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Detecting and Classifying UXO

Laurens Beran
Black Tusk Geophysics Inc. and the University of British Columbia

Barry Zelt
Black Tusk Geophysics Inc

Stephen Billings
Black Tusk Geophysics Inc

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This article presents state-of-the-art unexploded ordnance detection and classification, including examples from recent field-demonstration studies. After reviewing sensor technologies, with a focus on magnetic and electromagnetic systems, the authors discuss advanced processing techniques that allow for reliable discrimination between hazardous ordnance and harmless metallic clutter. Finally, the article shows results from a large-scale field demonstration conducted in 2011. In this case study, electromagnetic data acquired with an advanced sensor is used to identify ordnance at the site, reducing the number of excavations required with conventional metal detectors by 85%.

by Laurens Beran [Black Tusk Geophysics Inc. and the University of British Columbia], Barry Zelt and Stephen Billings [Black Tusk Geophysics Inc.]

The extent of global unexploded ordnance contamination has motivated research into improved technologies for unexploded ordnance detection and classification. In particular, the U.S. Department of Defense's Environmental Science Technology Certification Program has funded the development of sensors and data-processing techniques specially designed to reliably identify buried UXO.

As part of this research effort, ESTCP conducted a series of field demonstrations to validate detection and classification technologies. The first demonstration, conducted in 2010 at Camp Sibert, Alabama (U.S.), required the discrimination of large 4.2-in mortars from metallic ordnance debris.[1] Subsequent demonstrations progressively increased in difficulty. For example, the 2011 Camp Beale demonstration (Marysville, California, U.S.) required the identification of small 37-mm projectiles and fuzes in rigorous terrain. Throughout the demonstration program, a number of participants achieved near-perfect UXO identification.[1,2,3,4]

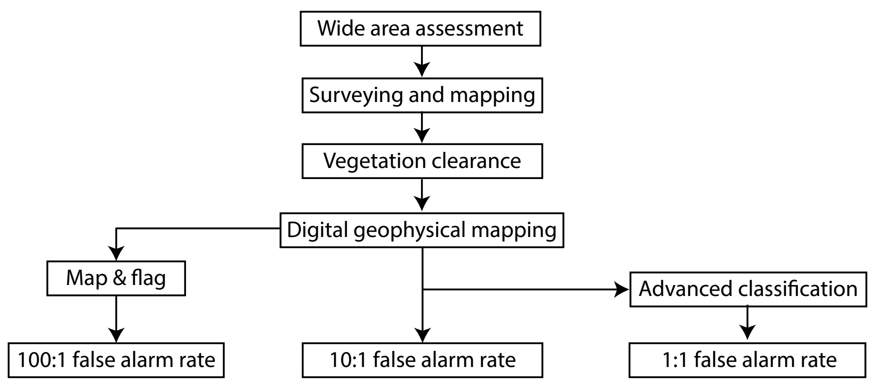


Figure 1. Flowchart for remediation of UXO. Wide area assessment identifies areas of likely UXO contamination at a site, followed by detailed mapping to delineate survey areas. Vegetation must also be cleared to allow deployment of sensors for detection of buried metal. Projected false-alarm rates for remediation strategies (mag and flag, digital geophysical mapping and advanced classification) are for typical munitions response sites within the United States. *All graphics courtesy of the authors.*

Detection

Figure 1 depicts paradigms for detection and classification of buried UXO. The conventional **mag-and-flag** approach uses metal detectors operated by expert technicians to identify targets, which are then flagged for subsequent digging. No digital data are recorded, and changes in an audio tone usually indicate detection. This method is not consistent because success depends upon the operator's skill. In addition, the mag-and-flag approach offers limited possibility for discrimination between hazardous ordnance and clutter. Although the projected cost of this approach is prohibitively high (Figure 1), the mag-and-flag approach will always have a role in UXO clearance—primarily to survey areas inaccessible to other sensors (e.g., around trees, in gullies) and as a first stage clearance of highly cluttered areas.

The second mode of UXO detection, **digital geophysical mapping**, uses geophysical sensors connected to a data-acquisition system to record digitized data acquired over a survey grid. DGM data are subsequently processed to identify high priority targets, which are likely to be buried ordnance. Simple processing techniques, such as digging detected targets based on the measured data's amplitude, can reduce the number of false responses to approximately 10 non-UXO per UXO excavated. Applying advanced classification methods to digital geophysical data further reduces the rate of these false responses and greatly increases confidence of successful ordnance clearance. In a technical report published by the U.S. Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, Delaney and Etter estimate the cost of UXO remediation projects within the U.S. at US$52 billion with mag and flag, versus $16 billion with advanced classification.[5]

Magnetic and electromagnetic geophysical data types are most commonly acquired for UXO detection and discrimination. Magnetic instruments are used to measure distortions in the Earth's geomagnetic fields produced by magnetically susceptible materials (e.g., steel). Magnetic sensors deployed for UXO detection typically either measure the total magnetic field (scalar measurement) or the difference between two closely spaced magnetometers, measuring

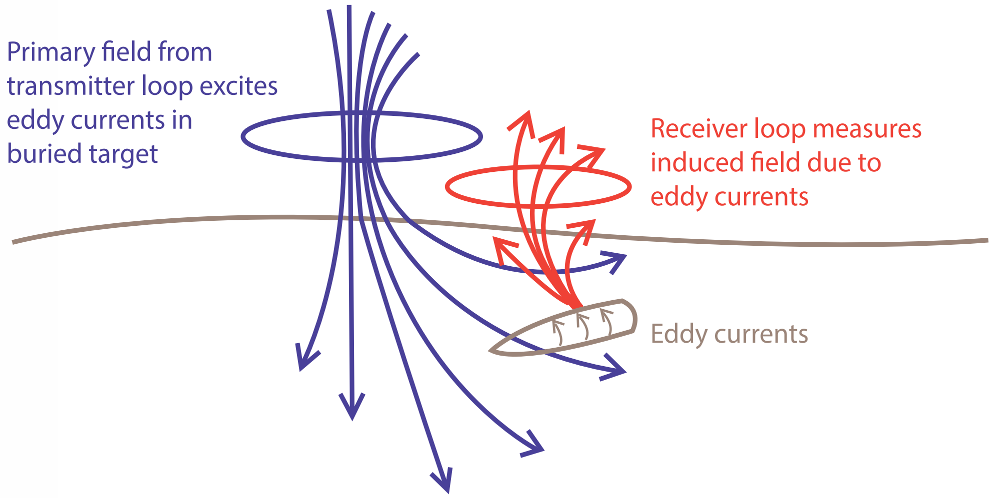


Figure 2. Electromagnetic induction survey. Eddy currents are induced in a buried target by a time-varying primary field. Decaying secondary fields radiated by the target are then measured by a receiver at the surface.

the vertical component of the magnetic field (gradiometer measurement). Magnetic-sensor arrays have been deployed for helicopter-borne surveys (**heli-mag**) in wide-area assessments.[6] Multiple magnetometers can also be arranged in arrays for ground-based surveying, using wider swaths to decrease the number of passes required to cover a given area. A significant background soil response, which can obscure identification of discrete targets in the measured signal, often complicates the processing of magnetic data. In addition, magnetic data can only provide limited information about intrinsic target properties (i.e., size and shape) and are rarely used to classify detected targets as UXO and non-UXO.[7] Therefore, the remainder of this article focuses on classification with electromagnetic data.

Processing of electromagnetic data produces a unique intrinsic response (or fingerprint) for each target, which can then be matched with responses for known ordnance types. As depicted in Figure 2, electromagnetic instruments actively transmit a time-varying, primary magnetic field that illuminates the Earth. The variation of the primary field induces currents in the ground, and these currents produce a secondary field that a receiver on the surface can measure. EM sensors measure the decay of these secondary fields after the primary field is switched off. The secondary fields, in turn, provide information regarding electrically conductive items in the ground.

EM sensors designed for UXO applications come in a wide variety of geometries, ranging from cart systems with multiple transmitters and receivers to single loop, man-portable systems. The Geonics EM-61, an ubiquitous time-domain instrument, transmits from a single horizontal coil. When the primary field is terminated, the EM-61 measures the decaying secondary field in a horizontal receiver loop at four discrete time channels. This instrument is robust, easy to use and consequently, popular for UXO detection and other environmental applications. However, the range of time channels is fairly short, and the paucity of receiver and transmitter combinations (relative to newer systems) limits this instrument's classification capability.

Table 1 shows EM sensors, which have been applied to UXO detection and classification problems. This is not a comprehensive list of EM sensors, but is intended to illustrate the recent evolution of sensors from few channels to many channels over a long period of time and the shift toward configurations with multiple transmitters and receivers.

Two types of surveys, or search patterns, are common with EM instruments.[6] A detection-mode survey passes the sensor over an area along closely spaced parallel lines, typically such that adjacent sensor passes are between 50 and 100 cm apart. Sometimes perpendicular lines are also acquired to maximize data coverage over targets and ensure their illumination from multiple angles. The data are acquired approximately every 10 cm along each line. Towed arrays of EM sensors can quickly cover large areas, while single-sensor pushcart systems are much slower. Pushcart or man-portable EM systems are therefore better suited to the cued-interrogation mode of surveying. In this mode, a DGM survey initially identifies anomalies, and high fidelity data are subsequently acquired over each target. Recently developed systems for stationary cued interrogation (e.g., MetalMapper and TEMTADS, Table 1) illuminate the target with multiple transmitters and receivers, thereby circumventing the requirement for accurate positioning of moving sensors.

Classification

Once a digital geophysical map with a ground-based sensor is acquired, a number of processing steps are required to produce a prioritized dig list of targets for excavation. Figure 3 shows the typical processing involved in advanced classification.

Target selection identifies anomalies in the digital geophysical map down to a pre-defined amplitude threshold. The threshold is usually based upon the minimum expected data amplitude for the smallest target of interest (i.e., UXO) at a site. All designated targets are then revisited to acquire cued-interrogation data from each one.

Each designated anomaly is characterized by estimating features from the cued data, which subsequently allows a data analyst to discern UXO from nonhazardous clutter. These features may directly relate to the observed data (e.g., anomaly amplitude at the first time channel), or they may be the parameters of a physical model. The former approach is appealing in its simplicity but is generally not an effective strategy for classification. An ordnance item at depth will produce a small anomaly amplitude and might be left in the ground with a dig list based solely upon anomaly amplitude. Most classification strategies therefore use physical modeling to resolve such ambiguities.

Bell et al., Pasion and Oldenburg, and Zhang et al. give detailed descriptions of the physical modeling used for processing EM data.[8,9,10] In the feature estimation stage, these models are fit to the observed EM data for each target anomaly. This fitting is analogous to fitting a straight line to data via least-squares regression. In that case the model is parameterized by slope and intercept; here the model is parameterized by target location,

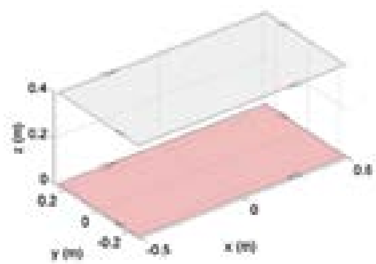
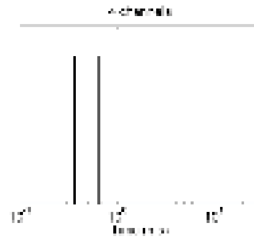
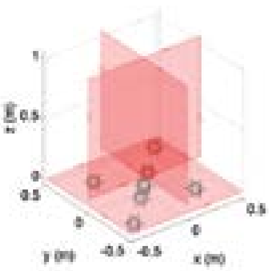
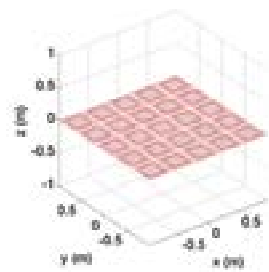
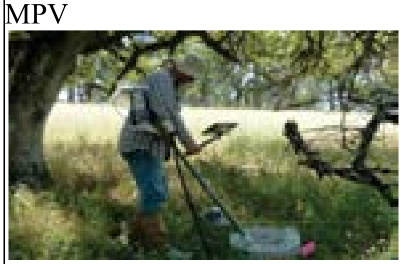
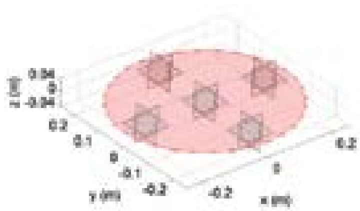
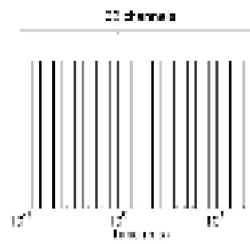
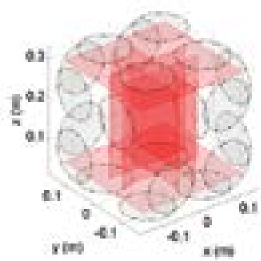
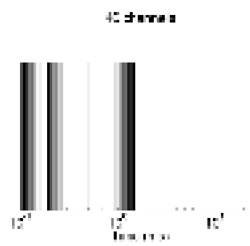
Sensor	Geometry	Time channels
EM-61 		
MetalMapper 		
TEMTADS 		
MPV 		
BUD 		

Table 1. Electromagnetic sensors used for UXO detection and classification. Red and black lines in the middle column indicate transmitters and receivers, respectively.

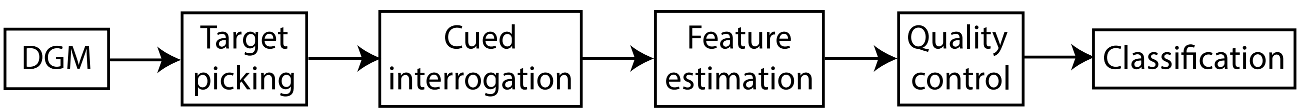


Figure 3. Processing steps for UXO classification.

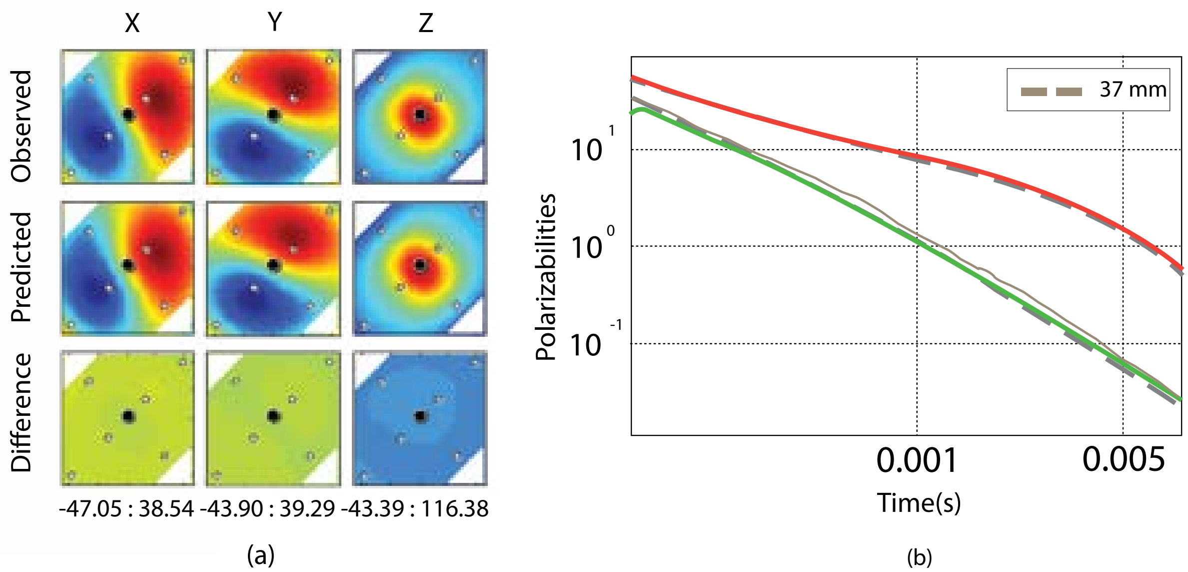


Figure 4. Fitting MetalMapper data. (a) Observed data (top row) and data predicted by fitting a physical model to the observed data (middle row). Bottom row shows the (negligible) difference between observed and predicted data. Each column shows the X, Y and Z components of the measured data, with MetalMapper receiver locations indicated by white circles. The black circle is the estimated location of the target. Numbers at the bottom of each column indicate the range of data values (in arbitrary units). Colored images map blue and red to low and high data values, respectively. (b) Estimated polarizabilities (colored lines) recovered via fitting, overlain on known polarizabilities for 37-mm projectiles. The excellent correspondence between recovered and reference polarizabilities indicates—with high confidence—that the detected target is a 37-mm item.

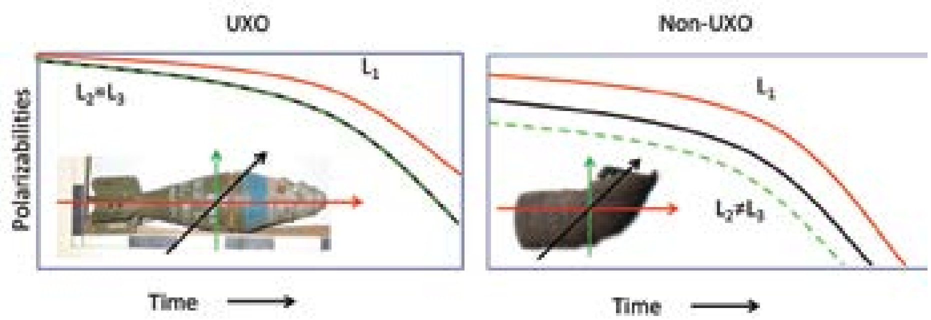


Figure 5. Comparison of representative polarizabilities for UXO and non-UXO items.

orientation and polarizabilities. The polarizabilities are intrinsic to each target and hence classification decisions can be made based on the match of the estimated values to those of known UXO types. Figure 4 shows an example of this fitting procedure and the recovered polarizabilities for MetalMapper data acquired over a 37-mm projectile.

Figure 5 compares typical polarizabilities for UXO and non-UXO items. The primary polarizability (L1) aligns with the long axis of the target. UXO generally have larger amplitude, slower decaying polarizabilities relative to small clutter. Shape information is encoded in secondary polarizabilities (L2 and L3). Most UXO have a circular cross section and will have L2 ≈ L3. In contrast, for irregularly shaped clutter, these parameters differ significantly. These differences in polarizabilities allow for distinction between buried UXO and clutter.

An important step in UXO data processing is visual quality control of the fit to each target. The example in Figure 4 represents the ideal case: a near-perfect fit to the data and an excellent correspondence between the estimated polarizabilities and expected values for the target's class. However, feature estimation is often complicated by neighboring target anomalies or low signal strength from small or deep (> 30-cm) targets. In these particular situations, noise will affect the fitting to the observed data, and may produce unreliable polarizabilities. An additional complication sometimes encountered in data processing can be a strong background soil response superimposed on the target response. Soil compensation algorithms can be applied to the EM data to remove these effects and recover reliable polarizability estimates.[11]

Careful inspection of all fits by expert data analysts is essential to ensure that the field data for each target anomaly can support classification decisions. When data quality is poor for individual targets, the data may be reacquired or, in the worst case, the target must be dug as a precaution. With newer sensor data and careful field practices, the number of anomalies that cannot be analyzed is usually negligible (less than 1% of the total).

Case Study: Pole Mountain

MetalMapper data were collected for an ESTCP demonstration of classification technologies at Pole Mountain, Wyoming (U.S.), in July 2011. The conditions at this site were relatively benign: Soil response was minimal, and little topography or vegetation impeded data collection. A total of 2,370 items were excavated at Pole Mountain, with 160 of these items identified as UXO. The UXO fell into six classes: Stokes mortars, 60-mm mortars, 75-mm, 57-mm and 37-mm projectiles, and small industry-standard objects (see representative photos in Figure 5). While ESTCP dug all targets, the identities of the objects were unknown to the analysts who needed to develop a classification strategy

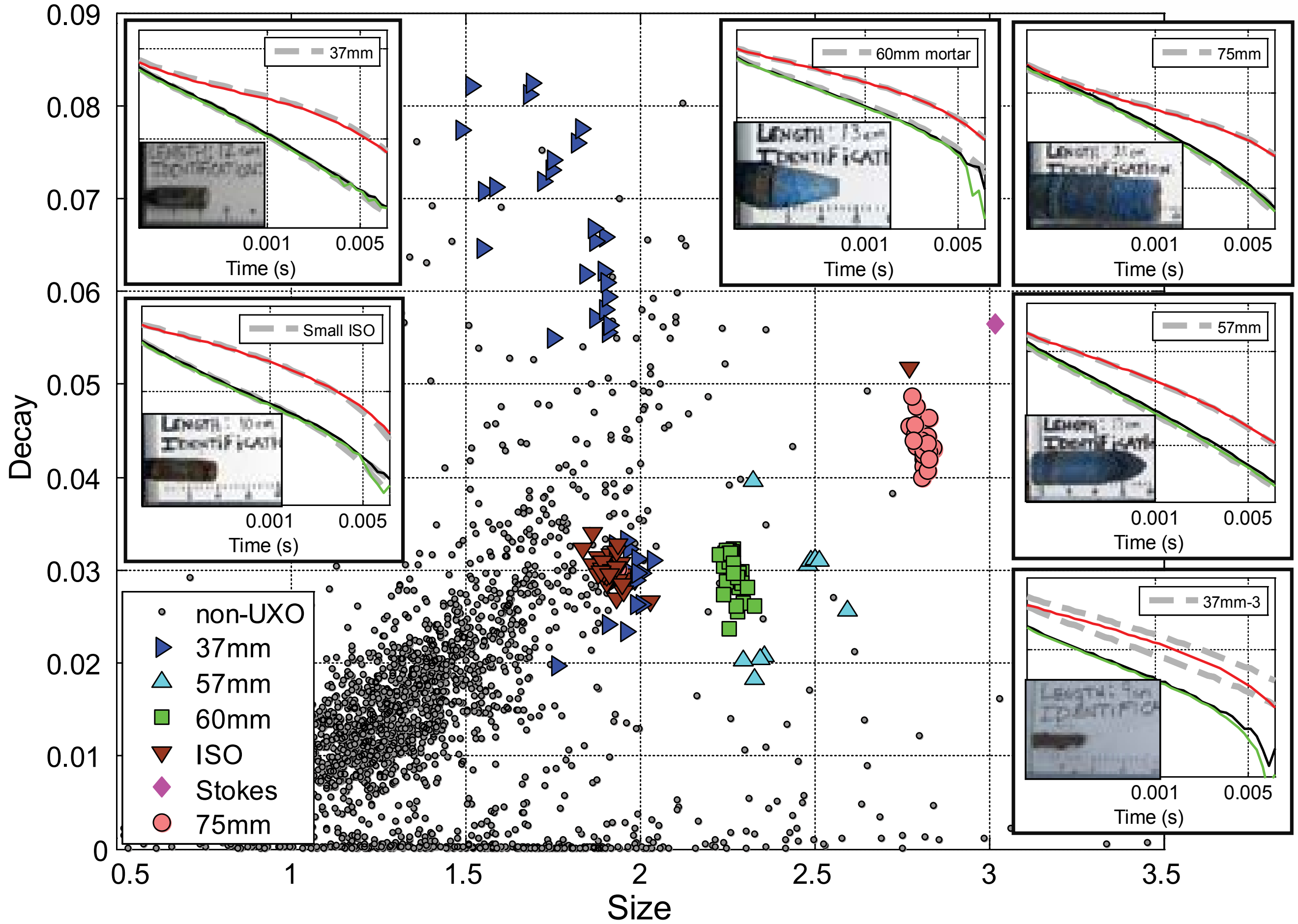


Figure 6. Decay versus size features space for Pole Mountain. Each point represents an individual target, with markers colored based on the similarity of the estimated polarizabilities to known UXO. Insets show estimated polarizabilities for selected targets, with heavy dashed lines indicating the expected reference polarizabilities for that item's class.

and decide which items were potentially hazardous UXO and which were harmless shrapnel or range debris.

Figure 6 shows a plot of size and decay parameters for all Pole Mountain targets. These parameters are computed from each target's estimated polarizabilities and provide a convenient way of visualizing the variability of target properties across the site. UXO are roughly characterized by large amplitude, slow-decaying polarizabilities and cluster in the upper right portion of Figure 6. Clutter items are generally smaller, fast-decaying and cluster near the origin. The degree of overlap between these two clusters dictates the difficulty of the classification task. The Pole Mountain data represents an easy classification task where UXO and non-UXO polarizabilities are readily distinguished. This is illustrated for selected items in Figure 6.

The end product of classification processing is an ordered list of targets prioritized by how well they match the polarizabilities of known UXO. The data analyst also specifies a **stop dig** point in this dig list at which all remaining targets are deemed nonhazardous clutter and can be safely left in the ground. Selecting the stop dig point is crucial to the success of remediation efforts at a site: The analyst must ensure all UXO are found while minimizing the number of unnecessary digs.

At Pole Mountain, a stop dig point that found all 160 UXO was easily chosen, resulting in only 153 non-UXO digs. Figure 7 shows the resulting reduction in digs relative to conventional data processing with the EM-61 instrument. These dramatic savings are typical of results obtained with next-generation sensors such as the MetalMapper, coupled with advanced classification techniques.

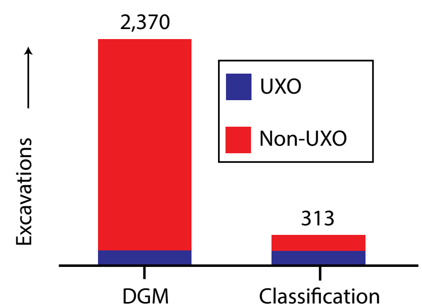


Figure 7. Comparison in total number of targets excavated in order to find all (160) UXO at Pole Mountain, for conventional data processing of a digital geophysical map acquired with the EM-61 and advanced classification with the Metal Mapper.

Conclusions

Sensor and data processing technologies developed under the ESTCP program have repeatedly achieved excellent classification performance in blind field demonstrations. Results depend on the difficulty of the classification task and the quality of the field data. However, improvements in field procedures, including real-time processing of acquired data, are expected to make results similar to those attained at Pole Mountain more routine.

The current ESTCP development emphasis is based on testing smaller, man-portable systems such as the Handheld Berkeley UXO Discriminator (BUDHH) and the Man-Portable Vector Sensor (Table 1 on page 59) and on deploying vehicular sensors to increasingly challenging sites (higher clutter densities, more varied ordnance types). The man-portable systems can be deployed at challenging sites with variable topography or dense vegetation. Results from the 2011 demonstration at Beale Air Force Base indicate that these systems will provide similar improvements in classification as their larger antecedents.[12]

The large-scale field demonstrations ESTCP sponsored demonstrated the feasibility of significantly reducing the costs of UXO cleanup by deploying advanced sensor technologies coupled with classification algorithms. While the existing set of hardware tends to be heavy, bulky, power-hungry and relatively fragile, some systems have been transitioned to production companies undertaking large-scale UXO remediation projects. Another iteration in hardware development will be required before large numbers of field personnel possess rugged, lightweight and field-ready instrumentation. The future prospects for achieving significant reductions in the costs and time frames required for UXO remediation are extremely promising and worthy of future investment.

See endnotes page 67

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Laurens Beran completed his Master of Science and doctorate degrees in geophysics at the University of British Columbia in Vancouver, Canada. He is a geophysicist with Black Tusk Geophysics and a research associate at UBC. He specializes in development and application of statistical algorithms for UXO classification. Laurens is principal investigator on two Strategic Environmental Research and Development projects examining practical classification techniques.

Laurens Beran
Research Geophysicist
Black Tusk Geophysics
Suite 112A, 2386 East Mall
Vancouver, BC V6T 1Z3 / Canada
Email: laurens.beran@btgeophysics.com
Website:
http://www.btgeophysics.com

Barry Zelt received his Master of Science and doctorate in geophysics from the University of British Columbia. Until recently his world revolved around crustal-scale seismology, but since 2010 he has specialized in UXO detection and classification. He is the primary programmer of Black Tusk's interactive classification software. He is also an experienced user of the software as an analyst of several Environmental Science Technology Certification Program live-site demonstration datasets.

Barry Zelt
Research Geophysicist
Black Tusk Geophysics
Email: barry.zelt@btgeophysics.com

Stephen Billings has more than 16 years of experience working with geophysical-sensor data, including 10 years where he mostly concentrated on improving methods for UXO detection and characterization. He is the president of Black Tusk Geophysics, Inc. and an adjunct professor in Earth and Ocean Sciences at the University of British Columbia. He has been a principal investigator on 10 completed munitions detection-related projects sponsored by Strategic Environmental Research and Development and the Environmental Science Technology Certification Program. He is based in Brisbane, Australia.

Stephen Billings
President
Black Tusk Geophysics
Email:
stephenbillings@btgeophysics.com

ENDNOTES

Detecting and Classifying UXO by Beran, Zelt and Billing [from page 57]

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