Naval Research Laboratory
Washington, DC 20375-5320 NRL/PU/6110--97-349

RESULTS OF THE *MTADS* TECHNOLOGY DEMONSTRATION #2

MAGNETIC TEST RANGE
MARINE CORPS AIR GROUND COMBAT CENTER (MCAGCC)
TWENTYNINE PALMS, CALIFORNIA
DECEMBER 3-12, 1996

J.R. McDonald
H.H. Nelson
Chemical Dynamics and Diagnostics Branch
Chemistry Division, Code 6110

Russell A. Jeffries
NOVA Research, Inc.

Richard Robertson
Hughes Associates

CONTENTS

FIGURES iii

TABLES iv

EXECUTIVE SUMMARY E1

1.0 BACKGROUND 1

2.0 HARDWARE DESCRIPTION 2

3.0 SITE DESCRIPTION 4

4.0 PRE-DEMONSTRATION SITE PREPARATION 4

5.0 DEMONSTRATION LOGISTICS 5

6.0 RANGE CLEARANCE APPROVALS 5

7.0 NAVIGATION BASE STATION AND MAGNETOMETER REFERENCE STATION SET UP 6

8.0 NAVIGATION, REGISTRATION TARGETS, AND SUBMUNITIONS 6

9.0 SURVEY SETUP STRUCTURE 7

9.1 Reference Magnetometer and Landmark Data 7

9.2 Magnetometer Survey 7

9.3 Gradiometer Survey 8

9.4 The EM Survey 9

10.0 RESULTS 11

10.1 The Registration Targets 11

10.2 Target Analysis Approach 11

10.3 IDA Data Analysis 12

10.3.1 The EM Survey 12

10.3.2 The Magnetometer Survey 16

10.3.3 The Gradiometer Survey 16

10.4 NRL Data Analysis 16

10.4.1 The EM Survey 16

10.4.2 The Magnetometry Survey 21

10.4.3 The Gradiometer Survey 21

10.4.4 Data Fusion 27

11.0 SYSTEM PERFORMANCE 27

11.1 Ordnance Detection 27

11.2 Ordnance Location Accuracy 32

11.3 Ordnance Depth Accuracy 32

11.4 Ordnance Size Evaluations 33

12.0 DEMONSTRATION COSTS 36

13.0 REFERENCES 37

FIGURES

1 The *MTADS* deployed with the magnetic sensor array 2

2. The *MTADS* deployed with the EM sensor array 3

3 Interior of the *MTADS* Tow Vehicle 4

4. Schematic layout of the Magnetic Test Range showing the control points 4

5. Photograph of the MTR taken from a hill overlooking the Range 4

6. Photograph of the MTR from ground level 5

7. Tractor/Trailer rig used to transport and store the *MTADS* equipment 5

8. Office trailer set up at the Pistol Training Range to support the *MTADS* 5

9. GPS Base Station set up over Monument 9601 at the MTR 6

10. Schematic of the MTR showing the corner posts and the two lines of rebar registration targets 7

11. *MTADS* Magnetometer Survey of the Magnetic Test Range at Twentynine Palms 10

12. *MTADS* Gradiometer Survey of the Magnetic Test Range at Twentynine Palms 10

13. *MTADS* EM Survey of the Magnetic Test Range at Twentynine Palms 12

14. Comparison of fitted and known ordnance depths from magnetometer surveys at the CBD test site 33

15. Comparison of fitted and known ordnance depths from EM surveys at the CBD test site 33

16. Comparison of the fitted and known ordnance depths for all analyzed targets at the Magnetic Test Range from the magnetometry, gradiometry, and EM surveys 34

17. Comparison of Fitted and Known Ordnance Sizes from Magnetometer Surveys at the CBD Test Site 34

18. Comparison of fitted and known ordnance sizes from EM surveys at the CBD Test Site 34

19. Comparison of the fitted and known ordnance sizes for all analyzed targets at the Magnetic Test Range from the magnetometry, gradiometry, and EM surveys 35

TABLES

1. Ordnance at the Magnetic Test Range for this demonstration 1
2. Coordinates of the First-Order Points established to support the demonstration 6
3. Comparison of the rebar landmarks with target positions analyzed from magnetometry data 13
4. Comparison of the rebar landmarks with target positions analyzed from EM data 14
5. Target analysis of the EM survey carried out by IDA 15
6. IDA target analysis of the Twentynine Palms MTR magnetometer survey to probability level 0 17
7. IDA target analysis of the Twentynine Palms MTR magnetometer survey to probability level 1 18
8. IDA target analysis of the Twentynine Palms MTR magnetometer survey to probability level 2 19
9. IDA target analysis of the Twentynine Palms MTR magnetometer survey to probability level 6 20
10. Summary of the IDA magnetometry survey analysis 21
11. IDA target analysis of the Twentynine Palms MTR gradiometer survey to probability level 0 22
12. IDA target analysis of the Twentynine Palms MTR gradiometer survey to probability level 1 23
13. IDA target analysis of the Twentynine Palms MTR gradiometer survey to probability level 3 24
14. IDA target analysis of the Twentynine Palms MTR gradiometer survey to probability level 5 25
15. IDA target analysis of the Twentynine Palms MTR gradiometer survey to probability level 6 26
16. Summary of the IDA gradiometer survey analysis 27
17. NRL target analysis of the Twentynine Palms MTR EM survey 28
18. NRL target analysis of the Twentynine Palms MTR magnetometer survey 29
19. NRL target analysis of the Twentynine Palms MTR gradiometer survey 30
20. NRL target analysis of the Twentynine Palms MTR fused data sets 31
21. Summary of the NRL target analyses for the MTR surveys 33

EXECUTIVE SUMMARY

The Environmental Security Technology Certification Program (ESTCP) provided funding to the Naval Research Laboratory (NRL) for the development and demonstration of a Multi-sensor Towed Array Detection System (*MTADS*), for the detection and classification of unexploded ordnance (UXO). The *MTADS* incorporates both cesium (Cs) vapor full-field magnetometers and active pulsed induction sensors. The sensors are mounted as linear arrays on low-signature platforms that are towed over survey sites by an all-terrain vehicle. All sensor data streams are integrated and recorded by the Data Acquisition System (DAQ). The position-over-ground is plotted using state-of-the-art Real-Time Kinematic, On-The-Fly (RTK/OTF) GPS technology that also provides vehicle guidance during the survey. Using mature sensor technologies, NRL has focused on the development and integration of a Data Analysis System (DAS) to locate, identify, and categorize all military ordnance at their maximum probable self-burial depths. The DAS is efficient and simple to operate.

The performance of the *MTADS* system has been evaluated during the course of a three-phase demonstration plan. The first of these was a technical evaluation ("TECHEVAL") demonstration at NRL/CBD to verify compliance with system requirements and performance specifications. During this phase, a database of sensor responses to diverse ordnance items at multiple depths and orientations was generated. The second demonstration was conducted at the Magnetic Test Range at The Marine Corps Air Ground Combat Center (MCAGCC) in Twentynine Palms, CA in December 1996. In the final test demonstration, conducted in January 1997, the *MTADS* was evaluated at the Jefferson Proving Grounds Site, following the completion of JPG III commercial demonstrations.

This report summarizes the technical results achieved during the Phase II test of *MTADS* at Twentynine Palms, CA. The Magnetic Test Range (MTR) at this facility contains a wide range of inert ordnance items, and represents what is arguably the most realistic example of the conditions that might be encountered on an active military range. Geophysically "noisy," and littered with a diverse spectrum of non-ordnance clutter, this site served as an excellent location for the first comprehensive field test of the *MTADS* hardware and software.

Conducted over a 10-day period, the *MTADS* was used to collect exhaustive data sets for the magnetometer, gradiometer, and pulsed induction sensor suites. Over 70 ordnance items of various types are located within the 8 acre site. Moreover, additional small ordnance items and sections of rebar were accurately placed prior to beginning the surveys. As a result, the classification algorithms for a broad scope of ordnance items were thoroughly evaluated, and data were gathered verifying the x-y position accuracy of the on-the-fly navigation system.

Capitalizing on the strengths of each of the individual sensor suites, two independent data analyses were completed by both NRL and personnel from the Institute for Defense Analyses (IDA). Master target lists were generated in which ordnance items were clearly identified with a statistical accuracy of approximately 95%, and average x-y positions derived from the navigational system were demonstrated to be accurate to within less than five centimeters.

In addition to establishing and validating the performance characteristics of the *MTADS*, a review of the anticipated logistical and manpower costs associated with conducting surveys utilizing the system has been initiated. Based upon the experiences gained in the field, it is possible to begin estimating the operational costs for conducting surveys with the *MTADS*. This may serve as the basis for cost/benefit analyses in comparison

with other survey methods, and may provide an initial foundation for life cycle analysis.

1.0 BACKGROUND

The Marine Corps Air Ground Combat Center (MCAGCC) in Twentynine Palms, CA is the largest live-fire training range in the United States. Resident on this facility is the Magnetic Test Range (MTR), a Navy-designed unexploded ordnance (UXO) test range that contains a challenging assortment of ordnance items buried at carefully controlled depths and orienta-tions. The field is located in a desert environment typical of the live-fire ranges located in the western half of the United States. Soils are fairly conductive and have a significant magnetic back-ground. Range deterioration due to environmental degradation is minimal. The MTR is secure, where the only activities are sporadic tank traverses or short-term personnel operations. Non-ordnance surface clutter such as tent stakes, com wire (iron), and discarded food and beverage containers are encountered.

The Magnetic Test Range at MCAGCC was established in the late 1980's to serve as a test and evaluation site for prototype magnetometer and GPR-based survey systems. In August of 1992, this site was used to evaluate the performance of two gradiometer systems: the Forster Model 4.021 (military designation MK-26) and the Schonstedt Model GA-72CV. Data collection for this evaluation was executed by four Marine groups from the MCAGCC Explosive Ordnance Disposal (EOD) team resident at Twentynine Palms. Results of these studies have previously been reported.[1]

The MTR at the MCAGCC encompasses approximately 8 acres. There are currently 70 inert ordnance items permanently emplaced at depths ranging from 0.5 to 17 feet. The ordnance items span the range from 60 mm mortars to a Mk 84 2000-lb bomb. In most cases, the larger the item, the deeper it is buried, consistent with projected self-penetration depths. In some instances, multiple targets are buried with small separations and some large targets are buried fairly shallow, as they are often found on live ranges. Table 1 lists the permanent ordnance at the MTR and the submunitions that we temporarily emplaced, including 20 and 30 mm rounds, 40 mm anti-tank rounds, and M 46 grenades. These items, particularly the latter two, are of specific concern on the active ranges at MCAGCC. The submunitions were positioned using the waypointing capability of the Trimble navigation and the Data Acquisition System (DAQ) system before of survey operations began.

The MCAGCC site has additional inherent advantages. Extensive support of R&D activities is provided by the excellent resident EOD detachment. The EOD detachment clears tens of thousands of ordnance items from their ranges every year. Accordingly, this represents an invaluable source of real-world experience to draw upon, and is an asset which could be brought to bear, as required, during field operations. The demonstration at Twentynine Palms took full advantage of a Navy-designed test range containing a challenging range of ordnance items that were buried under carefully controlled conditions.[2] The demonstration constituted a logical step in the evaluation process for *MTADS*, a survey in a controlled but realistic field environment.

Table 1. Ordnance at the Magnetic Test Range for This Demonstration.

Permanent Ordnance	Number of Items	Range of Depths (m)
60 mm mortar	10	0.15-0.46
81 mm mortar	7	0.46-0.76
105 mm projectile	10	0.46-1.10
155 mm projectile	10	0.61-1.22
8" projectile	10	1.83-2.74
Mk 81 bomb	10	1.43-3.11
Mk 82 bomb	10	1.22-4.42
M 117 bomb	1	3.96
Mk 83 bomb	1	5.09
Mk 84 bomb	1	4.88
Submunitions		
20 mm	1	flush
30 mm	5	flush

M 42	1	flush
M 46	5	flush

Surveys of the range were carried out by NRL personnel employing magnetometer, gradiometer, and the electromagnetic (EM) pulsed induction arrays. Although the ordnance locations were precisely known, the actual target analysis was carried out by Institute for Defense Analyses (IDA) personnel. Prior to analysis, the types of ordnance at the site were known to them, but the ordnance location truth tables were not.

The performance objectives for the demonstration at Twentynine Palms were twofold. The first objective was a continued evaluation of the operation of the *MTADS* in a realistic field environment measuring system performance against system requirements and performance specifications. Several evaluations were not completed at the TECHEVAL or were deferred for the second demonstration. These involved tests of the system under larger survey conditions to demonstrate that the system hardware, the DAQ and the DAS, can handle large survey areas, large data sets, and periods of extended and continuous operation. Undertaking an extended operation requiring shipping all equipment several thousand miles with an extended set up at a remote site also demonstrated the readiness of the *MTADS* system for transition as field hardware and allowed us to evaluate the system under rugged conditions and will determine the appropriateness of our choice of support components and system spares.

The second demonstration objective focused on the performance of the system for locating and characterizing buried ordnance. Target analysis of the three surveys was independently carried out by IDA personnel who were not involved in the development of the system. The IDA personnel, being physicists and computer specialists, are more highly trained than the probable ultimate users of the DAS, however, they had only a short learning period with the software and users manuals (that were still in rudimentary form) in preparation for this task. Their interaction with us in this demonstration provided very useful information in helping us to prepare the DAS as a transition product appropriate for the end user. The demonstration at Twentynine Palms also allowed us to evaluate the performance of the target analysis algorithms that were developed for *MTADS* and refined, based upon the development of the target training data sets taken during TECHEVAL.

2.0 HARDWARE DESCRIPTION

The *MTADS* technology has been described in detail previously.[3-7] The performance of many of the *MTADS* system components and some of the subsystems have been tested and verified against the performance requirements and manufacturing or procurement specifications.[8] Briefly, the system hardware includes a low magnetic signature vehicle that is used to tow linear arrays of magnetic and (EM) sensors to conduct surveys of large-areas to detect buried UXO. The *MTADS* Tow Vehicle, shown in Figure 1, is manufactured by Chenowth Racing Vehicles. It is a custom-built off-road 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. Details of the vehicle construction and performance are described in the Vehicle Owners and Shop Manuals.[9-11]

The *MTADS* magnetic sensor array, shown deployed in Figure 1 incorporates Cs vapor full-field magnetometers (a variant of the Geometrics 822 sensor, designated as the Model 822ROV). An array of eight sensors is deployed either as a magnetometer array or as a four gradiometer array measuring the vertical component of the Earth's total field. The time-dependence of the Earth's background field is measured by a ninth sensor deployed at a static site during survey operations. The magnetometers were acceptance tested at the manufacturers' facility to verify sensitivity, sensor noise, heading error, dead zones, intersensor compatibility, and performance with the multisensor interface modules.

The active EM sensor array, as shown in Figure 2, incorporates three pulsed-induction EMI sensors (a variant of the Geonics EM-61 instrument). These sensors, configured as an overlapping horizontal array, transmit a tailored electromagnetic pulse into the Earth. Metallic objects efficiently absorb the energy, inducing eddy currents that reradiate electromagnetic energy. This secondary signal is time sampled by three

Figure 1. The *MTADS* deployed with the magnetic sensor array

Figure 3. Interior of the *MTADS* Tow Vehicle

detection coils that are collocated with the three transmission coils and three coils positioned above the transmit coils.

The sensor positions on the surface of the Earth (latitude, longitude, and height above ellipsoid) are determined using GPS navigation (Trimble Model 7400), employing Real-Time Kinematic, On-The-Fly (RTK/OTF) mode resolution of integer ambiguities. This technology provides 5 cm level accuracy with 5 Hz updates. The GPS satellite clock time is used to time-stamp both position and sensor data information for later correlation. In addition, an electronic compass, attitude sensors (pitch, roll, and yaw), and tick wheel sensors provide navigation back-up and dead-reckoning capability. All navigation and sensor data are provided through electronic interfaces to the guidance computer in the Tow Vehicle. The computer also functions as a survey set-up tool and provides real-time guidance displays and information for the driver. The interior of the *MTADS* Tow Vehicle is shown in Figure 3.

Perimeter surveys or point landmarks are used to define the survey bounds. The DAQ develops a survey track grid that is presented to the vehicle operator via a touch screen display located beside the steering wheel. The survey course-over-ground (COG) is plotted in real-time on the display, as are presentations of the course heading error and distance-off-track information. This allows the operator to respond to both visual cues on the ground and to the survey guidance display. Following the survey, the operator can return to survey any missed areas before leaving the field.

Survey data in the DAQ computer is downloaded by tape or by hard-wire connection to a notebook computer for transfer to the DAS computer. The DAS software was developed specifically for this program as a stand-alone suite of programs. It was written using IDL development tools, and graphical user interfaces (GUIs) working in a UNIX-based workstation environment. The DAS is written in multiple levels for both sophisticated and novice users. Even the novice user can perform a complete data analysis using menu-driven tools and the background default analysis settings. An extensive range of expert options is also available to facilitate the cleanup of navigation data, sensor nulling and leveling, noise filtering, and other electronic data preprocessing options.

The DAS uses resident, independent physics-based algorithms to execute target analyses interactively using magnetometry, gradiometry, and EM data. Extensive training data sets (using inert

Figure 2. The *MTADS* deployed with the EM sensor array

Figure 6. Photograph of the MTR from ground level

ordnance) have been taken and used to refine the algorithms to improve target analysis. In addition to position, depth, and size solutions, magnetic analyses provide target orientation and effective caliber information and, using a "goodness of fit" analysis, provide guidance in distinguishing ordnance from nonordnance targets.

3.0 SITE DESCRIPTION

The schematic layout of the MTR is shown in Figure 4 and Figure 5 shows a photograph overlooking the MTR from a hill adjacent to the MTR. Figure 6 is a photograph of the MTR taken from ground level. On the MTR the terrain is relatively flat, with sparse desert vegetation. Soil conditions consist of a mainly sandy surface layer overlaying a dense hardpan.

As shown in Figure 4, the MTR is roughly trapezoidal in shape, and at each of the four corners are wooden posts, extending to a height of approximately 5 feet above the surface. These posts served as the reference points for the local coordinate system that was used to establish the MTR.

4.0 PRE-DEMONSTRATION SITE PREPA-RATION

Geo-Metrics, GPS, Inc., was tasked to conduct a survey and establish six first-order points prior to the initiation of this demonstration, and this work has been reported previously.[12] Monuments 9601 and 9602, shown in Figure 4, were established as first-order points. The former served as the reference point for this survey. Point 9602 was established on top of the hill as a backup because it wis unlikely to be disturbed by other military operations that might have taken place at the base. At the same time, the four corner posts that were originally used to define the MTR were shot in. These are designated as NE, NW, SE, and SW in

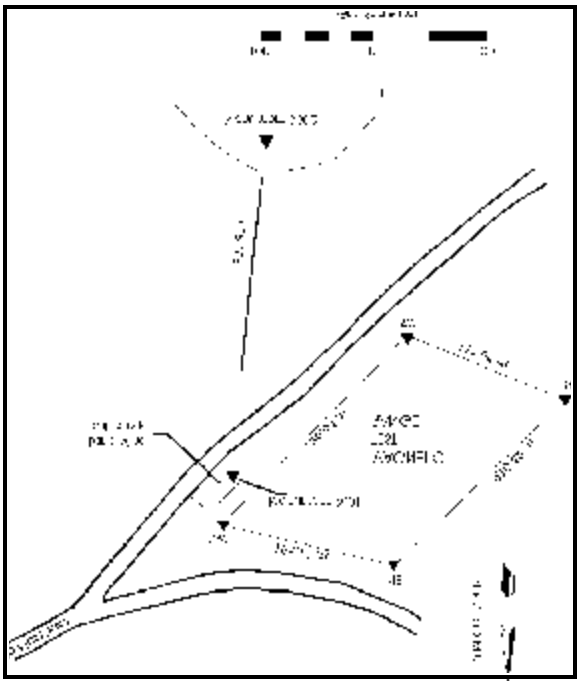

Figure 4. Schematic Layout of the Magnetic Test Range showing the Control Points

Table 2.

The wooden corner posts defining the perimeter of the survey were elevated and do not appear as targets in either magnetic or pulsed induction surveys of the site. Therefore, numerous additional control points (registration targets) were established by vertically driving short lengths of rebar flush with the ground near the edge of the MTR. These targets were landmarked using the DAQ system prior to beginning work. They appear on all surveys and can be used as registration points for imagery and graphics.

Figure 5. Photograph of the MTR taken from a hill overlooking the Range

Prior to beginning work on Demonstration 2, several additional targets were established on the MTR. These include 20 and 30 mm rounds, 40 mm rifle cartridges, and M 42 submunitions. These items from NRL inert stores were emplaced flush with the surface and waypointed to establish their absolute positions. These items were placed along the north boundary of the MTR and were removed from the range upon completion of the demonstration.

5.0 DEMONSTRATION LOGISTICS

The *MTADS* and its related support equipment were transported by a rented tractor/trailer. The bed of the trailer was modified to provide tie-downs for the Tow Vehicle as well as the two sensor platforms. A storage bay was fabricated at the front of the trailer to accommodate transportation of the data analysis computers and printers. The storage bay also was used to secure all of the ancillary support equipment for the *MTADS*, including tools and spare parts. Transportation of the *MTADS* from the Chesapeake Beach, MD to Twentynine Palms, CA was accomplished in seven days, which included packing the trailer and drive time. Figure 7 shows a photograph of the trailer. The trailer remained at this dock during the operation. Every night, the vehicle and tow platforms were locked in the trailer, providing secure overnight storage.

Prior to arrival at Twentynine Palms, an office trailer was rented and erected at the Marksmanship Training Unit (MTU) parking lot, to serve as the operational headquarters during the project. The trailer was equipped with furniture, which supported the DAS. Additional space was used for storage of tools and supplies and spare batteries and chargers. The office contained spaces for meetings and daily safety and operations briefings. Figure 8 shows the trailer set-up.

6.0 RANGE CLEARANCE APPROVALS

The MTR is located in a live-fire range, and prior to

Figure 7. Tractor/Trailer rig used to transport and store the *MTADS* equipment

Figure 8. Office trailer Set-up at the Pistol Training Range to support the *MTADS*

Table 2. Coordinates of the First-Order Points established to support the demonstration

Station	Latitude	Longitude	Elevation (m)	Height Above Ellipsoid (m)
9601	34º 15 '08.18782" N	116º 02' 35.06192" W	658.200	626.473
9602	34º 14' 58.43808" N	116º 02' 34.11701" W	685.581	653.850
NE	34º 15' 05.85400" N	116º 02' 23.64607" W	656.660	624.930
NW	34º 15' 10.67197" N	116º 02' 29.48860" W	653.235	621.508
SE	34º 15' 03.93305" N	116º 02' 29.09081" W	660.258	628.528
SW	34º 15' 09.53476" N	116º 02' 35.42163" W	657.909	626.183

departing for the MTR each day it was necessary to obtain permission from the Range Clearance Office (known as BEARMAT). It is also necessary to check in with the Range Clearance Office once situated on the site and again before leaving, thus requiring use of radios or cellular phones.

7.0 NAVIGATION BASE STATION AND MAGNETOMETER REFERENCE STATION SET-UP

The first-order reference point (Monument 9601) as shown in Figure 4 served as the geographic reference for setting up the Global Positioning System Base Station. The magnetometer reference station was set up approximately 50 meters south of the southern perimeter of the MTR, and approximately 30 meters east of the road shown in Figure 4. Procedures for assembling both the GPS and magnetometer reference stations have been described previously.[8] Figure 9 shows the base station setup over Monument 9601 just inside the Mine Field Test Range.

8.0 NAVIGATION, REGISTRATION TARGETS, AND SUBMUNITIONS

The Trimble 7400 hardware and firmware installations were made to the GPS just prior to leaving for Twentynine Palms. The hardware was checked out, however no extensive surveys were taken with the new navigation equipment before arriving at the MTR. While at the MTR we took survey data at both 1 Hz and 5 Hz for comparison. Because of the risks associated with using untested equipment and software, all survey data were taken at the MTR using the 1 Hz navigation updates and the firmware versions previously evaluated

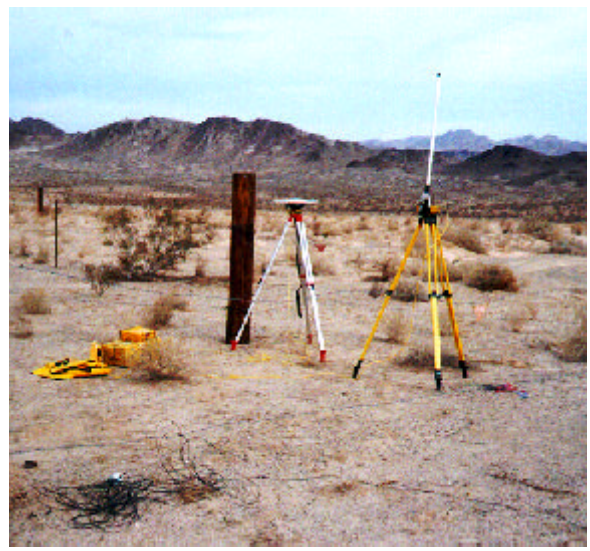

Figure 9. GPS Base Station set-up over Monument 9601 at the MTR

at TECHEVAL. Based upon the tests done during the MTR project, all hardware and firmware upgrades were permanently installed for subsequent demonstrations.

As an integral part of the *MTADS* evaluation, procedures were established to facilitate the determination of the overall performance of the combined data acquisition (DAQ), data analysis (DAS), and navigational hardware and software. Prior to begin-ing surveys, a number of reference points were established within the site. The registration targets include about 30 12-inch-long sections of 3/8" dia-meter steel rebar. In addition, 13 small items (includ-ing a shotput used for many prior reference studies) and numerous 20 and 30 mm rounds, 40 mm grenades and Mk 42

submunitions were temporarily installed.

The sections of rebar were vertically driven into the ground until flush with the surface. The rebar targets were driven about 5 meters apart along the north and south edges of the field, as shown in **Figure 10**. The submunitions were placed about 5 meters apart along the perimeter beginning at the NW and NE posts. The precise positions of the rebar registration targets and the submunitions were determined using the landmarking 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 positions to be accurate to 3 to 5 cm.

9.0 SURVEY SETUP STRUCTURE

The DAQ and the DAS software were used to create a project named "29Palms" and a site named "MAG_TEST_RANGE." The extent of the site was determined by a landmark file acquired by driving around the perimeter of the test range. The origin of the site was defined by the location of the corner post labeled "SE" in UTM coordinates (see Table 2 and Figure 10). All local coordinates in the *MTADS* DAS are in meters relative to this UTM position.

This project consists of five surveys, the reference magnetometer data files, and the landmark data files. There are three magnetometer surveys: the array at 0.25 m above the surface named "Mag TOTAL" the lower gradiometer array processed as a magnetometer array named "Mag LowerGrad," and the upper gradiometer array processed as a magnetometer array named "Mag UpperGrad." There is a gradiometer survey with the lower sensors at 0.4 m and the upper sensors at 0.95 m named "Grad TOTAL." Lastly, there is an EM survey named "EM61 TOTAL." The directory structure generated by the DAS for this project contains both the raw and processed data files. It has been archived using the UNIX "tar" command to 4 mm DAT tape and contains 431 MB of data.

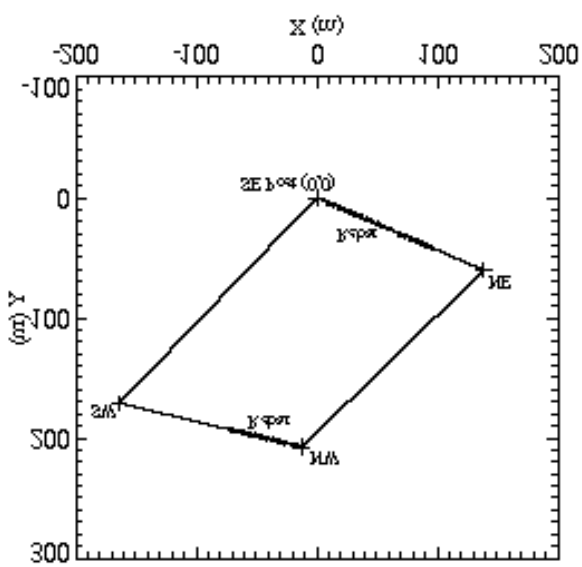

Figure 10. Schematic of the MTR showing the corner posts and the two lines of rebar registration targets

9.1 Reference Magnetometer and Landmark Data

The reference magnetometer files and the landmark files are read into and saved by the DAS project structure. When processing new magnetometer data, the appropriate reference magnetometer files, based upon the recorded satellite clock times, are called and subtracted if the reference subtraction processing option is selected. Landmarks waypointed by the *MTADS* GPS system are read in and displayed in both the SITE VIEW and the ANALYSIS VIEW windows if the landmark overlay option is enabled.

9.2 Magnetometer Survey

The navigation data were preprocessed with the DAS software to remove portions of the data where: the vehicle was in a turn, the vehicle was stopped, and when the GPS data were flagged as bad by the analysis system and could not be corrected. For a half hour of surveying, fewer than 10 of the 1800 GPS data points are typically flagged as bad (not RTK). The DAS software was used to correct these positions based on navigation information during straight legs of the survey. At most, only one or two points in sequence required correction. A few points were flagged as bad by the DAS software based on timing problems. Occasionally, the Trimble either repeats or skips over an expected one second reading. The DAS software allows the operator to correct the GPS time stamp and the GPS position as necessary. All these operations were made in the preprocessed data files.

The magnetometer array data was collected at 50 Hz at an array of height of 0.25 m above the surface. The DAS automatically flags as bad any sensor data that exceeds preset threshold values This occurred typically fewer than five times over a half hour survey. The reference magnetometer was used to remove the diurnal variation of the Earth's field. Once this subtraction takes place, the sensor data are reduced to magnetic anomaly data.

The GPS-reported positions were used to map out the positions of each sensor in the magnetometer array, interpolating between the 1 Hz updates. The DAS

software automatically corrects each sensor reading for directional offsets based on the differences in the median level of each sensor in the two dominant directions of travel.

The following mission files were used to construct the magnetometer survey. The area surveyed, the start time, the duration, and the number of lanes surveyed across the site are noted for each mission. A mission is defined as the survey data taken during a continuous survey period that is assigned to an independent file. A mission may be a few seconds or up to 4 hours long.

Survey Missions

96341682 First mission, starts at the southern corner (labeled SE) and driving back and forth northwest/southeast towards the western corner (labeled SW). 16:23:16, 11 minutes, 7 lanes across the site.

96341694 The second mission picks up where 96341682 left off. 16:40:16, 88 minutes, 54 lanes.

96341767 Third mission, picks up at end of 96341694. 18:25:18, 35 minutes, 20 lanes.

96341814 Fourth mission, picks up at end of 96341767. 19:32:19, 28 minutes, 16 lanes.

96341839 Fill in missed gap in 96341682. 20:09:20, 3 minutes, 2 lanes.

96340971 Done on previous day after GPS problem fixed. Fill in of northwest corner, driving northeast/southwest direction. 23:19:23, 14 minutes, 14 partial lanes.

96340983 Fill in of southeast corner, driving in northeast/southwest direction. 23:36:23, 6 minutes, 8 lanes.

These processed mission files are used to create a master survey file. This file is a random gridded array of fully corrected sensor data. Figure 11 shows this data interpolated onto a regular grid and displayed as a false color image. In this display, positive magnetic anomalies saturate as red at 40 nTesla. Negative magnetic signals saturate as deep blue at -40 nTesla. Numerous typical dipolar anomalies are apparent, even at this course grid. The dotted white line connects the posts at the corners of the site. A few of the rebar targets are visible at the top and bottom edges of the survey lying along the (dotted line) perimeter.

The missed areas in the northwest and southeast corners are areas where very rough terrain (i.e., deep gullies with soft sand and large clumps of plants) prevented access by the vehicle and sensor platform. It is immediately apparent that extensive magnetic signals associated with the local geology exist. These features occur on scales from submeter to tens of meters across the site. Other features which appear as extended sweeping structural anomalies are associated with shallow ditches or trenches that have been made by earth moving equipment. These features and the arroyo along the southeast edge of the site have changed little since the range was installed. The arroyo in the northwest corner of the site has become deeper and wider than when the site was installed. It is apparent that it has also been used on occasion as a road. The southeast to northwest streaks of missed area within the survey are all associated with bushes or cactus. In the northwest corner, the survey has been partially filled in by driving along the edge of the arroyo.

9.3 Gradiometer Survey

The navigation data were processed in a similar fashion to the magnetometer data. The gradiometer data were collected at 50 Hz. The sensor spacing was 0.5 m horizontally and 0.55 m vertically. The lower four sensors were 0.4 m above the surface. Bad magnetometer values were automatically flagged and removed. The sensor readings of the vertical pairs of magnetometers were subtracted, creating a vertical gradient signal. After subtraction, the gradiometer data were directionally corrected. The same layout was used for both the magnetometer and gradiometer surveys, traveling in lanes parallel to the long dimensions of the site. Part of the northwest corner of the site was filled in by again surveying along the arroyo.

The following missions were used to construct the gradiometer survey. The area surveyed, the start time, the duration, and the number of legs surveyed across the site are noted for each. The time required for this survey was 3 hours and 3 minutes.

96341934 First mission, starting at the southern corner (labeled SE) and driving back and forth northwest/southwest towards the western corner (labeled SW). 22:25:22,

96341957 Second mission, picks up where 96341934 left off. 22:59:22, 49 minutes, 25 lanes.

96342654 Third mission, picks up where 963341957 left off. 15:42:15, 39 minutes, 22 lanes.

96342684 Fourth mission, picks up where 96342654 left off. 16:25:16, 52 minutes, 29 lanes.

96345847 Fill in of northwest corner, driving northeast/southwest direction. 20:20:20, 11 minutes, 12 partial lanes.

Figure 12 shows an interpolated magnetic anomaly map of the 8-acre site from the gradiometer survey. The dashed white line is the outer perimeter of the site. The most striking contrast between the magnetometer and gradiometer anomaly maps is the suppression of the geological noise which dominates parts of the magnetometry map. The rebar targets are much more apparent along the southeast perimeter line than in Figure 11. Cursory examination reveals many common large magnetic features in each survey. The gradiometer image is overlaid by a relatively high frequency noise (on the meter scale) that appears as a yellow speckle on the green background. This noise results from eddy currents induced in the upper aluminum frame member by its movements in the Earth's field as it bounces over terrain. In the gradiometer configuration, the upper sensors lie close to the plane of the frame.

9.4 The EM Survey

The navigation data were processed as described for the magnetometer surveys. The EM data were collected at 10 Hz and correlated with the navigation data. The sensor measurements are mapped out separately for the upper three coils and the lower three coils. Offsets are automatically subtracted from each array to correct for a DC bias.

During the survey at the MTR, the upper coils were observed to drift over a time period of several minutes. This produces some streaking in the EM image. There were noise problem associated with a cable connection, and several sections of the survey were repeated. The defective data were discarded. The EM survey was laid out perpendicular to the other surveys, i.e., lanes were driven parallel to the short dimensions of the site. Because the sensor data are sampled at 10 Hz, the vehicle speed for EM surveys is one-half that used in the magnetometer surveys.

The following mission files were used to construct the EM survey. The area surveyed, the start time, the duration, and the number of legs surveyed across the site are noted for each.

96344677 First mission after correcting intermittent noise problem, starting in middle of the site and driving roughly west/east. 16:15:16, 9 minutes, 4 lanes across the site.

96344685 Next mission to the south. 16:27:16, 34 minutes, 16 lanes.

96344721 Next mission. 17:19:17, 9 minutes, 4 lanes.

96344731 Next mission. 17:33:17, 25 minutes, 10 lanes.

96344750 Next mission. 18:01:18, 18 minutes, 8 lanes.

96344765 Next mission. 18:21:18, 19 minutes, 10 lanes.

96344779 Next mission. 18:43:18, 4 minutes, 2 lanes.

96344804 Next mission, southeastern edge of site. 19:19:19, 18 minutes, 10 lanes.

96344823 Starting along northwestern edge of site. 19:45:19, 10 minutes, 6 lanes.

96344898 Next survey south of 96344823. 21:34:21, 17 minutes, 9 lanes.

96344912 Next survey to the south. 21:53:21, 6 minutes, 3 lanes.

96344919 Next survey to the south. 22:03:22, 29 minutes, 13 lanes.

96344940 Next survey to the south. 22:34:22, 16 minutes, 7 lanes.

96344952 Next survey to the south. 22:52:22, 79 minutes, 36 lanes.

FIGURE 11

FIGURE 12

96345678 Fill in gap in center of site. 16:16:16, 19 minutes, 8 lanes.

96345693 Fill in gap in the center of the site. 16:38:16, 18 minutes, 8 lanes.

96345713 Fill in area in southeastern corner. 17:06:17, 6 minutes, 8 partial lanes.

Figure 13 shows a false color image resulting from interpolating the sensor data from the upper coils onto a regular grid. The sensor output is sampled as a voltage. In this image, the presentation is allowed to saturate (red) at a value of 40 mV. However, the sensors do not saturate until signals reach 40 V. Thus, as in the magnetometer plots, we are displaying only a very small fraction of the dynamic range of the sensors. The largest anomalies on the site produce peak signals smaller than 1 V. The rebar registration targets stand out vividly along the northern and southern perimeters. The line of targets extending along the eastern perimeter from the northern corner are the 20 to 40 mm submunitions. There are both common features and significant differences between the EM images and the passive sensor surveys and these are discussed in more detail below. The dominant feature of the EM array is its extreme sensitivity to very small shallow targets. The array is more sensitive than the magnetometer or gradiometer arrays to all isolated ferrous targets to a depth of about 2 m. At depths greater than about 2.5 m, the magnetometer array is more sensitive to ferrous targets.

10.0 RESULTS

10.1 The Registration Targets

In the magnetometer and EM surveys the rebar registration markers were analyzed as targets using the DAS. Since the absolute positions of these targets are known from land marking, their analysis as targets can serve to evaluate the overall performance of the system. This rebar target analysis includes uncertainties propagated from the following sources of error: gross position uncertainty based upon the Trimble navigation system position readings; errors resulting from the directional and geometric corrections of the sensor positions relative to the GPS antenna; errors from the assumed linear position interpolations between the one second updates from the navigation system; uncorrected pitch, roll, and yaw errors in the sensor positions; corrections to the navigation data stream from timing or data quality lapses; errors created in the DAS target fitting resulting from approximations in the fitting algorithms; or from interferences from geological noise, clutter, other nearby targets; and incomplete survey target data.

The results for the rebar registration target analysis for the magnetometry survey are presented in Table 3. Table 4 presents the same information for the EM survey. In the magnetometer survey, the Tow Vehicle surveyed perpendicular to the two lines of registration targets which were placed at the ends of the site bounded by the arroyos. Because turns in these areas were difficult in certain places, eight of the registration targets do not appear in the survey. Eight more targets are noted as partial signatures. Of the 22 targets for which there are analyzable signatures, the average fit error is 3 cm in X and 5 cm in Y. In this context, X and Y are UTM Eastings and Northings. The survey tracks do not parallel either coordinate. This average fit error is approximately the same as is expected from the raw navigation uncertainties alone.

The EM survey lines were driven parallel to the registration targets and therefore covered them better. Only one target was missed and two others were recorded as partial signatures. The average fit error from the EM survey is 5 cm in X and 10.5 cm in Y. This position accuracy is even more surprising because of the relatively much sparser data set created by the EM array. These analyses build confidence in the overall *MTADS* ability to accurately locate targets. There are no sources of error among those cited above (or others that were unrecognized) that significantly affect the target location accuracy. Based upon this information, we expect an ordnance location accuracy of better than 0.5 meters. The accuracy in location of the rebar targets will be degraded in ordnance surveys by ordnance orientation effects, object remnant moments, by the presence of clutter, dense target fields, and other effects such as geological interferences.

10.2 Target Analysis Approach

The survey data were independently analyzed by NRL and the Institute for Defense Analyses (IDA). The *MTADS* DAS was installed on an SGI platform at IDA, and a data tape was used to transfer the processed data files for the magnetometer, gradiometer, and EM surveys. The operation of the analysis software routines was demonstrated and a draft of the DAS operator's manual was provided. IDA devised their own approach to target analysis, as described below.

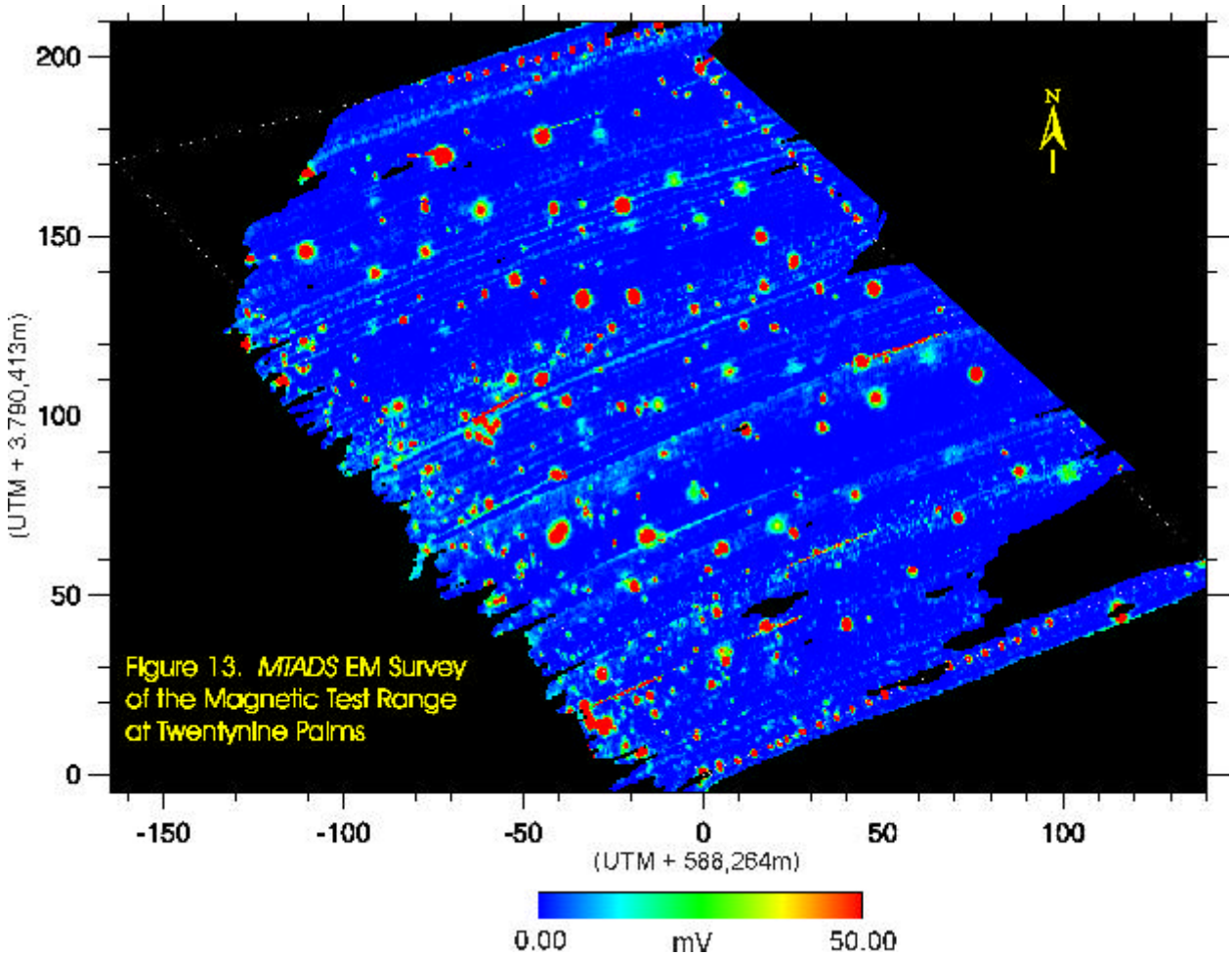

Figure 13. *MTADS* EM Survey of the Magnetic Test Range at Twentynine Palms

A software utility was written at NRL to evaluate the target analyses. The utility accepts baseline target information which is used for comparison with analysis results. The baseline information includes target position (in UTM coordinates) and depth (in meters) and ordnance azimuth and inclination angles. The *MTADS* output Target Tables are organized in a similar spreadsheet form. There is a provision in the Target Tables for inclusion of a comment. The EM Target Tables include an additional column where target size is recorded, assuming that the target is composed of non-ferrous metal. Target sizes are reported in the Target Tables based upon the equivalent radius of a sphere required to produce the fit magnetic moment at the calculated target depth. We intended to incorporate a scaling factor to correlate the sphere radius with the dimensions of ordnance. However, this proved unnecessary as the reported size correlates very closely, in practice, with the minor axis diameter of the ordnance producing the signal.

10.3 IDA Data Analysis

10.3.1 The EM Survey

Analysis of the EM survey was carried out as described in the DAS Operator's Manual and a Target Table was generated. 252 targets were analyzed; all were declared as ordnance. Their calculated ferrous sizes ranged rom 40 mm to 390 mm. Six targets were fit to a depth of 0 m, while the deepest target was calculated to have a depth of 4.09 m. The NRL utility was used to evaluate the fits based upon information in the *MTADS* Target Table. A summary of this information is presented in **Table 5**. The highlighted blocks denote the four target pairs that were buried with small horizontal separations. The IDA analysis detected these target pairs. but declared them as single targets.

All ordnance smaller than the 8 inch projectiles were detected, as were eight of the ten 8 inch projectiles. With the exception of the paired targets and Cl, all targets were correctly located to within 0.5 m.

Overall, 61 of the 70 ordnance targets were located. With the exception of the Mk 84 and the paired targets, all targets were located within a 1.0 meter critical radius. With two exceptions (C2 and C7) all the undetected targets were buried deeper than 3 meters.

10.3.2 The Magnetometer Survey

The magnetometer and gradiometer data sets were analyzed somewhat differently. Targets were boxed and fit as described in the DAS Operator's Manual. However, based upon a set of rules developed by IDA, each target was assigned a probability score between 0 and 6. The scores are based upon criteria meant to be associated with the probability that the target is buried ordnance. A classical dipole signature with a high goodness of fit parameter and a calculated depth within the expected self burial depth range is assigned a score of 0, denoting a likely buried ordnance target. Probability points are added if the goodness of fit parameter is a poor fit to a dipole signature, if the dipole orientation is unlikely (or impossible without inclusion of a large remnant moment), if the fit burial depth is smaller than the ordnance minor radius, or if the target lies in an obvious clutter field. Probability scores then range from 0 to 6, with a score of 6 being associated with the lowest probability that the target is buried ordnance.

The magnetometer and gradiometer analysis Target Tables were provided to NRL and adapted for analysis using the NRL-developed evaluation Utility. Tables 6-9 present the analysis summaries for the magnetometry survey. Table 6 includes only target picks with a probability score of 0. A total of 91 targets were declared. Within a 2.0 m critical radius, 42 of the 70 ordnance items were correctly located. This evaluation identified 60% of the ordnance while generating 49 false alarms. There is no particular correlation of burial depth or ordnance size with found or unfound ordnance. Table 7 shows the summary of the magnetometer survey including targets with a probability score of 0 and 1. The total declared targets rose from 91 to 138. Ordnance targets correctly identified (within a 2 meter radius) increased by 6 such that 69% of the targets were correctly declared. The number of false alarms effectively doubled, to 90. Table 8, in a similar fashion,. includes targets with a probability score of 0, 1 and 2. This adds 41 declared targets, for a total of 179, while increasing the correctly located ordnance by two items to 50 (71% of the total).

Adding probability scores of 3, 4 and 5 increased the declared targets to 202, 214 and 221. No additional ordnance targets were correctly identified by inclusion of these probability levels. Table 9 shows the summary for inclusion of all declared targets with a probability score of 0-6 from the magnetometer survey. In this case a total of 656 targets were declared. The correctly located fraction rose to 81% or 57 of the 70 buried items. This information is further summarized in **Table 10** which shows the information for all seven probability scores.

10.3.3 The Gradiometer Survey

IDA evaluated the gradiometer survey in the same manner as the magnetometry survey, *i.e.* assigning a probability score to each declared target. Table 11 presents the analysis summary including only targets assigned a score of 0. 111 targets were declared, 47 (or 67% within a 2 meter critical radius) were correctly identified ordnance. Including the probability 1 scores raises the declared targets to 140 and adds one correctly located ordnance item, as shown in Table 12. Including the level 2 scored items did not pick up more targets. Inclusion of the level 3 scores, however, raised the correctly located targets to 51 (73%) at a level of 156 total declared targets as shown in Table 13. Including the probability 4 and 5 scores added 14 declared targets and located one additional ordnance, as documented in Table 14. Table 15 summarizes the results for probability levels of 0-6. 302 total targets were declared resulting in 54 correctly located ordnance items, or a total of 77%. Table 16 summarizes the targets analyses for all levels of probability in the gradiometer survey.

No attempt was made in the IDA analysis to correlate the survey data sets with each other. IDA is preparing a separate report in which they will independently carry out an analysis of their target picks and consider the multiple data sets. Some provisions have been made in the *MTADS* DAS software for cross survey correlations. This approach is described below.

10.4 NRL Data Analysis

10.4.1 The EM Survey

The NRL target analysis of the EM survey was carried out according to directions in the DAS Operator's Manual. Targets were manually boxed and analyzed. Analyzed targets with predicted sizes of 20

Table 10. Summary of the IDA magnetometry survey analysis

Probability Score	Total Declared Targets	Ordnance Correctly Located Within Critical Radius			False Alarms/Hectare At Critical Radius		
		0.5 m	1.0 m	2.0 m	0.5 m	1.0 m	2.0 m
0	91	29	40	42	19.7	16.2	15.6
0-1	138	30	46	48	34.4	29.3	28.7
0-2	179	31	48	50	47.1	41.7	41.1
0-3	202	31	48	50	54.5	49.0	48.4
0-4	214	31	48	50	58.3	52.9	52.2
0-5	221	31	48	50	60.5	55.1	54.5
0-6	656	33	52	57	198.4	192.4	190.8

mm and below were declared as non-ordnance. These exclusions were based upon experience working with the baseline target sets from the NRL CBD TECHEVAL. These studies were not available to the IDA personnel when they undertook their target analyses. A total of 183 targets were declared, 63 were correctly located (within 2 m) ordnance targets. This correlates to a false alarm ratio of 2.0 or 38 false alarms per hectare.

The EM results are summarized in Table 17. The results are very similar to the IDA EM analysis. All ordnance 155 mm and smaller were correctly identified, as were eight of the ten 8 inch projectiles. All these small targets (with the exception of the paired targets) were located within the 0.5 m critical radius. Of the bombs that were not found by the EM array, all were buried at depths of greater than 3.0 meters.

10.4.2 The Magnetometry Survey

In the magnetometry analysis, all likely targets were boxed for analysis. Many anomalies that were obviously too small to be 60 mm mortars were excluded from analysis, i.e. they were not boxed for analysis. Targets were chosen for analysis based upon the assumption that 60 mm mortars were the smallest ordnance on the site. We did not attempt to assign probability scores to targets. Based upon the work at CBD with the baseline targets, an attempt was made to differentiate between ordnance and non-ordnance in the declaration made in the Target Table comment line. All targets with a fit size of 30 mm and smaller were declared as non-ordnance. Targets with a fit size of 50 mm or larger were declared as ordnance unless their visual image showed them as clusters of smaller items. Of the targets with fit sizes of 40 mm, some were declared as ordnance, some were not. Factors considered included dipole orientation, calculated depth, goodness of fit, and whether the target was located within a clutter region.

In the magnetometry analysis, 74 of the analyzed targets were declared as “not ordnance.” Of the 183 declared ordnance targets, 63 were valid ordnance targets, correctly located within the 2 m critical radius. The 10% missed targets included 60 mm mortars, 105 mm and 8 inch projectiles and 250- and 1000-lb bombs. All items missed in this analysis were also missed in the IDA magnetometry target analysis (probability levels of 0-2). The NRL false alarm ratio was 1.9 or 38 false alarms per hectare. In Table 18 summarizes the results for the magnetometry survey target analysis.

10.4.3 The Gradiometer Survey

In the gradiometer survey analysis, 47 targets were declared as “not ordnance” and 201 targets were declared as ordnance. Fifty-seven of these were valid targets, located within the 2 meter critical radius. This correlates with an 81% probability of correctly locating ordnance and a false alarm ratio of 2.5 or 46 false alarms per hectare. The ordnance items missed include 60 and 81 mm mortars, 105, 155 mm and 8 in projec-

Table 16. Summary of the IDA gradiometer survey analysis

Probability Score	Total Declared Targets	Ordnance Correctly Located Within Critical Radius			False Alarms/Hectare At Critical Radius		
		0.5 m	1.0 m	2.0 m	0.5 m	1.0 m	2.0 m
0	111	36	42	47	23.9	22.0	20.4
0-1	140	37	43	48	32.8	30.9	29.3
0-2	148	37	43	48	35.4	33.4	31.8
0-3	156	39	46	51	37.3	35.0	33.4
0-4	164	40	47	52	39.5	37.3	35.7
0-5	170	40	47	52	41.4	39.2	37.6
0-6	302	41	49	54	83.1	80.6	79.0

tiles and 250, 500 and 1000 lb bombs. The ordnance items that were missed were mostly missed because the signals were too weak to visualize or the signal-to-noise ratio was too small to allow a successful fit. The results of the gradiometer survey analysis are summarized in Table 19.

10.4.4 Data Fusion

The gradiometer survey analysis was carried out using a different approach from the magnetometer survey. In the gradiometer survey analysis, two analysis windows were used. Each display showed the same area, one window showed the previously analyzed magnetometer survey area with its numerically annotated target fits, the second window showed the gradiometer survey area to be analyzed.

The gradiometer target fits were carried out under conditions that allowed simultaneous comparison with the magnetometer fit and the magnetic anomaly images. The gradiometer survey analysis resulted in 34 target declarations that did not have analogs in the magnetometry analysis. In addition, there were five magnetometer target declarations that clearly broke up into multiple targets in the gradiometer displays. These targets were subsequently excluded from the magnetometer declarations - the gradiometer analysis was used, either resulting in declarations as non-ordnance, or reassignment. The fusion of the magnetometry and gradiometer analyses resulted in the correct identification of one additional ordnance item, G8, a 60 mm mortar. Fusing the gradiometer analysis added 34 gradiometer false alarms while deleting only 3 false alarms from the magnetometry analysis.

Following the combined magnetometry and gradiometry analyses, the magnetometry and EM analyses were reconsidered, comparing the magnetometry and EM analysis windows side by side. The analyses were reevaluated target by target. The resulting fused analysis of all three surveys resulted in a declaration of 263 targets as ordnance. Of the fit targets, 164 were declared as “not ordnance.” Sixty-six of the 70 emplaced targets were correctly identified within the 2 m critical detection radius with a false alarm ratio of 3.0 or 64 false alarms per hectare. The fused data analysis summary is presented in Table 20.

11.0 System Performance

Table 21 presents a summary of the magne-tometer, gradiometer, and EM survey analyses as carried out by NRL. Also included are the results of the fused analyses as described in the previous section. The results of the IDA analyses are similar. The IDA approach in analyzing the passive sensor data is intended for use in carrying out a statistical approach to target identification and discrimination. These studies are ongoing and will be presented in a separate report.

11.1 Ordnance Detection

As shown in Table 21, coordinating the results of surveys of the multiple sensor arrays led to an ordnance detection probability of about 95%. The MTR at Twentynine Palms is a very difficult and

challenging site because of the geological interferences, the extreme levels of ferrous clutter contamination, the tight clusters and paired ordnance targets, and the very deeply buried large ordnance. In earlier work at JPG and other prepared ordnance ranges using off-the-shelf magnetometers and EM-61 detectors there has been a demonstrated lack of detection capability at depths of 1 to 2 meters for ordnance in the size ranges including 60 and 81 mm mortars. The *MTADS* arrays, using the improved sensors, are effectively 100% efficient in locating ordnance in this size and depth range now.

The *MTADS* gradiometer array was designed to suppress geological noise and allow discrimination for clustered and cluttered targets to its effective detection limits. At Twentynine Palms, it effectively suppressed the large scale geological interference, but its value was limited for detection of shallow targets because of a relatively high frequency noise interference problem.

The improved sensitivity of the EM array allowed detection of many targets that the gradiometer array was intended to address. The EM array is even more insensitive to geomagnetic interferences than the gradiometer array. Given the level of detection efficiency of the EM array, it is not clear that the gradiometer array added significant value to the *MTADS* capabilities at Twentynine Palms. This may or may not be true at other sites with a different mix of ordnance and with different types of clutter and geomagnetic interferences.

11.2 Ordnance Location Accuracy

The rebar target analyses shown in Tables 3 and 4 demonstrate that for small compact targets, the overall *MTADS* location capability is better than 0.25 m. This was also observed to be the case in the TECHEVAL studies using degaussed ordnance targets carefully located in the test pits.[8] At the MTR, both the passive and active sensor arrays typically located ordnance targets with an accuracy of better than 0.5 m. The exceptions are the unresolvable target pairs and a few of the larger (and deeper) ordnance targets. At the Twentynine Palms MTR, it is likely that the Mk 84 and perhaps the A4 targets have incorrectly recorded positions (i.e. off by 1-2 meters) based upon all the surveys that we have conducted in this study. In other cases (targets A1, A2, B8, and C1), location accuracy was likely degraded by remnant moments and by local clutter and interferences. The 1 to 2 meter location errors for these large and deep targets would not impede their remediation.

11.3 Ordnance Depth Accuracy

We have examined the depth location capability of each of the sensor arrays in the studies at TECHEVAL. In general, the approximations made in the magnetometer fitting algorithms do not precisely take into account the ordnance orientation effects on the calculated magnetic moments. The calculated magnetic moments are used in the depth fitting routines. Figure 14 shows the correlation between fitted depth (based upon the magnetic moment calculation) and actual ordnance depth for a range of ordnance from the TECHEVAL studies at CBD. These items were all carefully degaussed and only targets with good signal-to-noise are plotted in the figure. Under these conditions the only significant deviations are seen for the shallowest (and smallest) targets. Overall, the agreement is very good for the depth fitting algorithm.

The *MTADS* development of the data analysis fitting routines for the EM array is unique. They are based upon studies carried out at NRL during the development of the array and incorporate information derived both from the signal shape and from the relative intensities of the signals measured by the upper and lower detection coils. Figure 15 shows the correlation between fitted depth and known depth for the ordnance targets studied at CBD during TECHEVAL using the EM array. This fitting routine is superior to the empirical calculation that the manufacturer provides with the instruments. However, we have demonstrated that the assumptions made in our fitting algorithm break down for very shallow targets, particularly for some combinations of ordnance orientations and sensor travel directions. An empirically fit curve to the data points could provide a better approximation to depth than the slope of 1 straight line shown in Fig. 15. Because of the better accuracy of the fitting algorithms using the passive array sensors, we rely on them for depth approximations in this demonstration.

Figure 16 shows the correlation between fitted depth and known depth for the detected ordnance targets at the MTR for all three sensor arrays. Note that this presentation is on a linear, rather than a logarithmic scale. In the magnetometer and gradiometer plots, with the exception of two or three outliers in each plot, the depth correlation is reasonably good. Those points lying far off the line

Table 21. Summary of NRL target analyses for the MTR surveys

Survey	Targets Fit	Declared "Not Ordnance"	Declared Ordnance	Valid Targets Within Critical Radius			False Alarms (2 m Critical Radius)	
				0.5 m	1.0 m	2.0 m	Ratio	Per Hectare
Magnetometer	257	74	183	48	57	63	1.9	38
Gradiometer	248	47	201	38	52	57	2.5	46
EM	227	44	183	54	60	63	1.9	38
Fused Analysis	427	164	263	51	60	66	3.0	64

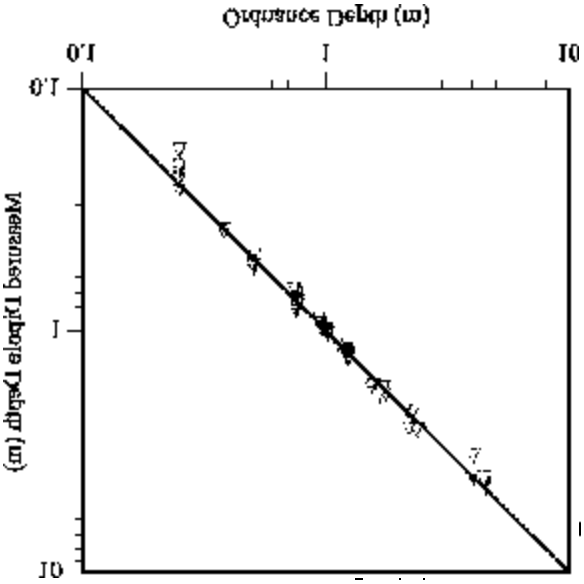

Figure 14. Comparison of fitted and known ordnance depths from magnetometer surveys at the CBD Test Site

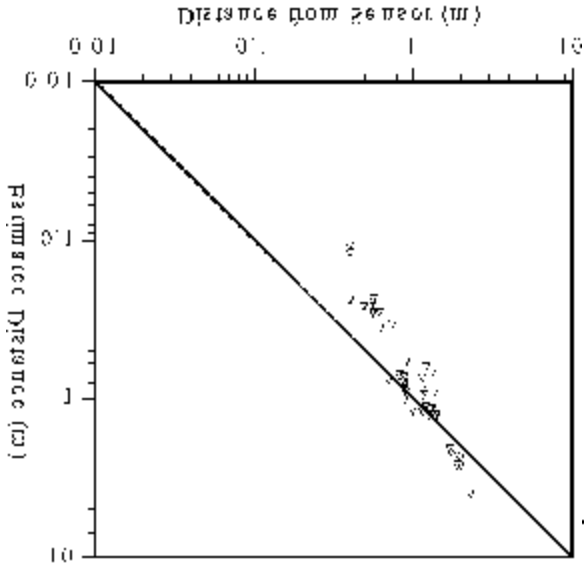

Figure 15. Comparison of the fitted and known ordnance depths from EM surveys at the CBD Test Site

should be investigated to determine if the fitted target corresponds to the buried ordnance item. Single target fits to paired targets converge to values that are both too deep and too large.

Also shown in Figure 16 are the depth fits for targets measured with the EM array at the MTR. There is considerably more scatter in the data than for the passive sensor arrays, however, for targets deeper than 0.5 m, the depth information provided by the DAS EM fits has significant operational value.

11.4 Ordnance Size Evaluations

The size fitting algorithms for both the passive and active sensor arrays were also evaluated during the CBD TECHEVAL demonstration. Figure 17 shows the comparison of the fitted magnetic moment (used to derive the ordnance size) with the known ordnance minor diameters. The size of the 20 and 30 mm shells are underestimated, while the remainder of the items generally scale with size. The fitted magnetic moments, as mentioned earlier, fail to

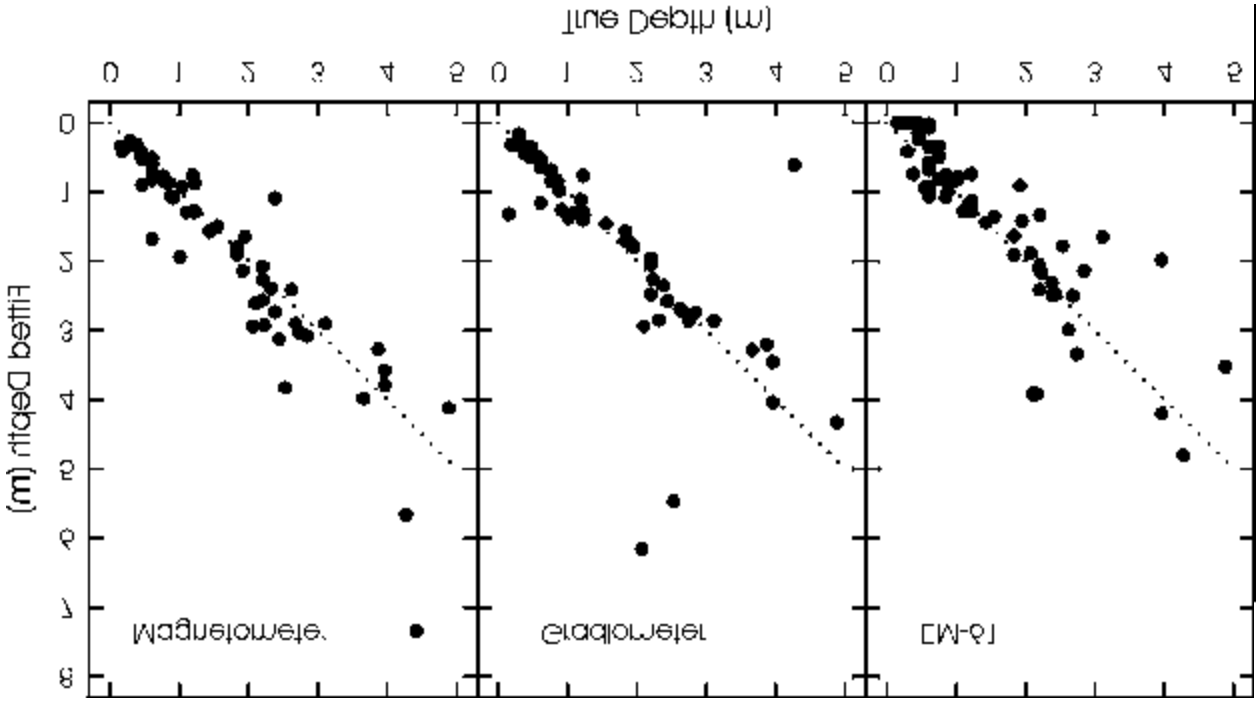

Figure 16. Comparisons of the fitted and known ordnance depths for all analyzed targets at the Magnetic Test Range from the magnetometry, gradiometry, and EM surveys

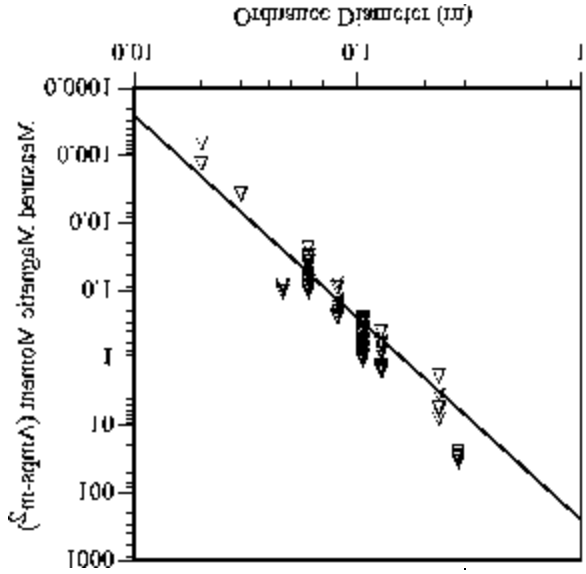

Figure 17. Comparison of the fitted and known ordnance sizes from magnetometer surveys at the CBD Test Site

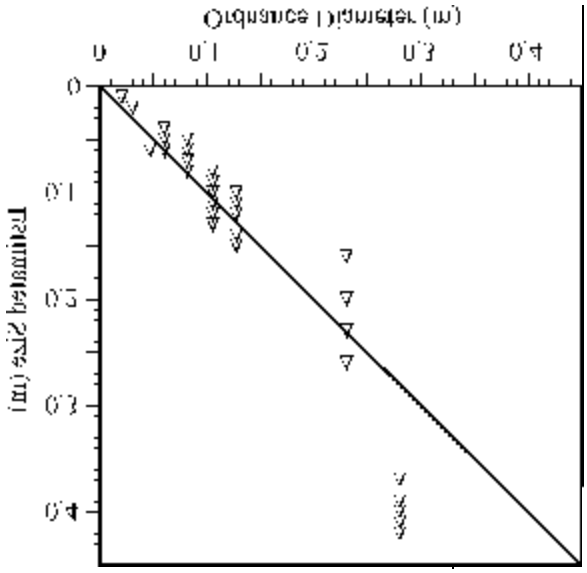

Figure 18 Comparison of the fitted and known ordnance sizes from the EM surveys at the CBD Test Site

recisely account for item orientation effects. This leads to the scatter in predicted sizes for individual items. Although the fitted prediction of size for an 80 mm mortar would not uniquely distinguish it from a 60 mm or a 105 mm target, it does give a reasonable estimate of ordnance category.

Figure 18 shows a similar display for the EM sensor array, this time plotted on a linear rather than a logarithmic scale. As we noted in Section 11.3, the

spherical approximation used for the EM fitting algorithmbreaks down for the smaller items, depending upon the relative orientations of the targets to the sensor direction of travel. It also appears that the fit overestimates the size of the 500 lb bomb by about 50%.

Figure 19 shows the ordnance size fitting plots for the magnetometer, gradiometer, and EM surveys at Twentynine Palms. These data are all presented on linear plots and do not show the information for the submunitions at the site. There are one or two points lying far above the slope-of-one lines in each plot.

These should be checked to determine if the points correspond to closely spaced target pairs or targets lying in a cluster of clutter. Even ignoring the outlier points, there is significant scatter in the size determination information from the fitting routines for each of the arrays. While it is, in general, possible to confidently differentiate between mortars and bombs, there is much less discrimination capability than was apparent in the CBD shakedown studies. The most likely important contributing factors are significant remnant moments for the individual ordnance items and the large amount of ferrous clutter at the site.

test range. The 60 and 80 mm targets are buried at the limit of detection for modern metal vapor magnetometers. The geological magnetic interference is severe at all spatial scales. The large deep bombs, while probably detectable in an interference-free environment, strain the detection limits of all three sensor suites in this study. The closely spaced targets still cannot be independently analyzed as separate targets, even with the very high density data sets acquired in this study.

The performance of the EM sensor array was very impressive. It is a more sensitive detector than the magnetometer array for all ordnance categories at depths to 2.5 m. Used in conjunction with the magnetometer array we feel confident that all ordnance at depths less than 2.5 m can be effectively detected. For range clearances to this depth, one could confidently use only the EM array. The value added by the magnetometer survey is from the precise evaluation of target depth that results from the magnetometer fitting algorithm. The overall performance of the *MTADS* at Twentynine Palms was excellent.

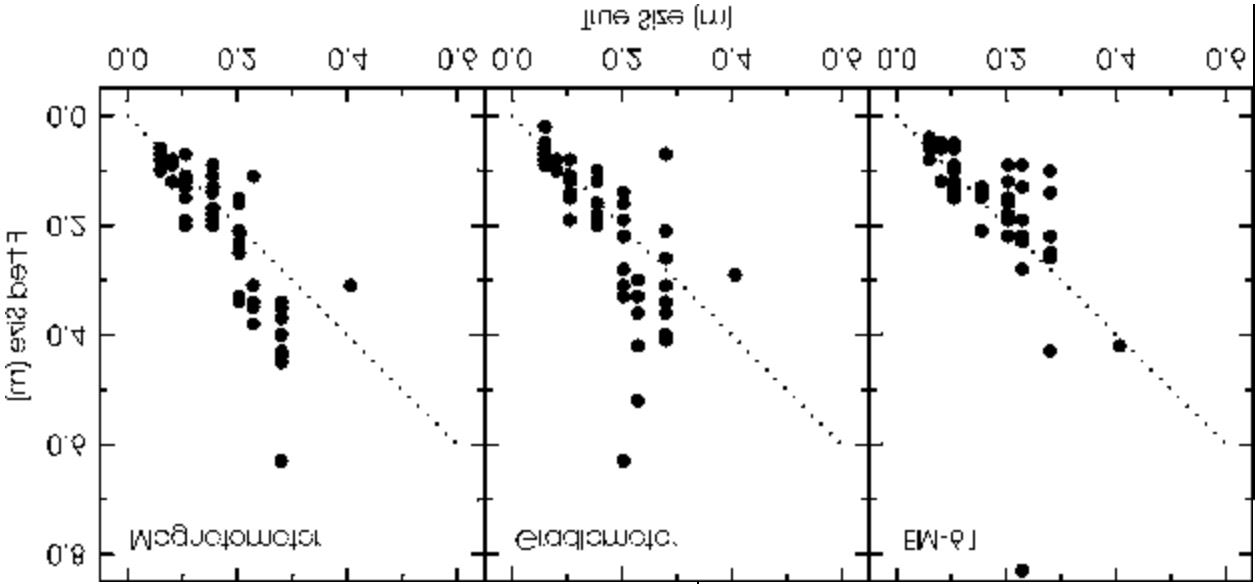

Figure 19. Comparison of the fitted and known ordnance sizes for all analyzed targets at the Magnetic Test Range from the magnetometry, gradiometry, and EM surveys

The MTR is a difficult and challenging ordnance

12.0 DEMONSTRATION COSTS

Presurvey Expenses			
MTADS Preparation		4.0	
Navigation Control Points			4.5
Subtotal			8.5
Logistics (Hardware Transport)			
Rental Truck	3.5		
Fuel	0.7		
Driver	1.5		
Subtotal			5.7
Logistics (On Site)			
Office Trailer Rental		2.4	
Portable Toilet Rental		0.5	
Electrician	0.9		
Sensor Repair		0.5	
Subtotal			4.3
On Site Support			
AETC	12.5		
GeoCenters	8.5		
Hughes	8.5		
NRL	17.5		
SRA	3.2		
Subtotal			50.2
Analysis and Report			30
Total Demonstration Cost			98.7

The costs presented in the above Table are in $K and do not include any equipment depreciation, maintenance and repair costs, or costs for spares procured specifically for the demonstration. One NRL employee and the SRA labor costs are partially associated with DAQ and guidance development work taking place during the demonstration. Part of a second NRL employee's costs are also associated with supporting and hosting Rockwell/Boeing demonstrators working in parallel with the *MTADS* demonstration.

Significant other costs were associated with meetings and planning with IDA in preparation for their parallel analysis and in contractor support in software preparation and training for the IDA effort. NRL spent about 2 weeks developing analysis routines to evaluate the NRL and IDA data analyses and in comparative studies of the two data analysis efforts.

We are gathering information required to determine cost of manufacturing a second *MTADS* assuming it would be effectively identical to the present system. This information will be presented in the next Demonstration Report. Our preliminary estimate is that a second unit would cost between $0.45 and $0.55 M assuming no software or engineering costs are borne by the second unit.

13.0 References

1. "Hand held Gradiometer Survey Test at The Marine Corps Air Ground Combat Center, Twentynine Palms, CA," NACEODTECHCEN TR, September, 1992. This report describes hand-held magnetometry surveys of the MCAGCC, Magnetic Test Range conducted by military EOD teams. Their ordnance detection efficiency at this site varied between 25% and 35%.

2. "Technology Demonstration Plan, MTADS DEMONSTRATION AT TWENTYNINE PALMS, 3 December, 1996," J.R. McDonald and Richard Robertson, Naval Research Laboratory, 4 November 1996.

3. "Magnetic Sensor Field Tests and Evaluations for Towed-Array Systems, Ft. Devens, MA," J.R. McDonald and Richard Robertson, NRL/PU/6110--96-303, 2 April 1996.

4. "Multi-sensor Towed Array Detection System (MTADS). An Automated High-Efficiency Survey System for Characterization of Ordnance and Explosive Waste (OEW) Sites," J.R. McDonald and Richard Robertson, Proceedings of the UXO FORUM 1996, Williamsburg, VA, 26-28 March 1996, p. 53.

5. "Performance of Electromagnetic Induction Sensors for Detecting and Characterizing UXO," Bruce Barrow, Nagi Khadr, and H.H. Nelson, Proceedings of the UXO FORUM 1996, Williamsburg, VA, 26-28 March 1996, p. 308.

6. "Magnetic Sensor Field Tests and Evaluations for Towed Array Systems, Ft. Devens, MA," J.R. McDonald and Richard Robertson, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Pub. The Environmental and Engineering Geophysical Society, Keystone, CO, 28 April - 2 May 1996, p. 451.

7. "The Combined Use of Magnetic and Electromagnetic Sensors for Detection and Characterization of UXO," Bruce Barrow, Nagi Khadr, Robert DiMarco, and Herbert H. Nelson, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Pub. The Environmental and Engineering Geophysical Society, Keystone, CO, 28 April - 2 May 1996, p. 469.

8. "Results of the MTADS Technology Demonstration # 1, TECHEVAL AT NRL/CBD," H.H. Nelson, Richard Robertson, and J.R. McDonald, NRL/PU/6110--97-348, in press

9. "Owner's and Shop Manual for the NRL *MTADS* Tow Vehicle," Chenowth Racing Products, Inc., El Cajon, CA.

10. "Shop Maintenance, Service, and Repair Manual for the MTADS Tow Vehicle," Chenowth Racing Products, Inc., El Cajon, CA.

11. "Repair Parts Manual for the MTADS Tow Vehicle," Chenowth Racing Products, Inc., El Cajon, CA.

12. "Magnetic Test Range, MCAGCC, Twentynine Palms, CA, A Geodetic Control Survey," Doug Richmond, GeoMetrics GPS, Inc., 16 May 1996.