Overview of multimethod geophysical system development for enhanced near-surface target detection, discrimination, and characterization

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Near-surface geophysical "targets" include unexploded ordnance (UXO), landmines, cavities (including tunnels and underground facilities), contaminant plumes, utilities (including underground storage tanks, pipelines, etc.), archaeological artifacts, graves, forensic evidence, structural foundation investigations for new and existing structures, and assessing the condition of engineered structures (e.g., bridges, dams, levees, roads, airfields, buildings). Application of near-surface geophysics to detect and characterize any of these "targets" is in the public interest, and many applications are clearly and directly related to public safety. While the detection of these targets in a geologic background can often be challenging, the discrimination of the desired target signatures or expressions from "false alarm" target signatures can be an even greater challenge. The discrimination challenge can be as simple as a "go/no-go" decision on the target, or the properties of the target may need to be further characterized after the decision. There is near unanimity among geophysicists (a rare thing) that multimethod, collocated complementary geophysical data enhance not only target detection but also the capability for discrimination and characterization. The U.S. Army Engineer Research and Development Center (ERDC) conducted a multiyear research and development effort that resulted in complementary, collocated simultaneous geophysical survey capabilities for near-surface targets.

Background. Complementary, multimethod geophysical surveys of an area/site for detection and characterization of near-surface targets is a common practice for geophysical practitioners. The "complete" coverage of an area by two or more methods, however, requires multiple passes over the area, and time and funding limitations will often allow only selected coverage of an area by the complementary methods. Since a major driver of public interest/public safety applications is cost avoidance, commonly the well-intentioned practitioner and the informed funding agency manager must settle for less than the ideal multimethod survey. For an application such as UXO cleanup, where public safety is clearly a driver, the cost-avoidance driver (i.e., funding constraints) commonly mandates complete coverage of sites but only with a single geophysical method. In an effort to overcome the limitations commonly imposed by funding constraints, a major thrust of the ERDC UXO program was to promote the development of dual-sensor and/or dual-mode sensor systems to allow acquisition of the complementary geophysical data in a single "pass" over the UXO cleanup site. Concomitant to the development of the dual-sensor and dual-mode systems, a major thrust of the program was development of geophysical response models for use in cooperative and joint inversion of multimethod geophysical data to support discrimination and classification algorithms.

Options for dual-sensor/dual-mode systems must consider two types of concerns: (1) the best combination of geophysical methods to achieve the detection and discrimination objectives, and (2) the system design and operational constraints and approaches to achieve simultaneous, complementary measurements (Figure 1). Measurement collocation

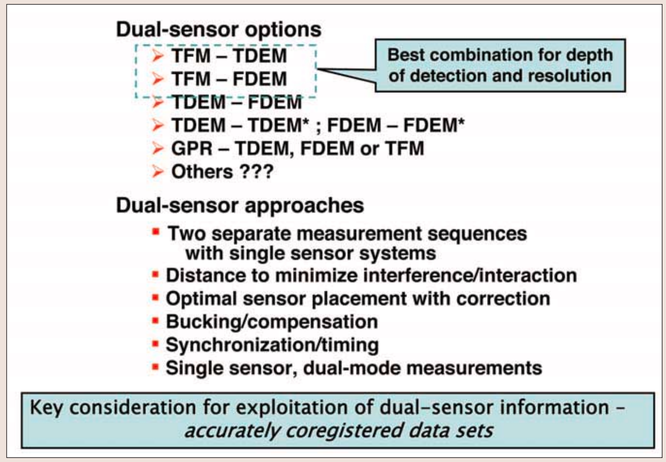

Figure 1. Dual-sensor and dual-mode system considerations-options and approaches. The asterisk indicates TDEM or FDEM systems with different operational or design characteristics, e.g., a very early-time TDEM system "simultaneous" with a late-time TDEM system.

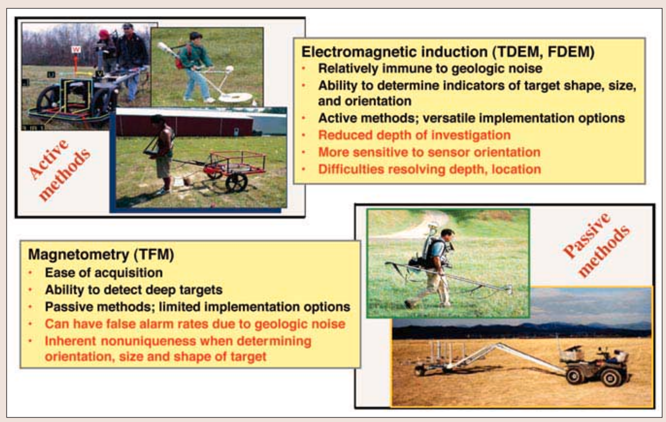

Figure 2. Characteristics, strengths, and deficiencies of two complementary geophysical methods.

is a major requirement for optimal utilization of cooperative or joint inversion and classification algorithms for dual-sensor geophysical data. The collocation requirement is a strong motivation for simultaneous measurements with a system having two sensor types at accurately fixed locations relative to each other.

Total field magnetometry (TFM) and electromagnetic induction (EMI) systems are the most commonly applied and generally applicable geophysical methods for UXO surveys. Both time domain (TDEM) and frequency domain (FDEM) EMI systems are applied to UXO surveys. Thus TFM and EMI are the obvious choices for development of dual-sensor systems. These two methods are truly complementary in many ways (Figure 2). The obvious problem with making simultaneous TFM and EMI measurements is interference with the TFM measurements caused by the EMI system transmitters. Several approaches for solving, overcoming, or compensating for the interference issues are under development.

Another consideration influencing the ERDC development effort is the need to obtain dual-sensor data in all types of topographic and vegetation settings. Conducting surveys in heavily wooded areas or areas with rugged topography requires hand-held or man-portable systems that are lightweight and easily maneuverable. Generally, these access requirements mandate a system with a single dual-sensor. Surveying large, "open field" type areas efficiently and cost-effectively with dual-sensor systems favors arrays of dual-sensors. The dual-sensor arrays can be vehicle- or man-towed and configured to cover a 2-3-m swath in a single pass.

Hand-held dual-sensor system development. Most research and development efforts to date for UXO detection and mitigation have targeted surveying large contiguous areas (often described as "open") of land. Clearly there are many terrains that survey methods applied to large, open areas cannot address, e.g., heavily wooded and topographically rugged areas. ERDC and its partners AETC (Raleigh, North Carolina), Arc Second (Dulles, Virginia), Geonics (Mississauga, Canada), and Geophex (Raleigh) designed, constructed, and field tested hand-held dual-sensor systems, with the goal of filling a widely perceived technology gap in sensor technology applicable to surveys in heavily wooded and topographically rugged areas. In addition, integrating an accurate and reliable positioning capability for these surveys was viewed as essential, considering the unreliability of GPS and laser tracking.

En route to a hand-held dual-sensor system, a prototype system was developed that integrated a cesium vapor total field magnetometer (Geometrics Model G823A) with a FDEM sensor designated the EM73 (Figure 3). The EM73, a new concentric, coaxial FDEM system developed by Geonics specifically for the ERDC effort, operates at 9.8 kHz, utilizing the familiar EM31 transmitter driver and receiver electronics. Achieving the dual-sensor operation relies on minimum separation distance, optimal TFM sensor placement, and correction/compensation algorithms. While successfully combining both EMI and TFM sensor technology, this original system was limited both ergonomically (couldn't be hand-carried effectively due to weight and low center of gravity) and by the fact that it operated at a single EM frequency. The system successfully collected dual-sensor data at two test sites, including the ERDC UXO Text Site in Vicksburg, Mississippi. We believe the complementary data sets (Figure 4) may be the first simultaneously acquired, complementary geophysical data sets using a dual-sensor (TFM-EMI) system. The TFM and FDEM measurements are very accurately collocated, due to the fixed arrangement of the sensors.

Based on the deficiencies of the original prototype system, a new system was designed that is lighter, ergonomically configured to allow hand-carried deployment, and capable of multiple frequency operation for the FDEM system. An existing multifrequency FDEM system design, the Geophex GEM-3, was chosen as the FDEM system. The current GEM-3 is an enhanced version of an older bucked transmitter-receiver design that has operating characteristics that allow it to be used in the dual-sensor system. The enhanced GEM-3 was additionally modified to allow simultaneous logging of additional serial data strings for positioning, the total field magnetometer, and a three-component fluxgate magnetometer. A 64-cm diameter GEM-3 system was selected that allows operation at multiple, user selectable frequencies ranging from 30 Hz to 24 kHz. EM field modeling for the GEM-3 geometry and operating characteristics, slight modification of the coil assembly head, and empirical verification allowed placement of the TFM sensor in the "magnetic cavity region" of the coil assembly offset from the center, minimizing the EM-induced offset of the TFM measured magnetic field (Figure 5).

Figure 3. Field measurements with the man-portable dual-sensor system at the ERDC UXO test site, Vicksburg, Mississippi.

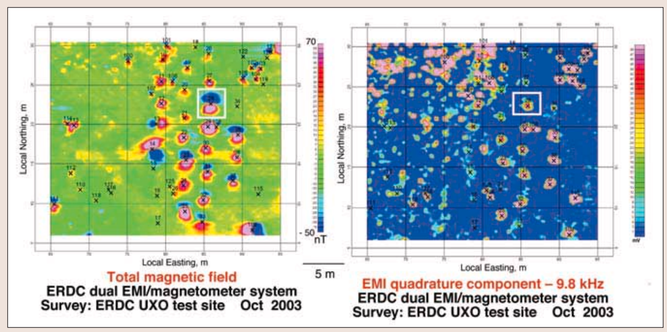

Figure 4. Example of simultaneously acquired TFM and EMI (quadrature component) data sets at the ERDC UXO test site using the dual-sensor system shown in Figure 3.

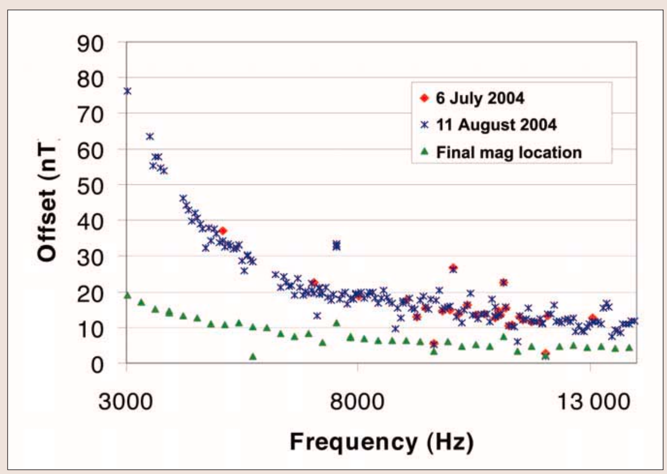

Figure 5. EM-induced magnetic offsets for TFM within the "magnetic cavity" region of the GEM-3 coil assembly as a function of frequency for a fixed orientation (courtesy of David Wright, AETC).

In addition to the frequency-dependence of the EM-induced magnetic offsets, the offsets depend on the angle of the EM field relative to the earth's field at the TFM sensor, which is highly variable during field deployment. Fortunately, the EM-induced offset can be accurately calculated if the angle is known. The angle of the earth's field relative to the system is determined from measurements with a three-axis fluxgate magnetometer with an accuracy <1°. Thus, the hand-held dual-sensor system relies on optimal TFM sensor placement, EM field bucking, and calculable offset correction to achieve simultaneous operation of the TFM and FDEM sensors. The resulting TFM and FDEM measurements are very accurately collocated.

Figure 6. Field demonstration of the ERDC hand-held dual-sensor TFM-FDEM system, with integrated Arc Second six-degree of freedom positioning system, at the ERDC UXO test site, April 2005.

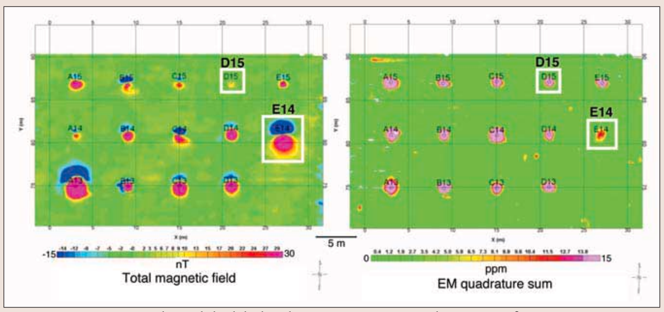

Figure 7. ERDC hand-held dual-sensor system data sets from survey at the NRL Blossom Point UXO test site, February 2005.

Two positioning systems can be utilized with the dual-sensor system, GPS and an Arc Second six-degree of freedom system. The Arc Second system utilizes multiple laser transmitter beacons and multiple roving receivers on the dual-sensor system. Total weight of the dual-sensor system with the integrated Arc Second positioning is 21 kg. The center of gravity of the 9.3-kg carry pole is directly under the attachment point of the carry straps to the backpack (Figure 6).

Two field tests have already been conducted with the hand-held dual-sensor TFM-FDEM system. The first field test was at the Naval Research Laboratory's (NRL) Blossom Point (Maryland) UXO Test Site (Figure 7), and the second was a demonstration at the Vicksburg test site. A third formal demonstration is planned at a Standardized UXO Technology Demonstration Site, Aberdeen Proving Ground (Maryland).

To date, analysis of the dual-sensor system data has included positioning performance assessment, qualitative assessment of the complementary nature of the two data sets (compare the corresponding signatures for targets D15 and E14 in Figure 7), signal-to-noise analyses of the sensor signatures, cued survey tests, and analysis of the quality of dipole fit inversion of the EM data as a function of sensor head sweep speed. A cued survey, generally for target discrimination, involves high-resolution data acquisition in a small area (e.g., 2×2 m) surrounding a target located by a prior geophysical survey. Typical open field type surveys are dynamic and are conducted at nominally constant speeds. Surveys in wooded and rugged areas and some cued type surveys generally require data acquired at variable sweep speeds. The dipole fit inversion analysis consists of finding the position, orientation, and diagonal (orthogonal) components of the polarizability

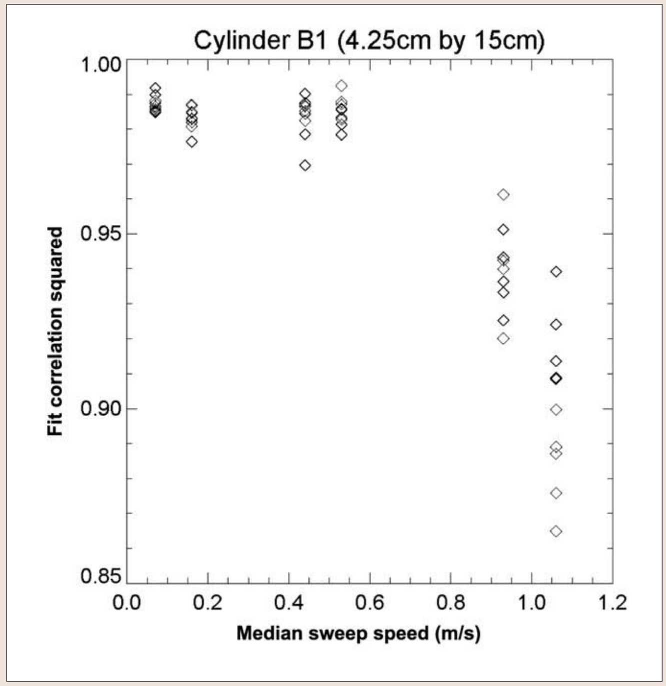

Figure 8. Analysis of "goodness of fit" of dipole-model inversions for cued surveys with the ERDC dual-sensor system, with Arc Second positioning, as a function of sensor head sweep speed. Multiple inversions at each sweep speed for different random samplings of the data (courtesy of David Wright, AETC).

tensor for a hypothesized target that best fits the observed target signature. Dipole inversions for surveys over a steel cylinder (4.25-cm diameter by 15-cm long) at six different mean sweep speeds were performed on different random samplings of the data, using the Arc Second system to determine positioning and speeds (Figure 8). The fit quality ("goodness of fit") at low sweep speeds approximates the quality of static measurements. The formal demonstration at the Aberdeen demonstration site will be analyzed to determine detection performance as well as discrimination performance for UXO versus false alarm (non-UXO) targets.

Towed array dual-sensor system development. Towed array UXO survey systems, such as the NRL MTADS (Multisensor Towed Array Detection System) and the Geocenters STOLS (Surface Towed Ordnance Locator System) have been successfully demonstrated at test sites and deployed at UXO cleanup sites. Both systems use TFM and TDEM sensor arrays but require two passes over a site if complementary data sets are desired. Both MTADS and STOLS utilize arrays of cesium vapor TFM sensors (typically Geometrics G822A or G858 sensors at 0.25- to 0.5-m spacing) and arrays of TDEM sensors (the Geonics EM61 or EM61 Mk II at 0.5-m spacing). These towed arrays acquire very high resolution data sets with very high area coverage rates (4-12 hectares/day, approximately 10-30 acres/day, depending on surface conditions and whether the TFM or TDEM array is used).

A towed array dual-sensor system was developed and demonstrated by Geocenters (now SAIC), sponsored by several Federal agencies, including ERDC, Corps of Engineers Huntsville Center (CEHNC), Environmental Security Technology Certification Program (ESTCP), Army Environmental Center, and Aberdeen Test Center. The new dual-sensor array consists of five G822A TMF sensors and five EM61 Mk II sensors (0.5- by 1.0-m), for 0.5-m cross-track sampling (2-m swath width). The dual-sensor array relies on distance (1.5-m separation) and time synchronization (measurement interleaving) to minimize interference. Positioning is achieved by three GPS receivers operating in a moving base configuration to give position as well as roll, pitch, and yaw of the platform. The new dual-sensor towed array system (Figure 9) is designated VSEMS (Vehicular Simultaneous EMI and Magnetometer System). Due to the known geometry of the two offset arrays, the two data sets can be accurately collocated. Two prototype versions of the final VSEMS have been demonstrated at the Standardized UXO Test Sites at Aberdeen and Yuma Proving Grounds. The final VSEMS will also be demonstrated at the two standardized test sites, and the data sets will be processed for detection, discrimination, and classification using two software platforms, developed by ERDC and the Strategic Environmental Research and Development Program (SERDP).

Dual-mode sensor system development. The SAM (Sub-Audio Magnetics) System is a true dual-mode system, where a TFM sensor or TFM sensor array is utilized in conjunction with a large diameter transmitter loop to acquire both TFM and TDEM data sets from a single pass over a survey area. A notable fact regarding the SAM dual-mode system is that the two data sets are exactly collocated. SAM was originally developed by G-tek Australia Party, Albion, Queensland, Australia, for mineral exploration. Realizing the potential for UXO and other near-surface detection and mapping objectives, G-tek utilized the SAM for feasibility demonstrations at UXO cleanup sites and for formal demonstrations at UXO test sites. Following the initial demonstrations, ERDC and CEHNC teamed with G-tek to develop a SAM system optimized for UXO surveys.

SAM simultaneously acquires both the magnetic and electromagnetic response of the subsurface. A transmitter wire is first laid along a "meandering loop of convenience" surrounding the area to be searched, which may be several hectares in size. The transmitter loop is energized with a bipolar, 12- to 20-amp square wave current, usually at 50% duty cycle, and typically operating between 10 and 32 Hz. TFM measurements are acquired at a rate of up to 8 kHz while systematically traversing the area within the loop, as would be the case for a conventional magnetic survey, using a single magnetometer, a hand-held array of magnetometers, or a towed array of magnetometers (Figure 10). The transmitter and the receiving magnetometer(s) are precisely synchronized using GPS time. Postprocessing then separates the total magnetic field intensity and the total field electromagnetic transient response (TDEM). Both are mapped to the position where the measurement was acquired using a differential GPS.

Development of detection, discrimination, and classification approaches for dual-sensor/dual-mode data sets. For UXO discrimination and classification, ERDC and its corporate and academic partners (Sky Research, University of British Columbia, Dartmouth, MIT, and Colorado School of Mines) have developed forward and inverse modeling approaches for individual and complementary geophysical data sets. For complementary data sets, empirical, cooperative inversion (constrained), and joint inversion approaches are used. Results of the inversion analysis are then used in various classification approaches to characterize the discrimination results with more specificity, e.g., a UXO-like target (from discrimination analysis) is likely a 105-mm projectile (from classification analysis). Discussion of the details of these developments is far beyond the scope of this paper, but the developments are documented in peer-reviewed papers, ERDC technical reports, and conference proceedings.

The result of a parametric (model-based) inversion analysis of TFM or EMI data sets is an assessment of whether the target is UXO-like, non-UXO-like, or the result is inconclusive (Figure 11). If both TFM and EMI data sets are available, the simplest type of complementary interpretation (Figure 11) suggests that the target should be excavated ("dig"), further evaluated, or not excavated ("no dig").

A formal comprehensive approach for analysis of complementary (TFM and TDEM) data sets is designed to "classify" all targets into those detected by both methods, detected by TFM only, and detected by TDEM only (Figure 12). For those targets detected by both methods, cooperative (constrained) inversion is used, where the target location (x,y,z) determined from TFM inversion is used to constrain the TDEM inversion. For all other targets, a complete (unconstrained) TFM or TDEM inversion is performed and the "dig/no-dig" decision made based on the appropriate TFM or TDEM discriminants, respectively.

__Figure 9.__ The VSEMS (a towed dual-sensor array system).

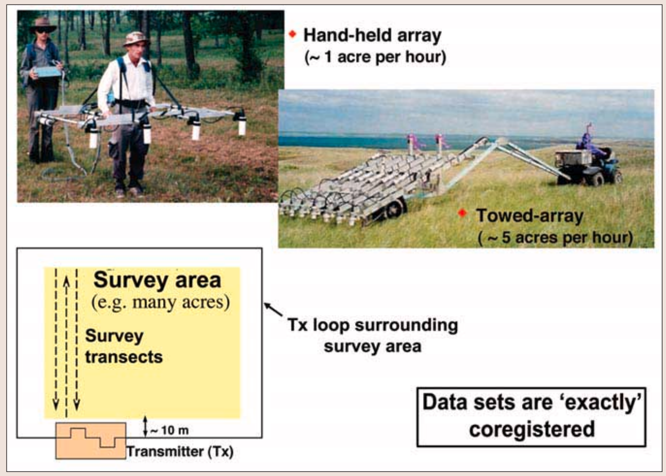

__Figure 10.__ SAM field setup and hand-held and towed magnetometer arrays for data acquisition.

Magnetic inversion results

EM inversion results	UXO-like	Inconclusive	Non-UXO
UXO-like	Dig	Dig	Evaluate
Inconclusive	Dig	Evaluate	No dig
Non-UXO	Evaluate	No dig	No dig

__Figure 11.__ Qualitative complementary geophysical interpretation approach using a decision matrix based on the results of individual data set interpretations.

Afterword. This paper presents an overview of efforts to develop a comprehensive capability for simultaneous, complementary geophysical surveys for UXO and other shallow targets of interest for environmental cleanup and public safety.

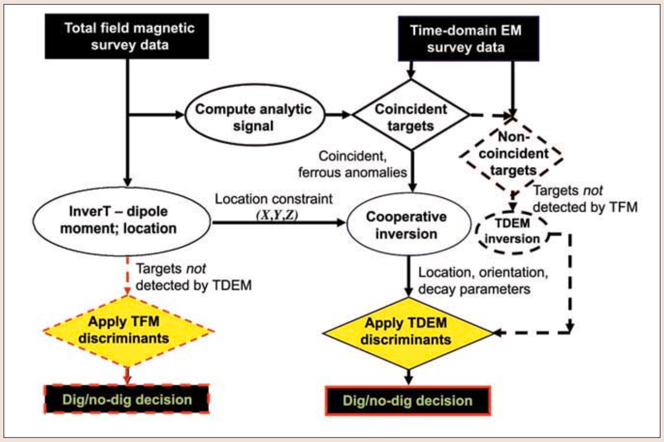

Figure 12. *A general cooperative inversion approach. For targets detected by both TFM and EMI surveys, the target location from TFM inversion is used to constrain the EMI (TDEM) inversion, with the dig/no-dig decision based on TDEM parametric discriminants or statistical classification approaches (see Beran et al., 2005). For targets detected only by TFM or by TDEM, use the TFM or TDEM discriminants, respectively.*

Three major factors drive the development efforts: time, cost, and safety. The goal is to reduce the overall cost of UXO cleanup, by significantly reducing the excavation of false alarm targets, to an extent that will allow UXO remediation to proceed to completion and turn over lands to the public in a timely manner. This process must proceed without sacrificing the safety of cleanup/remediation personnel and ultimately the safety of the general public in gaining access to lands declared free of UXO.

Suggested reading. Multisensor Methods for Buried UXO Detection, Discrimination and Identification by Butler et al. (*ERDC Technical Report SERDP-98-10*, 1998). "A discrimination algorithm for UXO using time domain electromagnetics" by Pasion and Oldenburg (*Journal of Environmental and Engineering Geophysics*, 2001). "Analytical modeling of gravity and magnetic signatures for unexploded ordnance" by Butler et al. (*Journal of Environmental and Engineering Geophysics*, 2001). Discrimination and Identification of UXO by Geophysical Inversion of Total Field Magnetic Data by Billings et al. (*ERDC Technical Report GSL-02-16*, 2002). "Evaluating the effects of magnetic soils on TEM measurements for UXO detection" by Pasion et al. (*SEG 2002 Expanded Abstracts*). "Joint and cooperative inversion of magnetic and time domain electromagnetic data for the characterization of UXO" by Pasion et al. (*Proceedings of SAGEEP*, 2003). "Model-based inversion for enhanced UXO detection and discrimination" by Butler et al. (*Proceedings of the Detection of Mines and Mine-Like Targets Conference*, 2003). "Development of a combined EMI/magnetometer sensor for UXO" by Wright et al. (*Proceedings of the UXO/Countermine Forum*, 2004; SAGEEP 2004). "Employing multiple geophysical sensor systems to enhance buried UXO 'target recognition' capability" by Butler and Yule (*Proceedings of the Army Science Conference*, 2004). "Statistical classification for discrimination of unexploded ordnance: a tutorial" by Beran et al. (*FastTIMES*, 2005). "Improvements to the Hand-held Dual Magnetic/EMI sensor" by Wright (*ERDC Technical Report*, 2005). "Simultaneous magnetic and electromagnetic mapping using subaudio magnetics" by Stanley et al. (*FastTIMES*, 2005). TLE

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