SENSOR EVALUATION STUDY FOR USE WITH TOWED ARRAYS FOR UXO SITE CHARACTERIZATION

J.R. McDonald
Chemistry Division, Code 6110, Naval Research Laboratory
Washington, DC 20375, 202-767-3556

Richard Robertson
Hughes Associates
Columbia, MD 21045, 202-767-3340

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ABSTRACT

The Naval Research Laboratory is developing a Multi-sensor Towed Array Detection System (*MTADS*) with support from the DOD Environmental Security Technology Certification Program (ESTCP). In this effort we seek to extend and refine ordnance detection technology to more efficiently characterize OEW sites, identifying nonferrous and smaller items, distinguishing ordnance from clutter and analyzing clustered targets to identify and locate individual targets within complex target fields. Our evaluation shows that these goals are best met by combining magnetic and electromagnetic sensors. We report on field studies at a prepared test range of commercial sensors in arrays in various configurations and including; Cesium vapor magnetometers in single sensor and gradiometric configurations, fluxgate gradiometers, proton procession magnetometers, and electromagnetic pulsed induction sensors. The advantages and disadvantages of each technology and their applicability based upon survey requirements is discussed. We also discuss recommended data densities including horizontal sensor spacings, survey speeds, sensor heights and make recommendations about the appropriate use of gradiometers and active sensors.

INTRODUCTION

The Chemistry Division of the Naval Research Laboratory (NRL), with support from the Environmental Security Technology Certification Program (ESTCP) [Marqusee, 1996], is developing an automated towed-array ordnance detection system for site characterization. This system will be used in support of environmental restoration of Ordnance and Explosive Waste (OEW) at Department of Defense (DOD) sites. The primary goal of the program is to provide a field demonstration of a towed array sensor system that utilizes state-of-the-art technologies for automated OEW detection. Additionally, we are developing a transition plan to make the technology available for public use by commercialization of the final product. The system under development is called the Multi-sensor Towed Array Detection System (*MTADS*). In this paper we describe field tests and evaluation of several passive and active commercial sensors considered for use with the *MTADS*.

Our experience with previous towed-array systems and testing at OEW sites [McDonald and Robertson, 1994] and at Hazardous, Toxic and Radioactive Waste (HTRW) landfills, [McDonald and Cochran, 1992], [McDonald, Robertson and Cochran, 1995], [McDonald and Robertson, 1995] and the results described in the Jefferson Proving Ground (JPG-1) Report [----, SFIM, 1994,] [----, SFIM, 1995] make it plain that no single sensor, even deployed in closely spaced arrays and aided by automated navigation systems and sophisticated data analysis systems, can be expected to detect all ordnance at realistic ranges, while effectively discriminating against false targets and clutter. It is our contention that the most effective sensors for multi-sensor arrays at ordnance ranges involve combinations of magnetometers, gradiometers, and active electromagnetic induction sensors. It is this premise that has led to the development of *MTADS* and to the sensor evaluation study reported in this paper.

The *MTADS* Sensor Array

Passive magnetic sensors (magnetometers, gradiometers) and active (cw and pulsed induction) electromagnetic (EM) sensors have been considered as candidates for the *MTADS*. Survey rates with vehicular towed arrays using a 10' wide array and actively surveying only 50% of the time, typically provides a capability to survey over 20 acres per day at reasonably large sites with intermediate to friendly terrain. This information, combined with the design of the Data Acquisition System (DAQ) and analysis of typical sensor performance characteristics for passive and active magnetic sensors, has led to an *MTADS* sensor platform design that will not simultaneously acquire data from active and passive sensors. It is our belief that simultaneous deployment of active and passive sensors adversely affects the quality of each data set. If both active and passive sensors are deployed with *MTADS* at a particular site, multiple site surveys will be used. This ensures that the performance of each sensor system is not degraded by the other.

Sensor Performance Criteria

Before making final commitment to the specific sensors for the *MTADS* arrays, NRL decided to conduct field tests of the sensors including metal vapor and proton procession (as reference magnetometer) sensors to be used as both full field sensors and gradiometers, fluxgate gradiometers and pulsed EM sensors. Geometrics, Schonstedt, and Geonics supported the field tests and worked with NRL in adapting their sensors into arrays for the study. Scintrex, in cooperation with Geo-Soft of Toronto, Ontario, chose to demonstrate their sensor in a hand survey at the field site. This report contains a summary of the results of the towed-array field tests. In addition, we provide recommendations for sensor configurations including sensor heights, vertical gradiometer spacings, horizontal sensor spacings and recommended survey data densities and survey speeds.

SURVEYS AT THE MAGNETIC TEST RANGE

An existing test site at the Fort Devens, MA was selected to conduct the sensor evaluation study. It is centrally located to the companies supporting the demonstration. We modified The Fort Devens Magnetic Test Site, which we previously developed for acceptance testing the original Navy Surface Towed Ordnance Locator System (STOLS). Thirty four ordnance and ordnance-simulant targets have been buried for over ten years. These include eleven 155mm projectiles and simulants, nine 250 lb. bombs and simulants, and thirteen 500 lb. bombs and simulants. During recent development work we buried eight 55 gallon cold rolled steel barrels and one 50 gallon aluminum drum. The buried targets range from 0.5 to 17.6 feet in depth. An additional 24 small targets (pipe segments, 1" and 2" in diameter, ranging from 3" to 12" in length) representing munitions on or near the surface were added to the field for this study. The Magnetic Test Site encompasses an area of about two acres, the terrain is reasonable flat, the soil is glacial till and characterized by low natural magnetic signature. The field has sparse grass and small brush coverage and is closely surrounded by mature forest on three sides.

Support Equipment and Instrumentation

The Geo-Centers commercial survey tow vehicle and sensor platform were used as field support equipment. The sensor platform was modified to accommodate magnetometers deployed as gradiometer arrays and an array of flux gate gradiometers. Magnetometers could be deployed at a variety of vertical positions (12" to 72") and variable vertical sensor separations (12" to 60") could be accommodated in gradiometer deployments. The trailer was modified to tow the Geonics EM-61 array behind the tow platform.

Trimble 4000 SSE DGPS units were used for navigation and target location. A DGPS Base Station was located north of the test site at a known first order survey position. The GPS radio link transmitted the navigational corrections to the DGPS unit in the rover. A Reference Site was also established for removing diurnal background variations during total field magnetometer surveys. Data files were down-loaded from the field data acquisition computer or from the data loggers and correlated with navigation and background reference data using the STOLS field workstation.

Data Analysis

Magnetometery and gradiometry analyses were carried out using the *MTADS* Data Analysis System (DAS) developed for use on SGI workstation platforms. [----, Applied Research, 1995] An operator, working interactively with the DAS can carry out an interactive analysis of targets using magnetometry data to determine position, depth and size of ferrous targets. Imaging and manipulation of gridded survey data and EM-61 data were carried out using PC's and commercial graphics software. Scientrex analyzed their magnetometry data using a PC-based software utility developed by Geo-Soft Inc. Discussion of the gridded surveys and the Scientrex survey are beyond the scope of this presentation. They are more fully described in the Ft. Devens Sensor Report. [McDonald and Robertson, 1996] The pulsed induction survey data and analyses methods are described in another paper presented by Bruce Barrow [Barrow, et al., 1996] in this meeting. A new *MTADS* DAS is currently under development for a workstation platform. This system will incorporate analysis routines and algorithms for magnetometry, gradiometry and electromagnetic induction data.

Sensors

CESIUM VAPOR MAGNETOMETERS AND GRADIOMETERS

Scintrex employed a single Cesium Vapor Magnetometer, their "Smart Mag," in a hand-held walking line survey. The results of this survey are not discussed in this presentation. See [McDonald and Robertson, 1996]. Geometrics Model 822 magnetometers were used both as magnetometer arrays and were configured vertically in arrays for gradiometer surveys. These studies are discussed below.

PROTON PROCESSION MAGNETOMETERS

A pair of Geometics Model 856 proton procession magnetometers were used to conduct a hand survey on a one meter grid of the Magnetic Test Range. In the first survey a single sensor was used to survey the grid at a height of 18" while the second magnetometer was used as a reference sensor. An additional survey was conducted with the sensor deployed at 96" above the ground to allow a gradiometric analysis using a gridded data set. These results, discussed in [McDonald and Robertson, 1996], are not addressed further in this presentation.

FLUXGATE GRADIOMETERS

Seven Schonstedt GA 52Cx fluxgate gradiometers were vendor matched and specially calibrated relatively to each other. Modifications were made to allow access to the sensor analog signals which were interfaced to the data acquisition computer via a specially constructed interface board. Custom housings were developed to mount the gradiometers on the sensor platform and three surveys were conducted at various gradiometer sensitivity settings.

EMI DETECTORS

A pair of Geonics EM-61 pulsed induction sensors were modified to allow them to be synchronously pulsed at 3 Hz. A special boom was constructed to deploy the sensors in an array with a horizontal separation of 1.15 meters with the DGPS antenna located between and above the sensors. The output signals were interfaced to a palmtop computer to record data. Sensor data were time correlated with the navigation files to provide position information.

Survey Results

CESIUM VAPOR MAGNETOMETER ARRAYS

Towed-array surveys were made using an array of seven Geometrics 822 magnetometers spaced at one-half meter horizontal separations. Separate surveys were done with the sensor array at 12, 18, 36 and 72 inches above the ground. Additional surveys were made with six sensors deployed in a three over three array as vertical gradiometers with a sensor spacing of 18 inches; the lower sensor was 18 inches above the ground. Figure 1 shows magnetic anomaly target images for the full site comparing the magnetometer array using a fixed reference and the gradiometer survey. Figure 2 shows expanded images of 50 X 50 meter section of the site containing the deep barrels and the 2" diameter pipe segments.

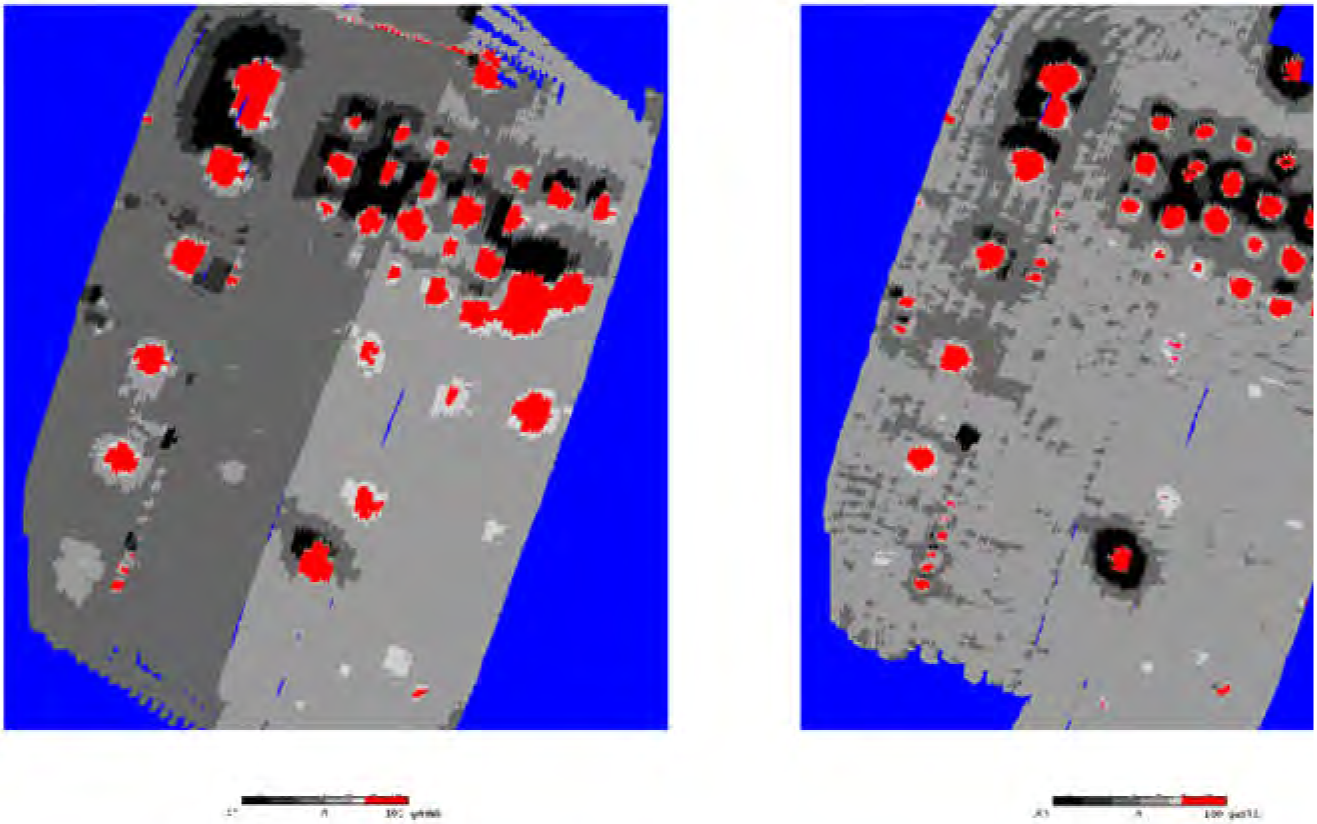

Figure 1. Magnetic anomaly images of the Ft. Devens Test Range using Geometrics Model 822 Mags. Magnetometry data on the left, Gradiometric data on the right. Displays saturate at -50 and +100 Gamma (or Gamma/18"). Positive anomalies > 50 Gamma are highlighted in red.

Magnetometry Surveys

Extensive analyses were carried out on the data to evaluate the ability to locate the positions and depths of the various targets and their magnetic moments as a function of sensor heights above the ground. Tables 1 and 2 present an example of these studies showing the depth analyses of magnetometry data for the ordnance items and barrels for the 12", 18" and 36" magnetometer surveys. In general, the depth analyses improve as the sensor to target distance increases until the targets are in the far field. The *MTADS* Version 1.0 DAS analysis algorithm uses a point dipole far field approximation. The shallower ordnance and the shallower barrels are in the near field for the lowest sensor settings.

Table 1. Model 822 Magnetometer Surveys - Analysis of Target Depths

Table 2. Model 822 Magnetometer Surveys - Analysis of Barrel Depths

The magnetometers can clearly detect and image the larger pipe segments (1" or 2" in diameter by 12" in length) as shown in Figure 2. The ability to detect the 6" long segments is highly dependent on orientation. The 3" long pipes are generally lost in the background noise. The X-Y position accuracy of the target fits is generally limited by the accuracy of the navigation positions and the accuracy of our knowledge of the ordnance position locations. The original ordnance was emplaced using a local grid before we began using DGPS survey and navigation. The DGPS navigation hardware used in these studies has an accuracy of about 0.5 meters. Since these data were taken the Trimble DGPS hardware has been upgraded to provide navigation accuracies of <0.2 meters in real time.

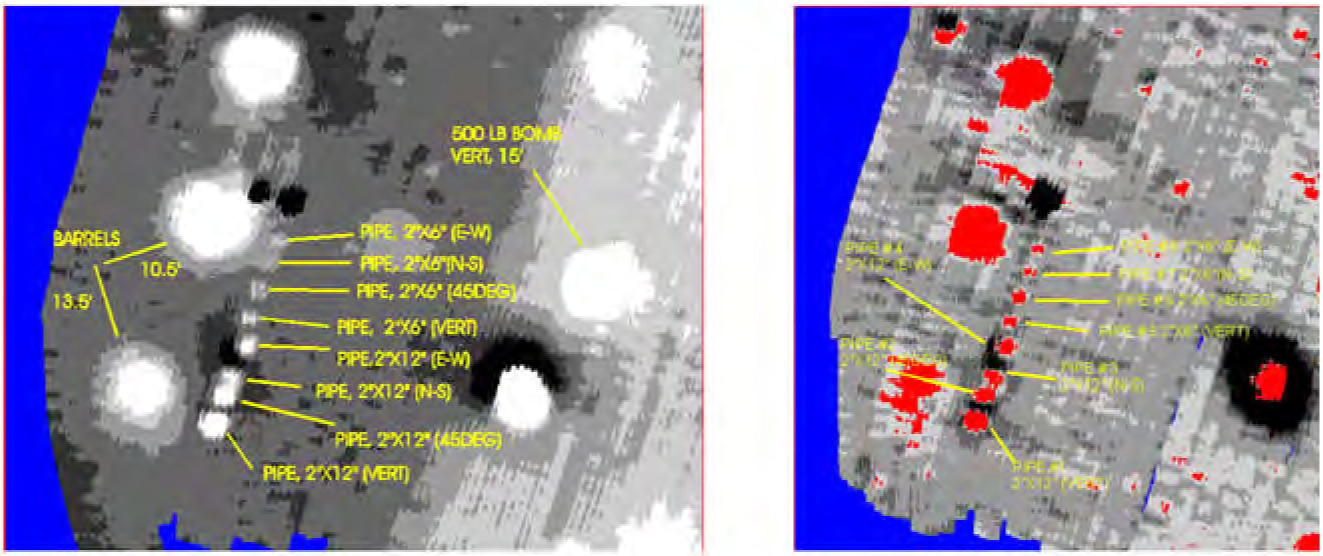

Figure 2. Pan window images of a 50 X 50 meter section including the lower pipe segments. Magnetometry on the left, Gradiometry on the right. Signals saturate at +/-35 Gamma. The Magnetrometry image is not highlighted.

Cesium Vapor Gradiometer Surveys

Comparisons were made relative to target detection and definition capabilities using magnetometer vs the gradiometer data. In general, the gradiometer surveys are less sensitive in detection of deep objects. The 500 lb. bombs (at >10 feet deep) and the barrels (at >9 feet deep) are lost in the background noise at these sensor settings. The gradiometer, however much more clearly resolves the shallow ordnance and the surface pipe segments. This is clear from the magnetic anomaly images shown in the Figures 1 and 2. The gradiometer array clearly defines the intermediate size pipe segments (6" in length) and depending on orientation, resolves some of the 3" pipes. Distinguishing these small surface items would be enhanced by deploying the gradiometers closer to the surface. Ultimately, detection of small and shallow ordnance depends critically on the data density of the survey. This issue is discussed further in a later section.

FLUXGATE GRADIOMETER SURVEYS

The seven Schonstedt GA 52Cx gradiometers spaced in a 0.5 meter array were used to conduct surveys at several heights above the ground. Figure 3 shows a gradiometer anomaly image from the survey taken with the sensors 12" above the ground at the maximum sensitivity level. The display, on a -100 to +200 nT/18" scale, is fairly insensitive compared to the gradiometer surveys shown in Figure 1 and 2. This was necessary because the data set was corrupted by either miscalibrated or incorrectly offset-corrected sensors. The loss of calibration may have taken place during the survey. More sensitive presentations are so streaky that they are unusable. Never-the-less, the fluxgate sensor performance is impressive considering that the sensors are less than 10% of the cost of the cesium vapor sensors. All ordnance targets except the four deepest items are detectible, as are seven of the barrels. The two deepest barrels are not detectable. The pipe segments are crisply defined and would be even better visible if more sensitive displays were possible. The fluxgate sensors would require further development to field harden them for this type of deployment. Such an investment is warranted because of their economy and because of their potential for application as a man- portable adjunct sensor for the towed *MTADS*.

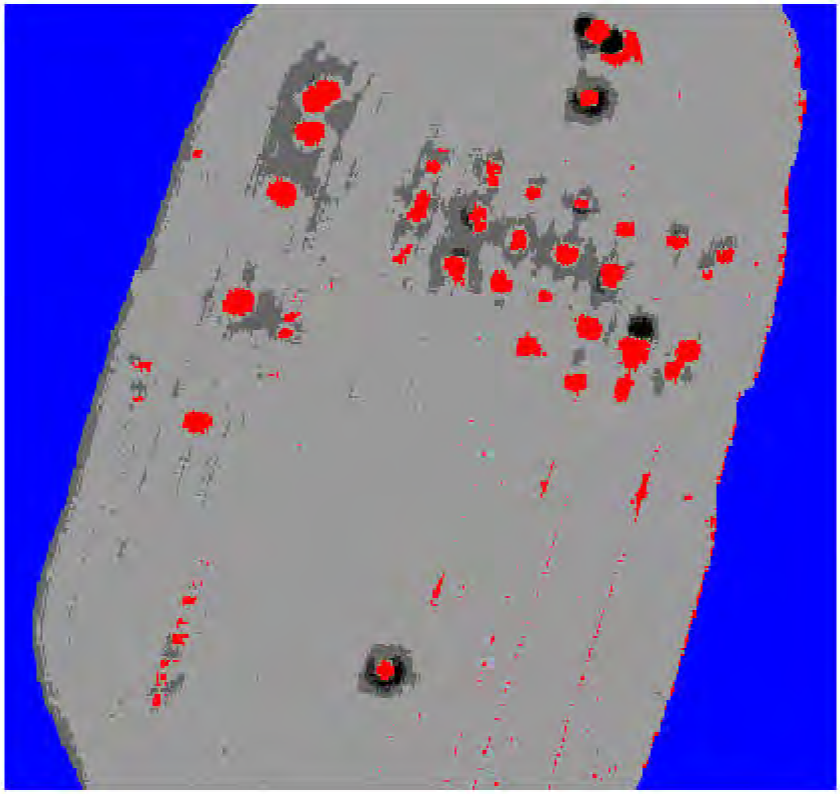

Figure 3. Magnetic anomaly image taken with an array of seven Schonstedt GA-52 Cx Gradiometers at 12 inches.

PULSED INDUCTION SENSOR SURVEYS

The commercial EM-61 instrument employs two one meter square receive coils. The lower coil at 16" is co-located with the transmit coil. The second coil is fixed 16" above the lower coil. Two EM-61 systems were deployed for these tests. The dual coil four-sensor array then collects four induction signals for each transmit pulse. The field was surveyed with the two instrument array towed behind the STOLS tow platform and was resurveyed in a hand-towed mode to determine the difference associated with removing metal signatures associated with the vehicle and tow platform. Figure 4 shows an EM-61 image of the Test Range constructed from the vehicular towed array survey. The image, constructed only from the upper coil data, is displayed on a very sensitive scale of that saturates at -5 and +10 mvolts. The linear dynamic range of the instrument is +/- 1 volt. The typical noise floor is at about 1 mvolt. The EM-61 detects all the ferrous barrels to a depth of 10.5' and the Al drum at a depth of 4.5'. The largest ordnance items, 500lb bombs, at 17.5' produce signals of one or two mvolts that are near the noise floor of the detector. Detection of ordnance items is sensitive to their orientation. A detailed analysis of the performance of the EM-61 sensor is presented [Barrow, et al., 1966] in this session in a separate paper. We defer further discussion of this sensor to his presentation.

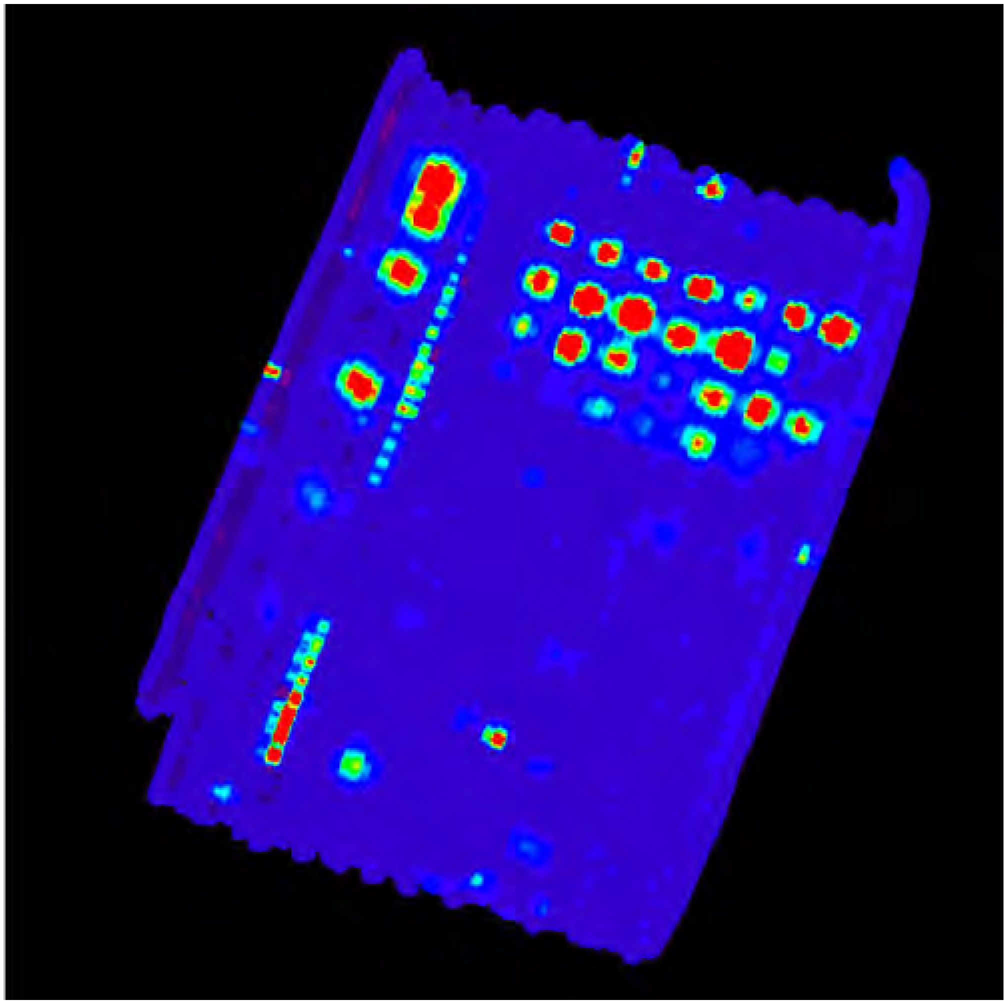

Figure 4. EM-61 Towed-array image from the upper coil at 36 inches.

RECOMMENDATIONS FOR SENSOR CONFIGURATIONS AND ARRAY SPACINGS

Site Survey Requirements

At ordnance sites vehicular-mounted towed sensor arrays such as *MTADS* have three primary uses; first, characterization of the site to determine whether ordnance contamination exists, second, assuming that ordnance is present, to aid the site manager in developing a remediation plan. Finally, the study is used to direct and support the remediation contractor in cleaning up the site. Quality data and a high quality analysis and evaluation is required to support each of these requirements. Choosing the appropriate sensors, setting their configuration and developing the site survey strategy requires consideration of the required detection sensitivity, the necessary discrimination against background and interferrants and the required spatial resolution to assure complete coverage.

Knowledge of the geophysics and local soil conditions is an aid in determining whether local interferrences will limit the value of total field sensors. The presence of local interferrences such as roads, fences, pipelines, power lines, buildings and other structures determine the need for gradiometric or active EM sensors and define the amount of man- portable surveying required. The detection of non-ferrous ordnance requires EM sensors. The presence of significant surface trash and ferrous clutter that cannot be removed before site characterization seriously increases the challenge to the survey planner. In these circumstances employing magnetometers, gradiometers and EM sensors may be required to "see through" clutter to distinguish large and deep ordnance. In these environments some targets will inevitably be marked that will not prove to be intact ordnance on remeditation. This is unavoidable, however, a multisensor system such as *MTADS* is best suited to differentiating between clutter and intact ordnance.

Conducting a survey by subsampling, target analysis and generation of pretty maps will often serve to define the presence of buried ordnance and, if carefully planned, can support development of a full survey and remediation plan. However, by far the majority of costs of an ordnance remediation effort is associated with ordnance clearance. The site characterization survey must generate a quality support product for remediation. One must be able to way point targets accurately and efficiently and provide a good estimation of depth. If the remediation contractor digs a lot of "dry holes" or has to continually enlarge holes to locate targets, confidence is quickly lost in the information provided by the survey team. The quality of the remediation effort suffers and remediation costs escalate.

SENSOR SENSITIVITY

Knowledge of the target magnetic moments and expected maximum depth of the smallest expected ordnance provides the information required to determine the absolute sensor sensitivity required. Background noise levels inevitably limit the useful detection sensitivity of a sensor or sensor array. This situation can be improved if the frequency of the background noise is considerably different than that generated by targets of interest. Smoothing or filtering the data to remove certain components of the recorded signature can aid the computer analyst in converging on magnetic dipole signals.

GRADIOMETER CONFIGURATIONS

Studies with gradient sensors, presented and discussed earlier in this document, demonstrated the advantage of gradiometers over magnetometers in resolving closely spaced targets and in detection of small near-surface targets. Additionally, we have shown on numerous occasions their value in suppressing sloping magnetic gradients such as generated by fences, pipelines, and above ground structures. The question that we have not addressed is how high should the lower sensor be deployed and how large should the vertical sensor separation be. We adopt the general premise that the target magnetic signal measured by the upper sensor should ideally be about 50% of that measured by the lower sensor. A value in this range assures that both sensors are primarily reading the same target. Assuming that the lower sensor is 30 cm above the surface, detection of targets at <0.5 meters below the surface ideally would be done with a vertical gradiometer- sensor separation of 15-20 cm. Targets at depths between 0.5 and 1.5 meters call for a vertical spacing of 30-40 cm. Imaging of the deepest targets calls for vertical separations of only 50-65 cm.

ARRAY CONFIGURATIONS AND DATA RATES

Survey data consist primarily of sensor and position measurements. *MTADS* navigation is based primarily upon DGPS technology which provides position updates at 1 Hz. Dead reckoning will aid in interpolation and position reconstruction in the event that initialization is temporarily lost. Survey design and track layout will minimize the impact of the sparse 1 Hz navigation update.

Data acquisition rates for the newest generation full-field magnetometers allow a choice of data rates up to 80 Hz. There are trade offs among sensor precision, effective time constant and sampling rate. We anticipate that nominal magnetometer data acquisition rates of 20 Hz will be used except when the smallest of ordnance items must be detected.

The horizontal sensor spacing on the earlier *MTADS* arrays has been 0.5 meters. Most site characterization magnetometer or gradiometer surveys that are conducted on fixed grids use grid spacings of 1 meter or larger. These designs were based upon the premise that it was important to detect ordnance larger than a 60 mm mortar and that resolving clusters or adjacent items was not imperative prior to remediation. These premises were based largely on economic considerations. Given the recent emphasis in this field on stressing economy in remediation operations, it has become much more important to accurately mark all ordnance including small shells and antipersonnel cluster munitions and to distinguish ordnance debris and clutter from intact ordnance.

These stringent requirements mandate that both sensor sensitivities and data densities be adjusted to detect minimal signals and to analyze complex targets near the noise floor. Data analysis routines must be able to identify the magnetic footprint of the target ordnance in a noise field. To guide the sensor array design we assume a ferrous target imposes a magnetic signature at the surface with a diameter equivalent to its depth. We assume that the magnetometer (or lower sensor of the gradiometer pair) is located 30 cm above the ground and has the sensitivity to detect the target within this footprint. Finally, we assume that sufficient data must be taken within the foot print of the target to allow either analysis or visual marking. This analysis leads to the information presented below.

Table 3. Required Survey Parameters to Detect Targets at Specified Depths

These guidelines are consistent with our observations using magnetometers and gradiometers at Ft Devens. Our experience working with pipe segment simulants for small ordnance indicate that these are not conservative requirements and do not assure our ability to detect very small ordnance and to distinguish tightly-clustered targets or non-ordnance clutter. The capability of an OEW characterization system to detect and locate the smallest targets to a large degree depends upon the background noise signature both from the sensors and from geophysical anomalies; the frequency spectrum of the background noise and the ability of the analysis system to filter unwanted signatures. These parameters are site dependent. It always will be our strong recommendation that in real ordnance survey situations where remediation is being considered, the surface must be cleaned of proud targets and ferrous clutter prior to site characterization. This represents by far the most economical approach to site characterization and remediation. The time and expense required to just way point and mark dense target fields considerably exceeds the costs associated with conducting the survey and the data analysis.

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