalies and locating targets than conventional peak picking on signal level.

Figure 8. Comparison of signal levels and detection filter output for a pair of anomalies at the Spencer Range. Top contours are for Tz-Rz signal from EM61, 2x2, and MetalMapper. Bottom two plots are detect filter results for 2x2 and MetalMapper. Ground truth target locations are shown by the blue diamonds.
Implementation

In a stationary cued mode, the advanced sensors (2x2 TEMTADS and the MetalMapper), were designed to correctly invert for an object well centered under the array. The 2x2 achieves this with four horizontal transmits and four receive cubes in a square pattern. For each transmit, there is a co-axial cube and three offset cubes. This collects a sufficiently diverse set of direct Ti-Ri monostatic and Ti-Rj bistatic coupled data for an accurate set of inversion parameters. When objects are off-centered around the outer 0.1 to 0.2 m edges of the platform, the inverted location parameters become increasingly inaccurate. The MetalMapper achieves similar results by using three large orthogonal transmits and seven receive cubes. Again, for the MetalMapper in cued mode, objects around the edges do not always invert well.

Figure 9 plots Tz-Rz contours from the 2x2 and MetalMapper over a sample region from the Spencer Range demonstration. Contour levels are: 1 mV/A-black, 2 mV/A-green, and 5, 10, 20, 50 … - red. The thick black squares indicate the sensor transmit coils and the blue squares the receive cubes. The gray dotted lines are the measurement points as the sensors survey back and forth in a north-south direction. The 2x2 surveys with lane spacings of roughly 0.4 to 0.6 m apart. The MetalMapper has track separations of 0.5 to 0.75 m. Unlike cued data, the objects in the field may not be centered under the sensors as they pass over. Added to this, the measured positions may have errors on the order of 0.02 to 0.10 m. Accurate inversions typically require data from at least several tracks around the object’s location. The MetalMapper has the added difficulty that it only fires the Tz transmitter in survey mode.

Figure 9. Contours of Tz-Rz data from 2x2 and MetalMapper surveys at former Spencer Artillery Range. Contour levels are 1 mV/A-black, 2mV/A-green, and 5, 10, 20 … -red. Gray dots indicate sensor measurement points. Black squares sketch transmit coils and blue squares indicate receive cubes.
The problem then becomes how much data to include in the filter window about the given filter location. If the window is too small, the filter inversion will produce irregular results. Figure 10 plots contours of filter output for the 2x2 region shown in Figure 9. The three plots have varying filter window sizes: 0.7 by 0.7 m, 1.3 by 1.3 m, and 1.7 by 1.7 m. The window size is shown in blue for each. The contour levels start at a coherence value of 0.2 and increase in increments of 0.05. The dots are the instrument measurement locations. The filter results become increasingly smooth at larger windows. Over several demonstrations, the best rule of thumb was to select a window that includes three to four tracks of data and roughly 1 to 1.5 m of data along each track. Selecting even larger windows increases processing time and reduces resolution of items with overlapping signal.

Figure 10. Effects of varying filter window size on detect filter output from 2x2, same region as Figure 9. Contours start at 0.2 and increase in 0.05 steps. Black dots indicate measurement points. Blue squares indicate window size.

The grid density of (X0,Y0) positions is limited by processing time and uncertainty errors in the inversion. The detect filter was run on sample regions of the 2x2 data at Spencer at 0.01, 0.02, 0.05, 0.10, and 0.20 m resolutions. At grid densities greater than 0.10 m, the filter output became irregular around the peaks. This is comparable to the position errors of the system. For both the 2x2 and MetalMapper systems, a horizontal grid density of 0.10 was found to produce reasonably smooth filter output. Typically, a boxcar smoothing of width 3 would be applied to the detect filter contours at this resolution to further even out the results. At this grid density, roughly a hectare of 2x2 survey data could be processed in a 6-8 hour time frame. This is in un-optimized code run in the Excelis’ higher-level Interactive Data Language (IDL). Presumably, processing times could be improved.

The original thought was to run the detection filter grid over depths, Z0, as well. Processing time limits the density of Z0. The 2x2 Spencer data was run at filter depths of 0.0 to 0.3 m in steps of 0.05 m. Figure 11 plots the peak detection filter output for ground truth items versus their ground truth depth. The top plots are for TOI (37mm, ISO’s, 70mm) and the bottom plots are clutter. The plots from left to right are at filter depths of 0.0, 0.15, and 0.25 m. As expected, shallow
items have greater filter values for a shallow filter $Z_0$. Deeper items peak up more at deeper $Z_0$. However, all TOI have detect filter outputs greater than a value of 0.5 for a single filter depth setting of 0.15 or 0.25 m. At these settings, even the shallow clutter have detect filter values greater than 0.4. Given these results, it seems sufficient to run the detection filter over the survey site at a single depth setting. Under situations of deep UXO versus shallow clutter, the detection filter depth could be set to a deeper value to de-emphasize clutter items.

Figure 11. Peak detection filter output versus depth for TOI and clutter items at Spencer. Plots from left to right are at filter depths of 0.0, 0.15, and 0.20 m.
Detection based on Tz-Rz signal amplitude uses the forward EMI model to determine the weakest possible peak signal for a given TOI at its greatest depth of interest. This becomes the detection threshold. The detection filter threshold for a given TOI can be calculated in a more realistic fashion by embedding modeled TOI signals in background regions of actual survey data and processing this signal plus noise through the detection filter. For the TOI signal, the forward model parameters for location, depth, and orientation are randomly selected. This modeled signal is added to the measured noise and the detection filter is run. The model depth, peak signal+noise, and peak detection filter output are recorded. The detection filter is also run on just the measured background to determine the filter noise. This is done for several thousand random realizations. Figure 12 plots the results of this process for a 37mm signal embedded in 2x2 survey data from the Southwestern Proving Ground (SWPG) demonstration [12]. The signal results are for the 0.137 ms time gate. The plot on the left shows peak Tz-Rz signal amplitude. The plot on the right shows peak filter output. The black symbols are model plus noise and the red symbols are just noise. To detect 37mm’s down to 0.30 m, the peak signal threshold would be set to just under 2 mV/A. This is not significantly greater than the average peak noise level of 1.1 mV/A. The green curve is the model-based minimum response curve for Tz-Rz signal from a 37mm. The detect filter threshold for a 37mm at 0.30 m is 0.20. The average peak filter noise is about 0.05. The threshold is noticeably greater than the filter noise level. The detection filter takes advantage of all of the Ti-Rj channels and can be applied over a range of time gates. All of the added channels over simply using Tz-Rz, significantly increases the Signal-to-Noise Ratio (SNR) of the detection filter.

Figure 12. Plots of modeled signal randomly embedded in measured 2x2 survey background regions. Left plot shows peak signal amplitude for a randomly placed 37mm. Right plot shows peak detection filter output for the same random realizations. Black symbols are for modeled signal plus measured noise. Red symbols are peak measured noise.
The 2x2 signal noise levels are driven by the spurious voltages induced by the motion of the platform in the earth’s magnetic field. This platform is on wheels, and as it bounces over rough ground, the pitching and rolling motion induces a distinct and correlated noise signal. Figure 13 plots the RMS noise levels as a function of time gate for the 2x2 at the Blossom Point Test Field (left plots) and at the Spencer Demonstration (right plots). From top to bottom the plots are for the Rx (horizontal/cross track), the Ry (horizontal/along track), and Rz vertical receive cube components. The black (#1), red (#2), green (#3), and blue (#4) curves indicate which transmit coil is firing. The magenta curves are the noise levels for the sensor stationary. The noise in the early time gates includes Tx/Rx ring down effects. After this, the stationary noise falls off as $1/\sqrt{t}$ with time gate, which is expected given external EMI noise sources [13]. When the sensor is moving, the noise becomes essentially constant with time gate. The levels are higher at Spencer where the terrain is rougher than the test field.

Figure 14 plots the noise correlation as a function of time gate for all of the Ti-Rj channels with the Ry cube component when transmit #2 is firing. The plots across are by cube number and the plots down are cube component. The colors indicate which transmit is firing (#1-black, #2-red, #3-green, and #4-blue). The red curve for Ry, cube #2 is straight and a value of one because it is correlated with itself. All of the other Ry components when transmit #2 is firing are strongly correlated with this channel. That is because they are all experiencing the same motion in the earth’s field during the #2 transmit cycle and collecting the same induced noise voltage. The result is the same for any common cube component during the same transmit cycle. These data were from the north-south Spencer survey. The Rz components are weakly correlated with Ry. As the platform pitches, both of these components are intercepting the largest portion of the earth’s field. For east-west surveys, the platform roll drives coupling of the Rx and Rz cube components.
Figure 13. 2x2 signal noise levels as a function of time gate. Left side is from Blossom Point Test Field and Right side is from Spencer. Top to Bottom shows different receive cube components. Black, red, green, and blue curves are for different transmit coils. Magenta curve indicates stationary levels.
Figure 14. 2x2 noise correlations plots as a function of time gate. Plots across are for the four receive cubes (#1, #2, #3, #4). Plots down are by receive component (Rx, Ry, Rz). Colored curves indicate which transmit coil is firing (#1-black, #2-red, #3-green, #4-blue). All channels are correlated with the Ry component of cube #2 when transmit #2 is firing.

At the Fort Bliss Castner Range demonstration [14], the 2x2 platform was mounted on a two man carried litter. This greatly reduces the short time scale bouncing motion of the 2x2 platform. Figure 15 plots a comparison of the 2x2 noise levels at Spencer (magenta curve) and Castner (blue curve). The Castner levels begin to reach the stationary levels shown by the dotted line. The correlation of the noise between channels is reduced as well with the motion noise becoming comparable to or less than the other noise sources. Unfortunately, the litter-based platform was somewhat more variable in its height above ground and in its side-to-side motion. The system tended to sway with the carriers’ gait. The increased height would reduce signal and the swaying would increase positioning uncertainty.
The MetalMapper system has been typically deployed “bulldozer” style in front of or behind various tractor-like vehicles. These suspended platforms bounce at a slower rate than the 2x2 with its small wheels directly on the ground. The MetalMapper noise has been observed to be closer to stationary levels like the 2x2 Castner data. In one deployment at Fort Ord, the MetalMapper was dragged in a ground-based sled. The noise observed was constant with time gate like the 2x2.

An alternative to reducing motion-related noise by trying out different sensor platforms for both the 2x2 and MetalMapper may be to make use of a differencing scheme. Because the noise is highly correlated for common cube components, these components could be differenced to remove the noise. For the 2x2, data from Spencer was differenced by subtracting the back cube pair from the front pair and the port cube pair from the starboard. In background regions, the noise levels were decreased significantly. Unfortunately, this also differences the signals from targets and the overall SNR was not significantly enhanced. A better approach would be to locate a receive cube up above the array by roughly a meter. Differencing this cube from the lower ones could significantly decrease motion noise at only a small cost to the signal from targets at typical depths.

The sensor noise characteristics are used in the general inversion algorithm and in the detection filter. The noise levels measured at each site are used to weight the measured data by time gate in the linear inversion. These weights are also used in the calculation of the detection filter coherence parameter. Originally, the detection filter processing made use of all stable time gates (> 0.100 ms). With the noise constant as a function of time gate, but the measured signals falling off to some power law, it was noted that the signals in the later gates were often below the noise (SNR < 1). Between the low SNR and the correlation of noise across time gates, it was noted that the detection filter output was comparable whether several or all of the time gates were used. By processing with fewer gates, there was a small improvement in overall computational time.

Lastly, the full inversion of dynamic EMI data is sensitive to position errors; so, it effects the partial inversion in the detection filter as well. Past studies have determined that errors need to be
on the order of 0.01 m or less. The advanced EMI platforms make use of Global Positioning System (GPS) location and an inertial measurement unit (IMU) to map out the full three dimensional position of the sensor. However, there have been issues with implementing these position sensors with the EMI system. The GPS antenna is up above the sensor to reduce the EMI response to metal in the GPS. Because of this, the yaw, pitch, and roll from the IMU is needed to correct for the GPS offset. At the Spencer demonstration, the IMU was not yet working on the 2x2. At Southwestern Proving Ground, it was observed that the electronic compass on the IMU was not tracking correctly. It had been inadvertently mounted off-center and either the firing of the transmit coils or some ferrous metal in the GPS antenna was affecting it. Most importantly, there is no accurate matching of the GPS measurement time to the EMI firing cycle in the current advanced systems. The GPS data is simply recorded during each transmit cycle. For the 2x2 in survey mode, a transmit cycle is the time to fire the four coils and is $4/30$th's of a second. At sensor speeds of up to one meter per second, position errors can be on the order of 0.10 m.
Results and Discussion

Dynamic 2x2 data from Camp Spencer, Southwestern Proving Ground, and Fort Bliss Closed Castner Range have been processed by the detection filter. Spencer results were compared to ground truth. SWPG results were compared to a small area of cued measurements and ground truth. The Castner Range analysis concentrates on the large number of seeded ISO’s (58) to compare detection filter and cued results. The filter has also been tested on MetalMapper data from Camp Spencer and Camp Ellis [15]. No complete analysis has been done on the MetalMapper results.

At Spencer, roughly 0.5 hectares were surveyed dynamically by an EM61 cart, the 2x2 on wheels, and the MetalMapper front-mounted on a tractor. Target locations were picked based on Tz-Rz amplitude signal peaks greater than a threshold needed to detect 37mm’s to a depth of 0.35m. Using the signal peaks from the three sensors (many in common, some unique to a single sensor), roughly 340 locations were flagged, measured by the advanced sensors in cued mode, and excavated for ground truth. An example of target response data from Spencer was shown in Figure 8. The plots across the top in that figure are Tz-Rz contours for the three sensors. The MetalMapper contour is for all seven cubes and because of overlap between tracks not as clean as other plots. The blue symbols indicate object locations based on ground truth. There are only two targets present, but the EM61 and 2x2 clearly show two peaks for the target on the left. This is an example of a horizontal, elongated object. The detect filter peaks clearly show only a single peak at the correct location. Figure 16 plots the distance from ground truth location of the detection filter peak versus the signal amplitude peak. The bulk of the results show comparable average distance from ground truth of about 0.10 m for the two peaks. There is, however, a distinct subset of targets where the signal peak location is farther off. These are double peak targets. Overall, the detection filter peak locations are always less than 0.40 m.

There were only 340 amplitude-based picks at Spencer, but at the detect filter threshold of 0.4 there were over 600 picks. This threshold was based on a modeled 37mm signal to 0.35m depths in the Spencer measured background. The detection filter was run at a depth setting of 0.15 m and appears to be enhancing the signal of a great deal of small clutter. To eliminate this small clutter selection, quick polarization estimates were found at each filter peak location. Basically, the filter value of X0, Y0 was frozen at each peak and the filter varied in Z0. The Z0 value with the best filter coherence result was kept along with the polarizations. Peak locations with polarizations too small to be a 37mm were eliminated. By doing this, over two thirds of the detect filter locations were eliminated. Based on the ground truth, no TOI were eliminated.
Figure 16. Location accuracy of signal peaks versus detection filter peaks. Distance from ground truth location is plotted for both. Peak signal locations were based on measurements primarily from the EM61 with added peaks where the 2X2 peak signal picked up an item not detected by the EM61 or resolved several items where the EM61 did not.

The 2x2 survey at SWPG covered roughly 1 hectare. The detection filter was set to a filter depth of 0.20 m. A detect filter threshold of 0.30 was selected based on finding a 37mm at a depth of 0.30 m. There were roughly 2500 detect filter peaks per hectare (Spencer ~1200/ha). Targets for cued identification were picked based on signal amplitude over a sub-area of roughly 1000 m². There were 500 cued targets giving a much larger density of 5000 targets per hectare. Figure 17 plots contours of Tz-Rz and detect filter coherence over the same area of cued targets at SWPG. The blue symbols show where cued targets were selected. There are a large number of very small footprint targets that are above the amplitude threshold but below the filter threshold.

Figure 17. Contours of Tz-Rz (left) and detect filter coherence (right) over a region of cued targets at SWPG. Tz-Rz contours are 1-black, 2-green, 5, 10, 20…-red. Detect filter contour levels are 0.3, 0.4, 0.5 … 1.0. Blue symbols are cued targets selected on signal amplitude.
Figure 18 attempts to separate out the clear cases of ground truth items where the both the cued fit locations and the detection filter location match the ground truth and where the cued fit matches, but there is no matching detect filter pick. There are some cases of multiple ground truth items near each other that are hard to resolve with either one or the other or both of the picks. In the plot, for each ground truth item, the x-axis is the distance to the nearest cued fit and the y-axis is the distance to the nearest detect filter pick. The region where both are within 0.25 m is very similar to the Spencer results in Figure 16. Items within this region are clearly being selected by both the cued fit and the detect filter. Note that the average distance from ground truth in this region is again about 0.10 m. The items highlighted in blue are within 0.25 m of the cued fit, but are farther than 0.40 m from the nearest detect filter pick. These are items that the detect filter clearly did not pick. The next two figures will look at the polarizations and fit depths of these two groups.

Figure 18. A plot of nearest detection filter pick distance from ground truth item versus cued target location distance from ground truth item. When both picks are within 0.25 m of the ground truth, it most likely indicates both match to the ground truth item. Items where the cued location is with 0.25 m but the nearest detect filter pick is greater than 0.4 indicates an item selected on signal amplitude but ignored by the detection filter (shown in blue).

Figure 19 shows the cued fit results divided between these two groups: location matches of cued fit and detect filter (black) and cued fit with no nearby detect filter location (blue). The first graph is secondary versus primary size parameter from the 0.210 ms time gate. The size parameter is just the cube root of the polarization. The six TOI, which were located by both, are plotted in red. In this plot there is no clear indication as to what the difference is between these groups. The second plot is primary size factor versus fit depth. There is a clear delineation in this
The detection filter threshold was set to 0.3 to catch 37mm’s down to a depth of 0.30 m. This filter threshold eliminates small, shallow objects and larger deeper objects. The dotted line is a rough separation between the two. The TOI at a depth of 0.125 and primary size just under 1.0 is a 37mm. Objects with a comparable size parameter are picked up by the filter down to a depth of 0.30 m. The bulk of the items not found by the filter are in a depth range of 0 to 0.20 m and a size range of 0.3 to 0.6. These are small clutter items too small to be TOI, but have signal amplitudes above the Tz-Rz based threshold.

![Cued and Detect Filter Results](image)

Figure 19. SWPG cued fit results divided into matches to detect filter (black) and not matched to fit detect filter (blue). The six TOI (red) matched between cued and detect filter locations. The plot on the left shows the secondary versus primary size factor (cube root of polarization) for the time gate at 0.210 ms. The plot on the right plots primary size factor versus fit depth.

To further process and characterize the detection filter locations, a hybrid approach was taken with the SWPG data. At each detection filter peak, a window of data was carved out and run through a full inversion. For the matched items, Figure 20 compares the cued polarizations and the dynamic data polarizations inverted at these data windows. The TOI are indicated by red symbols. The polarizations are plotted as a size parameter, the cube root of the polarization. The first plot is the secondary versus primary size from the cued fits at the 0.210 ms time gate. The second plot is the same size factors from the dynamic data fits. The last plot is the primary size from the dynamic fit versus the primary size of the cued fit. Overall, the fits results are in good agreement.
Figure 20. Polarization size parameters from cued and dynamic inversions for matching SWPG ground truth items. From left to right: secondary versus primary size from cued fit, secondary versus primary size from dynamic fit, and primary of dynamic versus primary of cued. Results are for 0.210 ms time gate. TOI are indicated by red symbols.

With the high target density at SWPG, it was noted that there are a significant number of regions with overlapping and merged signals from multiple targets. As seen in Figure 21, in regions where the signals are overlapping, the detection filter contours also overlap and merge. The top two plots show Tz-Rz and detect filter contours about several signal areas from SWPG data. The solid detect filter contours start at the threshold of 0.3 and increase. The dotted contours are below threshold at 0.1 and 0.2. The region to the upper left displays two merging peaks in the detect filter. The small, single targets on the right side have reasonably circular detect filter peaks. The center region has an elongated, distorted single peak. Detect filter peak locations are marked with a cyan triangle. In an effort to flag possible multiple targets, besides running a single dipole inversion on a data window about each detect filter peak, several N-dipole inversions have been run as well. Initially, N = 2, 3, 4 dipoles fits were run at every detect filter peak. The processing time for this was well over several days for the 2500 peaks on the hectare of SWPG data. The run time was reduced to one day by taking fewer initial conditions and only N = 2, 3. The blue diamond symbols indicate the results of a 3-dipole fit on the dynamic data about the central detect filter peak. The magenta X’s mark the ground truth locations where munition fragments were found. The match is quite good. Cued data was collected in the upper right and lower left of this region. The lower plots show the inverted, single dipole cued polarizations in black. The matching dynamic 3-dipole polarizations, items A, B, and C, are shown in blue and cyan. The left plot is for the upper right cued location and is closely matched by item A of the 3-dipole dynamic fit. The right plot is for the two lower left ground truth items. Only a single dipole fit was available for the cued data, but items B and C indicate two small pieces of clutter.
Figure 21. 3-Dipole fit example. Tz-Rz contour peaks indicated two fit locations, SW-31084 and SW-31099 (upper left plot). The detection filter found only a single distorted peak (upper right plot). As a hybrid approach a data window is clipped about each detect filter peak and full N-dipole inversions are run for N=1, 2, 3. In this case a 3-dipole fit matched the ground truth. Ground truth locations are plotted with magenta X’s. Detect filter peaks are cyan triangles. The 3-dipole dynamic data fit are blue diamonds. The lower plots show the two single cued fits and the 3-dipole dynamic fit polarizations.

The 2x2 survey at Fort Bliss, former Castner Range covered roughly 1.9 hectares. As noted before, the sensor platform was carried on a two man litter at a height of roughly 0.35 m. The litter platform reduced sensor noise, but at the price of positional accuracy from platform sway and reduced signal strength due to the increased platform height. The lane spacing of the survey was 0.6 m instead of 0.4 m. It is not clear if the increased lane spacing reduces detection based on signal strength or detection based on the detection filter. With the other changes (platform type, sensor height, terrain, etc.), this is not the data set to determine the effect of lane spacing.
The detection filter threshold was set at 0.20 in an attempt to correct for the increased sensor height. Filter thresholds lower than this are too close to the filter noise levels. There were 4050 detection filter peaks above this threshold, giving roughly 2100 peaks per hectare (slightly less than SWPG). The site was divided into 30 square grids and cued targets were selected from 15 of these grids. The selection was presumably based on some signal strength above threshold. For typical TOI at desired depth, the threshold is in the 1 – 2 mV/Amp range in the 0.137 ms time gate. The final cued list had roughly 1500 locations resulting in a density of 1580 locations/ha. The final ground truth lists about 1800 items dug probably indicating a higher target density and a reasonable probability of multiple targets at a given location. The TOI included fifty-eight small ISO’s, nine 37 mm’s (of a type not seen at other demonstrations), a single 25 mm, and a single 105 mm. The clutter included fuzes, pieces of 37mm’s, 50 caliber bullets, other larger shell fragments, and other metallic scrap. There were 125 cued locations given as “no contact,” but many of these listed small bits of metal in the vicinity. Overall, it was a cluttered site.

Figure 22 plots contours of Tz-Rz and detect filter coherence over the same area at Fort Bliss. The blue symbols show where cued targets were selected. While there are some small footprint Tz-Rz targets eliminated by the detect filter, there are a number of cued targets where we see no Tz-Rz signal. There are also detect filter peaks with no apparent Tz-Rz signal. Lastly, the areas of significant signal seem occur in streaks from northwest to southeast.

Figure 22. Contours of Tz-Rz (left) and detect filter coherence (right) over a region of cued targets at Fort Bliss. Tz-Rz contours are 1-black, 2-green, 5, 10, 20…-red. Detect filter contour levels are 0.2, 0.3, 0.4, 0.5 … 1.0. Blue symbols are cued targets selected on signal amplitude.
The Fort Bliss survey tracks ran from southwest to northeast orthogonal to elevation changes and drainage channels. Figure 23 compares elevation contours to the 2x2 Tz-Rz signal contours. There are alternating regions of high and low signal running orthogonal to the sensor tracks. To zero background level shifts in the sensor data we run a long scale length demedian filter. If there are sudden shifts in the background level, the filter does not work as well. The contours of Tz-Rz have blue levels indicating negative values of -1, -2, and -5 mV/Amp. Basically, these regions of low signal have changing values that the filter cannot correct for. It is assumed that these changing levels result from changing soil/geology signal strengths and possibly changing platform height as drainage channels are traversed. It also seems like much of the metallic debris is washed to the sides of these channels.

![Figure 23](image)

**Figure 23.** The left plot shows contours of elevation based on the 2x2 platform’s GPS antenna. The contour steps are 0.20 m and lower elevations are to the right side. The right plot shows contours of Tz-Rz signal amplitude. The black, green, and red contours are the same as in previous figures. The blue contours show negative signal levels of -1, -2, and -5 mV/amp.

Given the complexity of resolving the cued picks and detection filter peaks with the ground truth, we have chosen to concentrate our analysis on the one consistent TOI item on the site, the small ISO. Of the 58 ISO’s emplaced, one was missed due to lack of coverage; it was placed in a patch of cactus. Of the remaining 57, ten ISO’s were greater than 0.40 m from a detection filter peak. Figure 24 plots the separation of signal peak, detect filter peak, and N-Dipole fit location from the ground truth location of the 57 ISO’s. The left plot is detect filter peak versus signal peak. For 10 of the ISO’s, the detect filter peak was greater than 0.40 m. For 4 of these (green diamonds), the standard N-Dipole fit from the data clipped about the detect filter peak found the ISO’s. Six were missed either because the region was complex with multiple targets or because
the detect filter peak was below the 0.20 coherence threshold (Note: one of these, CR-1506 is off the y-axis in the left plot). For the six missed ISO’s, the data was re-clipped about the ground truth location and fit by the N-Dipole model with N = 1 through 6. The plot on the right shows the fit location separation from ground truth versus the signal peak separation with the six corrected fits (red triangles). All fit locations but one were within 0.20 m of the ground truth. The outlier, CR-1503, does not show any signal at the ground truth location. The N-dipole fit for N = 4, finds an object with ISO like polarizations 0.70 m away.

Figure 24. Separations of signal peaks, detect filter peaks, and N-Dipole fits from the ground truth location of the 57 ISO’s emplaced at Fort Bliss. The left plot shows detect filter separation versus signal peak separation. The right plot indicates N-Dipole fit location versus signal peak separation. The green diamonds indicate ISO’s found by the N-Dipole fit at a detect filter peak. The red triangles indicate ISO’s not near a detect filter peak that was above the 0.20 threshold. For missed ISO’s, data was re-clipped about the ground truth location and run through the N-Dipole fit with N = 1, 2, … 6. All but one of the fit locations was within 0.20 m.

Figure 25 plots an example where the detect filter peak missed the ISO, but an N-Dipole fit in a window about the peak picked up the ISO. The problem is that a nearby item dominates both the measured signal and the detect filter output. The peak signal location is on top of an M48 fuze (blue triangle) with the ISO (magenta X) 0.65 m away. A fit of the cued data indicates only the fuze. In a similar fashion, the detection filter contours are dominated by and peak at the fuze. The contours, however, are distorted in the direction of the ISO. The dynamic data clipped about the filter peak (blue rectangle) returns the polarizations of both the fuze and the ISO for an N=2 dipole fit.
Figure 25. Contours of signal and detect filter about an ISO detected with N-Dipole fit from data clipped at detect filter peak. The left plot is signal amplitude with 1 mV/Amp-black, 2 mV/Amp-green, and 5, 10, …-red. The dotted lines are the platform tracks. The blue triangle is the field selected peak signal. The magenta X is the ground truth location. The right plot is contours of detect filter output. Solid lines are steps of 0.2, 0.3, 0.4 …. Dotted contour is below threshold at 0.10. The blue diamond is the filter peak. The cyan diamond is the N-Dipole fit location of the ISO. The magenta X is the ground truth location. The blue rectangle is the window of data about the filter peak used for the N-Dipole fit.

Figure 26 shows an example of a complex region about an ISO missed by the detect filter peaks and by N-Dipole fits from data about the peaks. There are multiple regions of larger signal about the ISO. It is not clear why the field analysis picked the signal peak location (blue triangle); we do not see a peak there…presumably, differences in mapping of the sensor and interpolation of the data. There is a region to the left (negative signal - blue contour) where our processing did not properly zero the data. The detect filter peaks are dominated by the adjacent regions. The data carved out and fit about each was dominated by multiple objects near the peaks. The localized negative signal also produces a detect filter peak. The N-Dipole fit produced a result with completely negative polarizations. This occurred in a number of the small negative regions. By carving out just a small region about the ground truth, we managed to get a fit to the ISO indicated by the cyan diamond in the right plot.
Figure 26. Contours of signal and detect filter about an ISO missed by detect filter peaks and by N-Dipole fits at the peaks. The left plot is signal amplitude with 1 mV/Amp-black, 2 mV/Amp-green, and 5, 10, …-red. The blue contours are for negative signal of -1, -2 mV/Amp. The dotted lines are the platform tracks. The blue triangle is the field selected peak signal. The magenta X is the ground truth location. The right plot is contours of detect filter output. Solid lines are steps of 0.2, 0.3, 0.4 …. Dotted contour is below threshold at 0.10. The blue diamond is the filter peak. The cyan diamond is the N-Dipole fit location of the ISO from data re-clipped about the ground truth location. The magenta X is the ground truth location.

Along with the difficulty in detection, there appears to be a bias in the polarization fit results from the ISO’s. Figure 27 plots the polarization fit results for the ISO’s in the field at Fort Bliss (left and right plot) and for the IVS strip ISO’s (middle plot). The left plot is from dynamic survey data. The IVS plot is also dynamic data taken over the same five ISO’s over multiple days. The right plot is from cued data over the field ISO’s. For comparison, the standard library response for the ISO to dynamic data is plotted in blue. While the IVS and cued data shows variability about the expected polarization, the dynamic field data shows a bias towards smaller polarizations. Our best guess is that the offsets in the background levels bias the fit results in this direction. The offsets tended to be on the order of minus 1 to 2 mV/Amp and many of the ISO’s were in the 5 to 10 mV/Amp range.
Figure 27. Polarization fit results from the Fort Bliss ISO’s. The left plot is from the dynamic survey data of ISO’s in the field. The middle plot is from multiple fits of the 5 ISO’s in the IVS strip at Fort Bliss. The right plot is from fits to the cued data of the field ISO’s. The polarizations are plotted primary-black, secondaries-red, green. The blue curves are the expected library response from dynamic data for the ISO’s. The dynamic field fits show a bias to smaller values.

As a sanity check on the difficulty of detecting ISO’s at Fort Bliss, we ran the simulation embedding modeled ISO signals in actual background noise regions of the Fort Bliss survey. Figure 28 plots the peak modeled signal plus measured noise (black diamonds) and peak noise signal (red diamonds) as a function of modeled object depth (sensor height of 0.35 m above ground). The green curve is a calculation of the minimum signal an ISO should give as a function of depth given a 0.60 m lane spacing. There are a scattering of black diamond’s occurring below the green curve. Presumably, the modeled signal has been added to a background region with a negative offset. The actual peak ISO signals from the field survey are plotted as a function of fit depth (blue diamonds). Again, a scattering of points falls below the expected curve.

The ground truth lists the ISO depths ranging from 0.08 to 0.30 m. A plot of the ground truth depth versus fit depth showed little correlation. Between the uneven terrain and the sway of the sensor platform, this is not surprising. The sensor height above ground probably varied by at least 0.10 m. Combining this with all of the other limiting factors, it is not surprising that some ISO’s went undetected by either signal amplitude, detect filter amplitude, or both.
Figure 28. Simulation result of embedding modeled ISO signal in measured background regions of Fort Bliss noise. The resulting simulated peak signals are plotted as a function of depth with black diamonds. The peak noise signals from the background regions are plotted with red diamonds. The green curve is the calculated minimum response curve for an ISO given the 0.6 m lane spacing. The blue diamonds are the peak signals and fit depths for the ISO’s measured in the field with dynamic data. A sensor height of 0.35 m has been assumed.

Conclusions and Implications for Future Research/Implementation

A detection filter has been implemented for dynamic survey data from advanced EMI sensors. By applying the standard dipole inversion model to a fixed grid of locations, the fit quality parameter, coherence between model and measured data, can be used as a single detection quantity. Contour plots of detection filter coherence can be used to pick peak locations as possible targets.

This approach has several advantages over the current technique of looking at only measured signal amplitude and picking regions of peak signals. Typically, only a single component (Tz-Rz) of the multi-channel sensor data is looked at, because it peaks up with only positive polarity at roughly the target’s location. However, there are situations where the Tz-Rz signal has double peaks for a single target. Based on the dipole model, the detection filter makes use of all channels of data and peaks only at the target location.
Similar to the signal amplitude approach, forward model signals can be used to set a detection filter threshold for a given TOI at its maximum depth of concern. Unlike the model-based Tz-Rz threshold however, the detection threshold is based on embedding the model signal in background areas of the actual survey data and applying the filter to both model+noise and just the measured noise. Doing this gives an estimate of both the filter signal output and the filter noise. Because the filter is making use of all data channels, the SNR of the filter output is greater than the SNR of just the Tz-Rz signal amplitude.

In applying the detection filter concept to dynamic 2x2 survey data at Spencer, SWPG, and Castner Range, the detect filter processing was refined and several limiting factors noted.

Rather than running the filter at a variety of depth settings, it was observed that a single moderate depth was sufficient to give a good filter response to all TOI over a range of sizes and depths. At SWPG, the filter response was found to de-emphasize a large number of small, surface clutter items and place them below the filter detection threshold. The same items were above the signal amplitude threshold.

As part of the processing, data windows were taken at each detect filter peak and full N = 1, 2, 3 dipole inversions were run. At Spencer, the single dipole inversion result was found to be sufficient to eliminate two thirds of the detect filter peaks based on the inverted polarizations being much smaller than the TOI. At SWPG, a large number of merging and overlapping signal regions were found. Typically, this would produce corresponding overlapping and distorted peaks in the detection filter. Applying the N-dipole fit was found to flag multiple item cases and often matched the ground truth. Finding TOI at Fort Bliss also required the N-dipole fit. However, in concentrated regions of clutter, some TOI were still missed. Increasing the number of dipoles fit may improve this, but there were several other factors limiting the Fort Bliss results.

Stationary EMI noise levels fall off with time gate and do not correlate across receive channels. Unfortunately, in motion, the 2x2 sensor on a wheeled platform is dominated by induced voltages from the receive coils bouncing in the earth’s magnetic field. This noise is constant across time gate and correlated between common receive cube components. This in turn reduces the SNR boost from applying the detection filter. This noise is apparent in the MetalMapper on a ground dragged sled, but reduced when it is on a vehicle mount. This noise source could also be reduced by differencing the receive cubes with an extra one mounted above the sensor.

Because the detection filter is based on the inversion model, the quality of the results is strongly affected by position errors. The current advanced EMI acquisition systems do not adequately match the position measurements in time to the EMI data. It is hoped that future systems address this issue.

The IDL code for processing 2x2 and MetalMapper dynamic data, running the detection filter, and inverting any EMI sensor data are available for distribution. Eventually, this code will be
implemented in UX-Analyze. The detection filter process was applied to 2x2 dynamic data collected for the Former Camp San Luis Obispo Treatability Study by associates at Acorn SI. They have also used the algorithm on MetalMapper data collected for an ESTCP Live Site Demonstration at 29 Palms [16].
Literature Cited


List of Scientific/Technical Publications
