# Multisensor Towed Array Detection System for UXO Detection

H. H. Nelson and J. R. McDonald

***Abstract*—The multisensor towed array detection system (MTADS) was designed to be an efficient, sensitive tool for the detection and characterization of buried unexploded ordnance. It comprises arrays of total-field magnetometers and time-domain electromagnetic induction (EMI) sensors, associated navigation and data acquisition hardware, and a custom Data Analysis System. The MTADS has conducted eleven demonstrations and surveys over the past four years. The system has shown the ability to detect ordnance at its likely self-penetration depths with a probability of detection of 0.95 or better. The model-derived positions and depths of the detected ordnance items are generally well within the physical size of the targets, making remediation much quicker and less costly than with standard techniques. Data sets corresponding to many of the MTADS surveys are available to others in the field.**

***Index Terms*—Electromagnetic induction (EMI), magnetometry, multisensor towed array detection system (MTADS), unexploded ordnance (UXO).**

## I. INTRODUCTION

UNEXPLODED ordnance (UXO) is a serious and prevalent environmental problem currently facing Department of Defense (DoD) facility managers. Mitigation and remediation activities are often hindered by the fact that UXO is collocated with other environmental threats including ordnance explosives wastes (OEW), chemical wastes, and other toxic and hazardous materials. Not limited to active sites and test ranges, these problems also occur at DoD sites that are currently dormant, and in areas adjacent to military ranges that belong to the civilian sector, are on Native American reservations, or are under control of other government agencies.

Traditional techniques for UXO detection, site characterization, and remediation are very slow, labor intensive, and inefficient. Typical detection and characterization technologies involve the use of hand-held detectors operated by explosives ordnance disposal (EOD) or civilian UXO technicians who must slowly walk across a survey area. Time consuming and sometimes dangerous, this process has been documented as inefficient, as well as marginally effective [1]. Often, ordnance items are disguised by the presence of extensive surface clutter and fragments from ordnance operations. Large and deep ordnance targets are often not found because either their footprints are too large to be "visualized" by the walking operator, or their signatures are lost in magnetic disturbances associated with geophysical anomalies. Developing an image of a deep target, especially in a field of shallow targets, is most difficult for the hand-held surveyor. The multisensor towed array detection system (MTADS) technology is designed to address these issues.

The primary goals of the MTADS Demonstration/Validation Program were the following.

1) Field a vehicular-based system employing arrays of sensors for efficient surveying of ranges.
2) Develop a system with sufficient sensitivity to detect all buried UXO to its self-penetration depths.
3) Integrate a precise position location and survey guidance system based on global positioning system (GPS) navigation.
4) Develop and integrate software routines to efficiently analyze, locate, and characterize buried UXO targets for remediation.
5) Develop techniques to create a permanent record in global coordinates of the positions of all targets suitable for geographic information system (GIS) integration.

In this paper, we describe the MTADS hardware and software subsystems and present examples of the data collected by the system on both prepared and live-site ranges. Then we describe some measures of the performance of the system and finally, list the survey data sets available for others to use in developing their own alternative data analysis strategies.

## II. MTADS SYSTEM DESCRIPTION

### A. Field Hardware

The MTADS system hardware includes a low magnetic signature vehicle that is used to tow linear arrays of magnetic and electromagnetic (EM) sensors to conduct surveys of large-areas to detect buried UXO. The MTADS Tow Vehicle, manufactured by Chenowth Racing Vehicles, is a custom-built offroad vehicle, specifically modified to have an extremely low magnetic self-signature. Most ferrous components have been removed from the body, drive train, and engine, and replaced by nonferrous alloys. The vehicle is powered by a modified Volkswagen aluminum engine.

The MTADS magnetic sensors are Cs-vapor full-field magnetometers (a variant of the Geometrics 822 sensor, designated as the Model 822ROV). An array of eight sensors is deployed as a magnetometer array with a 25-cm horizontal spacing. The Tow Vehicle and passive magnetometer platform are shown in Fig. 1. The time-dependence of the Earth's background magnetic field is measured by a ninth sensor deployed at a static site during survey operations. The specially selected magnetometers, which

Manuscript received June 6, 2000; revised November 1, 2000. This work was supported by the Environmental Security Technology Certification Program.

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Publisher Item Identifier S 0196-2892(01)04834-3.

Fig. 1. MTADS deployed with the magnetic sensor array.

Fig. 2. MTADS deployed with the EM induction sensor array.

are airborne quality, were acceptance tested at the manufacturer's facility to verify sensitivity, sensor noise, heading error, dead zones, intersensor compatibility, and performance with the multisensor interface modules.

Three 1-m square, EMI sensors are arranged in an overlapping horizontal array with a spacing of 0.5 m, as shown in Fig. 2. Commercial EM-61 sensors were modified to make them more compatible with vehicular towing speeds and to increase their sensitivity to small and relatively shallow objects. These modifications include an increase in the transmitted pulse power and repetition frequency, increased amplifier gain, and a decrease in the system time constant. The sensor array transmits an electromagnetic pulse into the Earth. Currents are induced in nearby metallic objects, which reradiate electromagnetic energy. This secondary signal is sampled during a fixed time-gate after the transmit pulse by six detection coils that are colocated with, and 40 cm above the three transmission coils.

Magnetometer data are collected at 50 Hz. Combined with our typical survey speed of 6 mph, this results in a sampling interval of 5 to 6-cm along track and 25-cm across track. The EM induction sensors are sampled at 10 Hz at a nominal survey speed of 3 mph. This results in a sampling interval along track of approximately 15-cm and 50-cm across track.

The sensor positions on the surface of the Earth (latitude, longitude, and height above ellipsoid) are determined using satellite-based GPS navigation, employing the latest real-time kinematic (RTK) technology, which provides a real-time position update (at 5 Hz) with an accuracy of about 5 cm. GPS satellite-derived time is used to time-stamp both position and sensor data streams for later correlation.

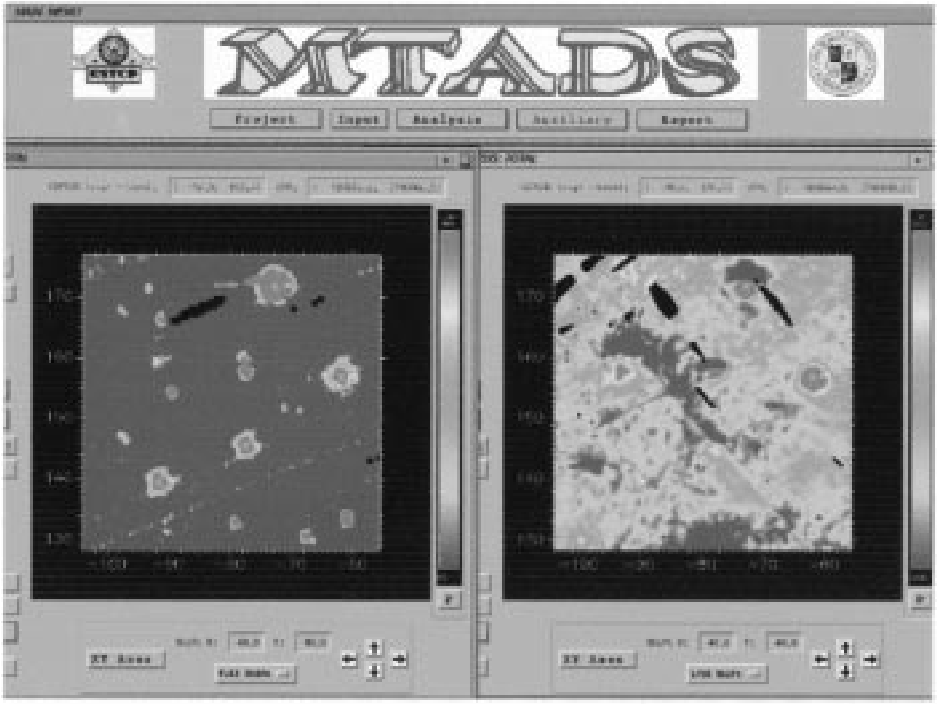


Fig. 3. Example of the target analysis window of the MTADS DAS with the joint magnetometer and EMI fit active.

All navigation and sensor data are provided through electronic interfaces to the Data Acquisition Computer (DAQ) in the tow vehicle. The DAQ computer also functions as a survey set-up tool and provides real-time guidance displays and system performance information for the driver. Perimeter surveys, or point-landmarks, are used to define the survey bounds. The survey course-over-ground (COG) is available in real time on the vehicle display, as are presentations showing the data quality for the primary sensors and the GPS navigation fix quality. This allows the operator to respond to both visual cues on the ground and to the survey guidance display.

### *B. Data Analysis System*

Survey and navigation data recorded in the DAQ computer in the Tow Vehicle are downloaded onto magnetic media for transfer to the data analysis system (DAS) computer. The DAS software was developed specifically for this program as a stand alone suite of programs written using IDL development tools and graphics user interfaces (GUI) working originally in a UNIX-based workstation environment, and more recently, on a LINUX-based PC. The DAS is written in multiple levels for both sophisticated and novice users. A novice user can perform a complete data analysis using menu-driven tools and the background default analysis settings. An extensive range of expert options are also available to facilitate the cleanup of navigation data, sensor nulling and leveling, noise filtering, and other electronic data preprocessing options as desired. The DAS uses resident independent physics-based algorithms to execute target analyses interactively using magnetometry and EM data. Fig. 3 shows a display of the DAS analysis screen used during a joint magnetometry-EM analysis. Extensive training data sets (using inert ordnance) have been taken and used to refine the algorithms to improve target analysis and identification. In addition to position, depth, and size solutions, magnetic analyses provide dipole orientation and effective caliber information and, using a "goodness of fit" analysis, provide guidance in distinguishing ordnance from nonordnance targets. Descriptions of the analysis methodology of the baseline MTADS DAS [2] and current research efforts [3] have been published previously.

The DAS provides a range of graphical and numerical outputs to document the results of the target analysis process and to support remediation efforts. Visual images of selected parts of a survey in a variety of color and gray scale presentations can be created showing target data overlaid by landmark information and analysis results in bitmap (GIS-compatible) (tif) or editable (ps) formats. Local, state plane, or global coordinate system (UTM or Lat/Lon) presentations are selectable. The graphics are appropriate either for reports or to support target way pointing and remediation.

Numerical target analysis results are prepared in tabular form in any combination of desired coordinate systems. These outputs are formatted for incorporation into reports or to be imported into spreadsheets, which can be electronically loaded into the GPS navigation equipment to reacquire the targets in the field in preparation for remediation.

## III. SYSTEM PERFORMANCE

The MTADS has conducted eleven demonstrations and surveys during the past four years [4]–[14]. Three of the surveys were against prepared ordnance sites (Jefferson Proving Ground [JPG] III, Twentynine Palms, and JPG IV), five were at (or associated with) current or former military practice or training ranges (The Badlands Bombing Range, the Laguna Pueblo bombing targets, Walker River Paiute Reservation adjacent to Range B-19 at NAS Fallon, the Former Ft. Pierce Naval Amphibious Training Range, and the Former Buckley Air Base), and two were on landfills (the Portsmouth Naval Shipyard and the Naval District of Washington, Anacostia Annex). At five of these demonstration surveys, remediation operations were carried out either simultaneously with, or shortly after, completion of the survey operations. At several of these deployments, careful measurements of system performance were carried out. These results are summarized below.

### A. Detection Performance

In January 1997, the MTADS was used to survey the 40-acre test site at Jefferson Proving Ground, IN [6], [15], [16]. This site was established at the direction of Congress to evaluate the detection, and later the classification performance, of UXO survey systems. There have been a total of four annual demonstrations at JPG. The MTADS surveyed the site after the commercial demonstration known as JPG III. At this time, the site was divided into three range scenarios, Aerial Gunnery, Artillery and Mortars, and Submunitions and Grenades. Both MTADS magnetometry and EMI surveys of the three sites were performed.

The survey data were analyzed using the MTADS DAS, described above. Target locations derived from the analysis were reported along with a target declaration of ordnance or nonordnance. The MTADS target list and classification were independently compared to the baseline data by scientists from the Institute for Defense Analyzes (IDA) [15]. A summary of their analysis of the MTADS detection performance is shown in Table I. As can be seen, the documented probability of detection within a 1-m critical radius is approximately 0.95 for the site as a whole, slightly higher for the scenarios with larger items, and slightly lower for the scenario with submunitions and grenades. With a 2-m critical radius, the probability of detection increased to 0.975. Although this deployment was a detection exercise, the false alarm rate achieved by MTADS was similar to systems achieving much lower probabilities of detection.

TABLE I
SUMMARY OF THE IDA ANALYSIS OF MTADS DETECTIONS AT JPG III USING A 1.0-m CRITICAL RADIUS

| JPG Scenario | Number of Ordnance in Baseline | Number of *MTADS* Ordnance Declarations | Number of Correct Ordnance Declarations | $P_D$ | False Alarm Rate (hectare$^{-1}$) |
|---|---|---|---|---|---|
| Aerial Gunnery | 47 | 185 | 45 | 0.96 | 42 |
| Artillery and Mortar | 73 | 216 | 70 | 0.96 | 38 |
| Submunitions and Grenades | 86 | 222 | 80 | 0.93 | 45 |

[a] Based on Table 1 of [15]

### B. Sensor Location Precision

One of the goals of the MTADS evaluation at the Twentynine Palms Magnetic Test Range [5] was to determine the overall performance of the combined DAQ, DAS, and navigational hardware and software. Prior to beginning surveys over the prepared ordnance field, a number of reference points were established within the site. The registration targets were 30 12-in-long sections of 3/8-inch diameter steel rebar. The sections of rebar were vertically driven into the ground until flush with the surface. The rebar targets were driven about 5 m apart along the north and south edges of the field. The precise positions of the rebar registration targets were determined using the land-marking tools associated with the DAQ and the Tow Vehicle. Independent landmark data files were created to record these positions. Based upon prior experience, we expected these way pointed positions to be accurate to 3 to 5 cm.

Surveys of the range were carried out by NRL personnel employing the magnetometer and EM-pulsed induction arrays. The rebar targets were analyzed for positions using the MTADS DAS. In the magnetometry survey, the average difference between the analyzed positions and the way-pointed positions was 6 cm. This value is very close to the accuracy expected from our way pointing accuracy alone. The average discrepancy in the analyzed positions of the rebar targets in the EM survey was about 11 cm.

A similar test of system accuracy was carried out on a World War II bombing target and an aerial gunnery target at the Badlands Bombing Range, SD [7]. Examples of the output of the MTADS DAS for the magnetometry and EM induction surveys of a portion of this sight are shown in Figs. 4 and 5, respectively. Following MTADS surveys of the two ranges, approximately 400 targets, both UXO and clutter, were carefully remediated. After an individual target was uncovered, its position was carefully documented using a high-quality GPS system. The actual reacquired target locations were compared to those predicted by the MTADS DAS.

A histogram of the average horizontal miss-distance for the predictions is shown in Fig. 6. The average miss-distance was 13 cm, while 95% of the ordnance were within 29 cm of the prediction. This latter number is due to a few outliers at miss-distances above 0.5 m. These are likely surface clutter items that were moved from their original positions during remediation of the larger, deeper targets. A comparison of the estimated depths of the bombs remediated versus their actual depths is shown in Fig. 7. The distance plotted is depth below the sensors (which are 25 cm above the ground) to avoid complications from targets near the surface. All depths estimated were correct to within the diameter of the target.

### C. System Production

The best measure of system production rate was obtained in a second visit to the Badlands Bombing Range [14], this time to an area known as the Impact Area. This area has been used for ground artillery practice by the National Guard over the years and was expected to have unexploded 105-mm, 155-mm, and 8-in projectiles. The terrain at this site was flat to very gently rolling, and the site set-up allowed for long survey lanes, minimizing the time spent in vehicle turn-arounds. At this site, we were able to survey over 1 ha/h using the MTADS magnetometer array. For an 8-h survey day, this translates to a production rate of 22–25 acres/day.

## IV. MTADS DATA SETS

ASCII data sets corresponding to the surveys discussed in this paper and several others are available from the authors. These data sets consist of preprocessed sensor data. The magnetometer

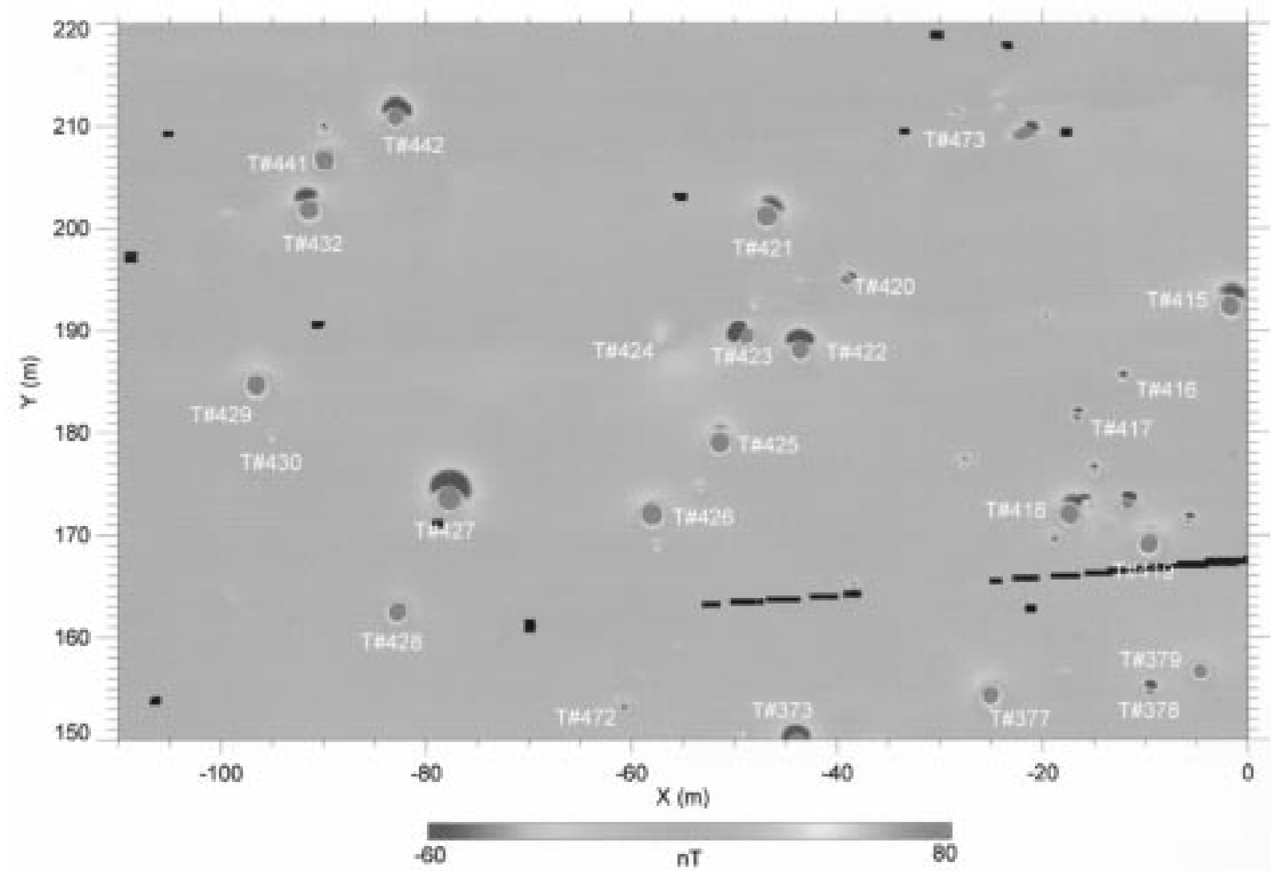


Fig. 4. Magnetic anomaly image of a portion of the Badlands Bombing Range, BBR I. The targets selected for digging are noted in the image.

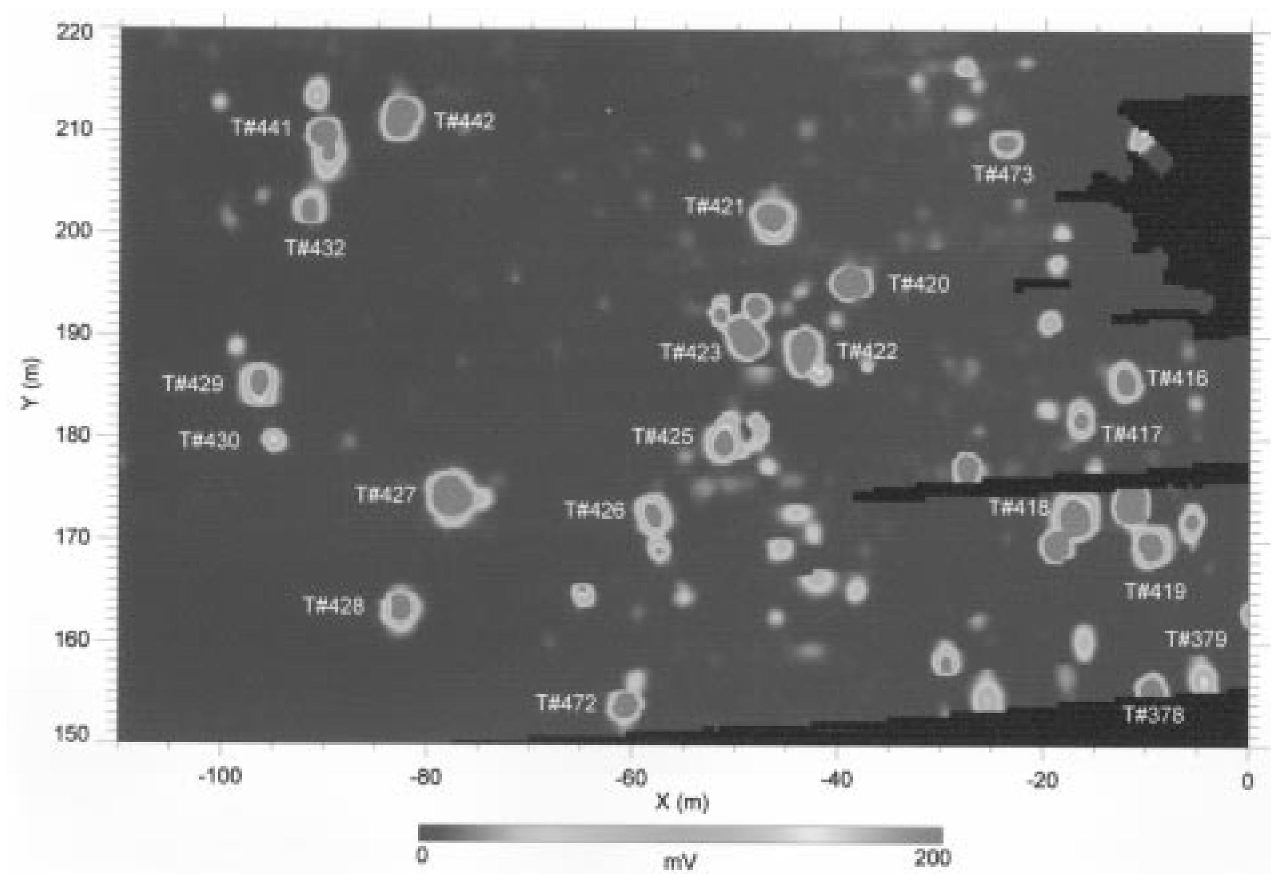


Fig. 5. EM anomaly image of a portion of the Badlands Bombing Range, BBR I. The black areas were not surveyed due to standing water following heavy rains.

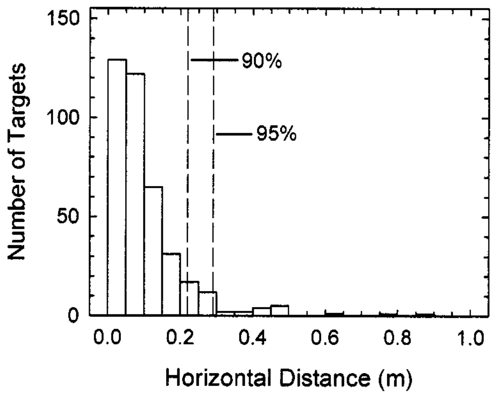


Fig. 6. Histogram of horizontal miss-distance for targets analyzed by the MTADS DAS and remediated at the Badlands Bombing Range.

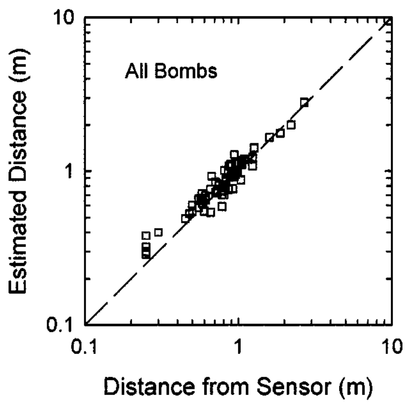


Fig. 7. Comparison of predicted and actual depths of the bombs remediated at the Badlands Bombing Range plotted as distance from the sensors that are 25 cm above the ground.

data are corrected for diurnal variations, using data from a reference sensor, and interpolated to an $x$, $y$ position using the measured GPS locations. The magnetometer files consist of $x$, $y$ intensity triplets. The EM induction data are corrected for sensor drift by removing a running, long-term median from the raw readings and are similarly located. These files consist of location, intensity, and sensor number since the arrangement of the MTADS array makes the sensor positions inequivalent.

## V. Summary

We have described the MTADS developed by the Naval Research Laboratory, Washington, DC, for the detection of buried UXO. The system can detect ordnance at its likely self-penetration depths with a probability of detection of 0.95 or better. The model-derived positions and depths of the detected ordnance items are within the physical size of the targets, making remediation much quicker and less costly than with standard techniques. Data sets corresponding to many of the MTADS surveys are available to others in the field. We have described these data sets and their locations.

## Acknowledgment

The authors would like to thank R. Jeffries, R. Robertson, and L. Koppe for their support of the MTADS field operations and Dr. T. Bell, Dr. N. Khadr, B. Puc, and Dr. B. Barrow for their efforts on the DAS.

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