DEMONSTRATION REPORT

Empirical Evaluation of Advanced Electromagnetic Induction Systems - Factors Affecting Classification Effectiveness in Challenging Geologic Environments - TEMTADS 2×2 Demonstration Report
MRS-R04A (West)
Tobyhanna Army Depot FUDS, Pennsylvania

ESTCP Project MR-201314

OCTOBER 2016

Tamir Klaff
CH2M HILL, Inc.

Distribution Statement A
This document has been cleared for public release

Page Intentionally Left Blank

This report was prepared under contract to the Department of Defense Environmental Security Technology Certification Program (ESTCP). The publication of this report does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official policy or position of the Department of Defense. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Department of Defense.

Page Intentionally Left Blank

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*
10/19/2016

2. REPORT TYPE
Demonstration Report

3. DATES COVERED *(From - To)*
July 2013 - October 2015

4. TITLE AND SUBTITLE
Empirical Evaluation of Advanced Electromagnetic Induction Systems - Factors Affecting Classification Effectiveness in Challenging Geologic Environments - TEMTADS 2×2 Demonstration Report
MRS-R04A (West)
Tobyhanna Army Depot FUDS, Pennsylvania

5a. CONTRACT NUMBER
W912HQ-13-C-0039

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Mr. Tamir Klaff
CH2M HILL

5d. PROJECT NUMBER
MR-201314

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
CH2M HILL
15010 Conference Center Drive, Suite 200
Chantilly, VA 20151

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Environmental Security Technology Certification Program Program Office
4800 Mark Center Drive
Suite 17D03
Alexandria, VA 22350-3605

10. SPONSOR/MONITOR'S ACRONYM(S)
ESTCP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
N/A

14. ABSTRACT
CH2M performed an Environmental Security Technology Certification Program (ESTCP) Munitions Response Live Site Demonstration at Munitions Response Site (MRS) R-04A West, at Tobyhanna Army Depot (TOAR) Formerly Used Defense Site (FUDS), in Pennsylvania, in the summer of 2015.The demonstration involved the participation of two advanced electromagnetic induction (EMI) sensors and was designed to investigate the use of these advanced EMI sensors at a densely wooded site with challenging microterrain features (e.g., impact craters, rocks, boulders, gullies) for detecting munitions down to the size of 37-millimeter projectiles.

15. SUBJECT TERMS
N/A

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Tamir Klaff
Unclassified	Unclassified	UU	UL	51	19b. TELEPHONE NUMBER *(Include area code)* 202-596-1199

Page Intentionally Left Blank

CONTENTS

Abbreviations and Acronyms v

Executive Summary vi

1.0 Introduction 1
- 1.1 Background 1
- 1.2 Objective of the Demonstration 1
- 1.3 Regulatory Drivers 2

2.0 Technology 3
- 2.1 Technology Description 3
- 2.2 Limitations of the Technology 5

3.0 Performance Objectives 7

4.0 Site Description 8
- 4.1 Site Selection 8
- 4.2 Brief Site History 11
- 4.3 Munitions Contamination 12
- 4.4 Site Geodetic Control Information 12
- 4.5 Site Preparation 12

5.0 Test Design 13
- 5.1 Calibration Activites 13
- 5.2 Data Collection Activities 16
- 5.3 Classification 26
- 5.4 Intrusive Activity and Procedures 29
- 5.5 Deliverables 30

6.0 Performance Assessment 30
- 6.1 Dynamic Survey Spatial Coverage 32
- 6.2 Along-line Measurement Spacing 33
- 6.3 Detection of All TOI 33
- 6.4 Initial Dynamic IVS Survey Data Positioning 34
- 6.5 Ongoing Dynamic Survey Data Positioning 34
- 6.6 Initial Cued Survey Data Positioning 35
- 6.7 Ongoing Cued Survey Data Positioning 36
- 6.8 Initial Cued Measurement Polarizabilities 37
- 6.9 Ongoing Cued Sensor Polarizability Precision 38
- 6.10 Cued Interrogation Anomalies 38
- 6.11 Correct Classification of Targets of Interest 39
- 6.12 Model Results Support Classification Decision 39

7.0 Cost Benefit Analysis 41

8.0 Implementation Issues 42

9.0 Conclusions 43

10.0 References 44

Figures

2-1 Single-element TEMTADS Three-axis Receiver and Transmit Coil and Sensor Array 3

2-2 TEMTADS 2×2 System 4

2-3 Dynamic Data Acquisition Interface and Cued Data Acquisition Interface 5

4-1 MRS-R04A (West) Representative Site Photos 8

4-2 MRS-R04A (West) ESTCP Demonstration Area 9

4-3 MRS-R04A (West) Anomaly Density Estimates and Selected Demonstration Grids 11

5-1 As-built IVS 15

5-2 Dynamic TEMTADs 2×2 Survey in Grids 78/46 and 79/46 (Western) 17

5-3 Dynamic TEMTADs 2×2 IVS Survey Position Results (Initial Processing) 19

5-4 Dynamic TEMTADs 2×2 IVS Survey Position Results (after Reprocessing) 20

5-5 Dynamic TEMTADS IVS Survey Sensor Function Results 20

5-6 Dynamic TEMTADS Data with Locations of Anomalies Selected for Cued Data Collection, Grids 78/46 and 79/46 (Western Grids) 22

5-7 Dynamic TEMTADS Data with Locations of Anomalies Selected for Cued Data Collection, Grids 82/47 and 83/47 (Eastern Grids) 23

5-8 TEMTADS Cued Data IVS Dipole Fit Position Results: Offset from Ground Truth and Offset from Average Position 24

5-9 TEMTADS Cued IVS Data Dipole Fit β (Polarizability) Amplitude Results 25

5-10 TEMTADS Cued Data Sensor Function Test Results Rx Response 25

5-11 TEMTADS Cued Data Sensor Function Test Results Rx Response Variation 26

5-12 TEMTADS Cued Data Sensor Function Test Results Tx Current 26

5-13 Initial and Final, Site-specific TOI Library for TOAR 29

6-1 Dynamic IVS Position Precision (Errors Relative to Average Derived Positions) 35

6-2 Cued IVS Position Precision (Errors Relative to Average Derived Positions) 37

6-3 Decision Metric for IVS ISOs 38

6-4 Classification Results for Cued Investigations of 497 Targets 39

Tables

5-1 Geodetic Control Locations 13
5-2 Details of the Instrument Verification Strip 15
6-1 Performance Objectives and Results for this Demonstration 31
6-2 TEMTADS QC Seed Detection 33
6-3 TEMTADS Initial Dynamic IVS Survey Positioning Results 34
6-4 TEMTADS Dynamic IVS Positioning Results 35
6-5 TEMTADS Initial Cued IVS Survey Positioning Results 36
6-6 TEMTADS Cued IVS Positioning Results 36
7-1 Costs for TEMTADS 41

Appendixes

A Points of Contact

ABBREVIATIONS AND ACRONYMS

µs	microseconds
ACD	analyst calibration dig
CH2M	CH2M HILL, Inc.
cm	centimeter
EMI	electromagnetic induction
ESTCP	Environmental Security Technology Certification Program
FUDS	Formerly Used Defense Site
GPS	global positioning system
HE	high explosives
IMU	inertial measurement unit
in.	inch
ISO	industry standard object
IVS	instrument verification strip
m	meter
mm	millimeter
MPV	man-portable vector
MQO	measurement quality objective
MR	munitions response
MRS	munitions response site
MRSIMS	Munitions Response Site Information Management System
mV/A	millivolt per ampere
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NRL	Naval Research Laboratory
PLS	Professional Land Surveyor
QC	quality control
RTK	real-time kinematic
ROC	receiver operating characteristic
RTS	robotic total station
SUXOS	senior UXO officer
TEMTADS	Time-domain Electromagnetic Multisensor Towed Array Detection System
TOAR	Tobyhanna Army Depot
TOI	target of interest
Tx/Rx	transmit or receive
UTM	Universal Transverse Mercator
UXA	UX-Analyze
UXO	unexploded ordnance
UXOSO	unexploded ordnance safety officer
VSP	visual sample plan

EXECUTIVE SUMMARY

CH2M performed an Environmental Security Technology Certification Program (ESTCP) Munitions Response Live Site Demonstration at Munitions Response Site (MRS) R-04A West, at Tobyhanna Army Depot (TOAR) Formerly Used Defense Site (FUDS), in Pennsylvania, in the summer of 2015.The demonstration involved the participation of two advanced electromagnetic induction (EMI) sensors and was designed to investigate the use of these advanced EMI sensors at a densely wooded site with challenging microterrain features (e.g., impact craters, rocks, boulders, gullies) for detecting munitions down to the size of 37-millimeter projectiles. The Naval Research Laboratory's Time-domain Electromagnetic Multisensor Towed Array Detection System 2×2 (TEMTADS) was demonstrated in both dynamic and cued modes in a two-person litter carry mode. Collection and processing of dynamic and cued data with a man-portable vector (MPV) was performed by Black Tusk Geophysics; those results are not addressed in this report. Both instruments were coupled with a Trimble Robotic Total Station for positioning.

Approximately 0.71 acre was dynamically surveyed with the TEMTADS system. Production was significantly hindered by the remote location and site conditions, and only one of the four grids initially selected for investigation achieved 100% coverage (not including gaps due to physical obstructions). Based upon this effort, production rates are estimated to be much lower than production rates would be under less challenging conditions.

A total of 429 anomalies were identified by the TEMTADS dynamic data analysis. These anomaly locations and an additional 68 targets selected by the MPV survey were interrogated (cued data collection) and classified with the TEMTADS system. The cued data were used to classify each target as being a potential target of interest (TOI) (dig) or high-likelihood non-TOI (do not dig). The TEMTADS successfully detected and classified all known TOIs (seeds and native TOIs).

1.0 INTRODUCTION

This demonstration report details the Environmental Security Technology Certification Program (ESTCP) Munitions Response Live Site Demonstration at Munitions Response Site (MRS) R-04A West, at Tobyhanna Army Depot (TOAR) Formerly Used Defense Site (FUDS), in Pennsylvania, performed in the summer of 2015. The project involved the demonstration of two advanced electromagnetic induction (EMI) sensors, the Time-domain Electromagnetic Multisensor Towed Array Detection System 2×2 (TEMTADS) and the man-portable vector (MPV) systems, both of which were coupled with a Trimble Robotic Total Station (RTS) for positioning. The MPV data collection and processing were performed by Black Tusk Geophysics and are not addressed in this report. The demonstration was performed in accordance with the *Live Site Demonstrations TEMTADS 2×2 Demonstration Plan MRS-R04A (West), Tobyhanna Army Depot FUDS, Pennsylvania, ESTCP Project MR-201314* (ESTCP, 2015).

1.1 BACKGROUND

CH2M HILL, Inc. (CH2M), performed this work for ESTCP under contract W912HQ-13-C-0039. The demonstration was designed to investigate the use of advanced EMI sensors at a densely wooded site with challenging microterrain features (e.g., impact craters, rocks, boulders, gullies) for detection of 37-millimeter (mm) projectiles. As a result of the site conditions, the TEMTADS was operated in two-person litter carry mode during dynamic (i.e., detection) data collection.

1.2 OBJECTIVE OF THE DEMONSTRATION

The overall objective was to demonstrate the detection and classification performance of the sensors in challenging conditions for targets of interest (TOI) as small as 37-mm projectiles and to provide data for comparing the TEMTADS capabilities under these conditions to those of the MPV. (Note that this report covers the TEMTADS operations and analysis only; comparison of the results achieved with those of the MPV will be performed by the ESTCP Program Office.)

CH2M performed the following tasks:

- Collection of dynamic transect data across an 11-acre parcel using a Geometrics G-858G magnetometer
- Selection of demonstration site based on G-858G data
- Reduction of vegetation
- Placement of subsurface “blind” seeds within the demonstration site
- Establishment of an instrument verification strip (IVS)
- Collection of dynamic data cueing the TEMTADS
- Interrogation of cued targets using the TEMTADS
- Processing of dynamic and cued geophysical data
- Reacquisition and intrusive investigation of targets selected for cued interrogation

1.3 REGULATORY DRIVERS

The Military Munitions Response Program (MMRP) is charged with characterizing and, where necessary, remediating MRSs. When an MRS is remediated, it is typically mapped with a geophysical system, based on either a magnetometer or EMI sensor, and the locations of all detectable signals are investigated. Many of these detections do not correspond to munitions, but rather to harmless metallic objects or geology; field experience indicates that often in excess of 90% of objects excavated during the course of a munitions response are found to be nonhazardous items. Conventional geophysical technology, as it is traditionally implemented, does not provide a physics-based, quantitative, validated means to discriminate between hazardous munitions and nonhazardous items.

With no information to suggest the origin of the signals, the sources of all anomalies are currently treated as though they were intact munitions when they are dug up. They are carefully excavated by certified unexploded ordnance (UXO) technicians using a process that often requires expensive safety measures, such as barriers or exclusion zones. As a result, most of the costs to remediate a munitions-impacted site are currently spent on excavating targets that pose no threat. If these items could be determined with high confidence to be nonhazardous, some of these expensive measures could be eliminated or the items could be left unexcavated entirely.

The MMRP is severely constrained by available resources, and remediation of the entire inventory using current practices is cost prohibitive within current and anticipated funding levels. With current planning, estimated completion dates for munitions response on many sites are decades out. The United States Department of Defense's (DoD's) Defense Science Board (DSB) observed in its 2003 report that significant cost savings could be realized if successful classification between munitions and other sources of anomalies could be implemented. If these savings were realized, the limited resources of the MMRP could be used to accelerate the remediation of MRSs that are currently forecast to be untouched for decades.

2.0 TECHNOLOGY

The technology used by CH2M for this project consisted of a TEMTADS advanced electromagnetic sensor, coupled with an RTS positioning system. Data collection is initiated and monitored using the data acquisition user interface provided with the TEMTADS sensor.

2.1 TECHNOLOGY Description

2.1.1 TEMTADS 2×2

The TEMTADS comprises four individual sensor elements arranged in a 2-by-2 array. Each element consists of a transmit coil and a three-axis receiver cube. Each cube has dimensions of 8 centimeters (cm). The center-to-center distance is 40 cm, yielding an array 80 cm by 80 cm. A TEMTADS sensor element under construction and the sensor array (with protective cover removed) are shown in **Figure 2-1**.

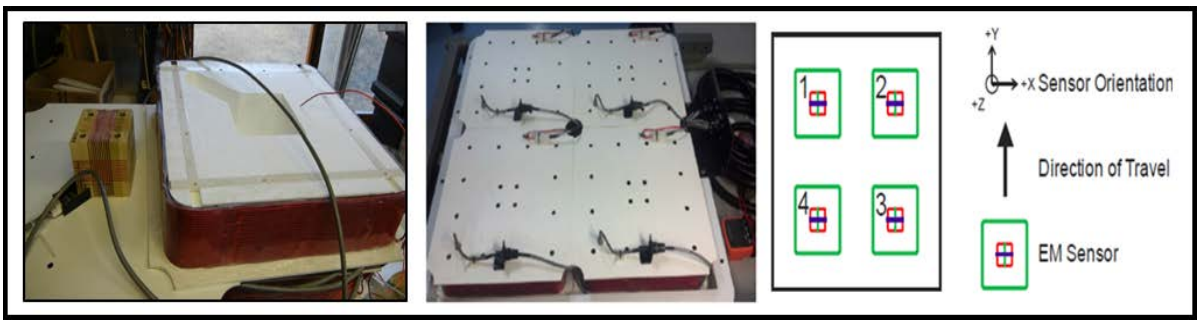


Figure 2-1. Single-element TEMTADS Three-axis Receiver and Transmit Coil (Left) and Sensor Array (Right)

Decay data are collected with a 500-kilohertz sample rate until 25 milliseconds (ms) after turn off of the excitation pulse. This results in a raw decay of 12,500 points, which is too many to be used practically. These raw decay measurements are grouped into 122 logarithmically spaced "gates" with center times ranging from 25 microseconds (µs) to 24.35 ms with 5 percent widths and are saved to disk.

The TEMTADS is a person-portable system (**Figure 2-2)**. The array structure is fabricated from PVC and Garolite fiberglass. The array is normally deployed on a set of wheels, resulting in a sensor-to-ground offset of approximately 18 cm. For this demonstration the unit was deployed in two-person litter configuration on skids with approximately the same sensor height as the wheeled configuration. The transmitter electronics and the data acquisition computer are mounted on the operator backpack, an RTS prism is mounted on top of a Garolite fiberglass pole, and an inertial measurement unit (IMU) is mounted above the array. The TEMTADS can be operated in two modes: dynamic and cued. Data collection is controlled in dynamic mode using G&G Science's EM3D application suite. In cued mode, the locations of previously identified anomalies are flagged and surveyed with static measurements directly over the flag location.

Figure 2-2. TEMTADS 2×2 System

Custom software written by the Naval Research Laboratory (NRL) is used to control the cued data acquisition. Both sets of software are accessed through a remote desktop on a computer tablet by a third operator accompanying the two carriers.

2.1.2 Positioning System

Because the reliable use of a global positioning system (GPS) was not possible for the conditions at the site, positional data were recorded using a Trimble R7 RTS with an MT1000 active prism centered over the TEMTADS array. A pole was added to the system to raise the height of the prism above the heads of the operators, thus allowing the operators to walk without blocking the prism from the RTS base station. Positional data were logged at a nominal rate of 10 hertz. The pitch, roll, and yaw of the cart were recorded using an IMU mounted beneath the prism.

2.1.3 Data Acquisition User Interface

Data collection is controlled using a tablet, which wirelessly (IEEE 802.11g) communicates with the data acquisition computer on the operator backpack. The tablet operator also manages field notes and team orienteering functions.

Screenshots of the tablet user interface are shown in **Figure 2-3**.

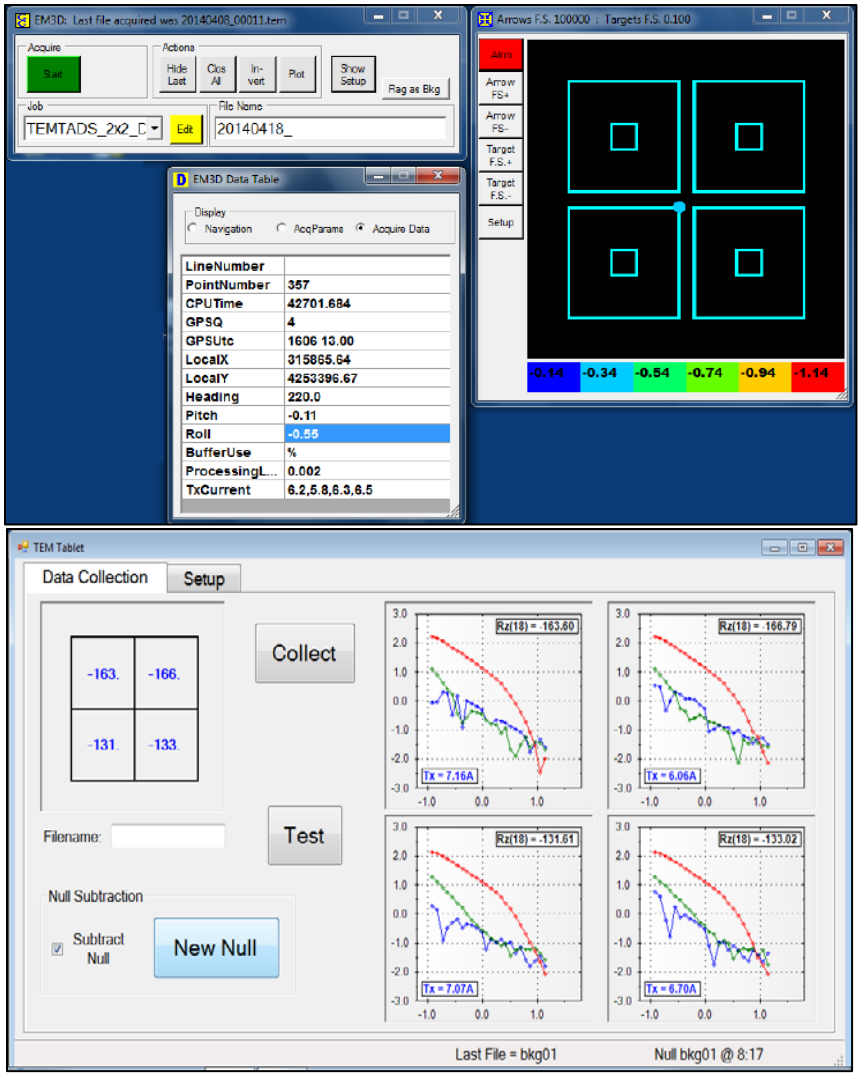


Figure 2-3. Dynamic Data Acquisition Interface (Top) and Cued Data Acquisition Interface (Bottom)

2.2 Limitations of the Technology

Although the TEMTADS was designed to be used in difficult terrain and in wooded areas that its larger predecessors (e.g., MetalMapper) could not access, the microterrain features at TOAR FUDS likely would result in increased sensor noise levels due to the bouncing and shaking of the array as its skids made contact with the ground surface, rocks, and fallen logs. Irregular heights due to its being lifted over objects may also decrease sensor sensitivity. In addition, imprecision in the positioning data may result from increased pitch and roll movements exacerbated by increased height of the RTS prism. As a result, one of the objectives of this demonstration was to determine how well the TEMTADS performs in litter carry mode in order to assess the efficacy of this modality under the expected site conditions.

Another serious limitation is anomaly density; for all advanced EMI systems there is a limiting anomaly density above which the response of individual targets cannot be separated. Recent

developments in multisource solvers have facilitated improved results within elevated anomaly density areas, although for sites with areas of significant anomaly density the result may still be saturated response areas that cannot be subjected to classification. An exploratory G-858G (magnetometer) survey was conducted to identifying suitable density survey areas for the demonstration.

Densely wooded environments are challenging for positioning the TEMTADS sensor. The advantages of using the TEMTADS as a dynamic detector rely upon precise positioning that cannot be achieved using fiducial marks and interpolation. Although RTS systems can be used in wooded environments where the line of sight along the survey transect is disrupted, localized gap-fill surveying requiring multiple base station setups is needed to achieve 100 percent coverage along the transects.

3.0 PERFORMANCE OBJECTIVES

Performance objectives for the demonstration were designed to provide a basis for evaluating the performance of the TEMTADS. The minimum acceptable criteria were the thresholds used to determine that the system was working properly. Values below this threshold are a potential cause for rejection of the data and require a root cause analysis/corrective action if appropriate (including potential re-collection of data). The nominal success criteria represent the expected achievable threshold. Failure to meet these thresholds requires a discussion in the project report but are not cause for rejection of the data.

To avoid repetition, the specific performance objectives for the demonstration are presented along with the results in Section 6.

4.0 SITE DESCRIPTION

The demonstration site is located within MRS-R04A (West) at TOAR FUDS, which is situated within Pennsylvania State Game Lands. The site is used for recreational activities such as camping, hiking, fishing, mountain biking, and snowmobiling. Parts of the MRS are located within a designated natural area open only to passive recreation and hunting.

Munitions Response (MR) actions are ongoing within the MRS. CH2M is not involved with these actions.

4.1 Site Selection

MRS-R04A (West) encompasses approximately 250 acres and is characterized by densely wooded, uneven terrain. **Figure 4-1** shows photos of the existing site conditions taken by CH2M during a site reconnaissance visit on May 19 and 20, 2015. **Figure 4-2** shows the MRS with the operational grid system used by the MR contractor performing work at the site. Each grid square measures 100 feet by 100 feet. This figure also presents an enlarged view of the 11-acre portion of the MRS that had not yet been cleared by the MR contractor and from within which up to 2 acres was selected for the demonstration. Based on historical live-fire training conducted on artillery ranges at TOAR FUDS, and the results of a previously completed remedial investigation, this MRS encompasses an impact area.

Figure 4-1. MRS-R04A (West) Representative Site Photos

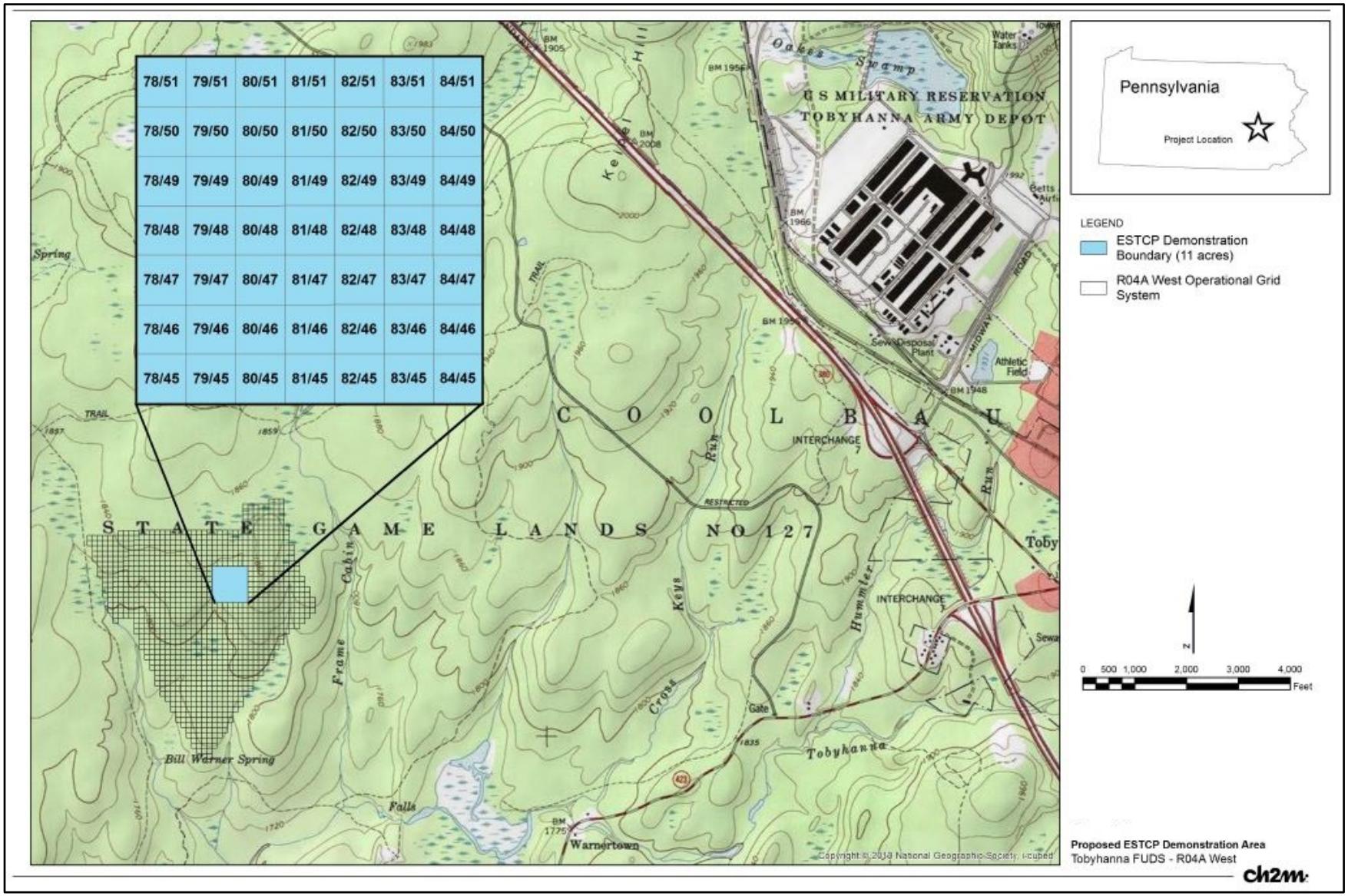


Figure 4-2. MRS-R04A (West) ESTCP Demonstration Area

Information that would enable estimation of anomaly densities for the MRS had not been provided; therefore, CH2M performed a digital geophysical mapping survey with the Geometrics G-858G cesium vapor gradiometer along transects extending through the accessible portions of the approximately 11-acre area shown on **Figure 4-2**. The intended nominal transect spacing was 6 meters (m); however, because no vegetation reduction was performed in advance of the G-858G survey, transect spacing and percent coverage was variable across the area. The objective of the G-858G survey was to assess relative anomaly density in order to identify candidate grids for the TEMTADS and MPV demonstration. Positional data for the G-858G survey were recorded using a Trimble ProXRS differential GPS system with an intended submeter horizontal accuracy. A Geometrics G-856 proton precession magnetometer was used as a stationary base station to record ambient magnetic field fluctuations throughout each day of G-858G data collection in order to facilitate evaluation of total field data recorded by each G-858G sensor.

Processing and target selection of the G-858G transect data were performed using Geosoft, and Visual Sample Plan (VSP) (Battelle Memorial Institute, 2015) was used to obtain estimates of anomaly density within the 11-acre area. Transect paths and calculated anomaly densities are shown on **Figure 4-3**. From these data, two grid pairs (78/46–79/46 and 82/47–83/47) were selected for the demonstration. CH2M identified these two sets of grids because they were sufficiently far apart from each other to facilitate concurrent data collection with the TEMTADS and MPV without the risk of the two sensors interfering with each other.

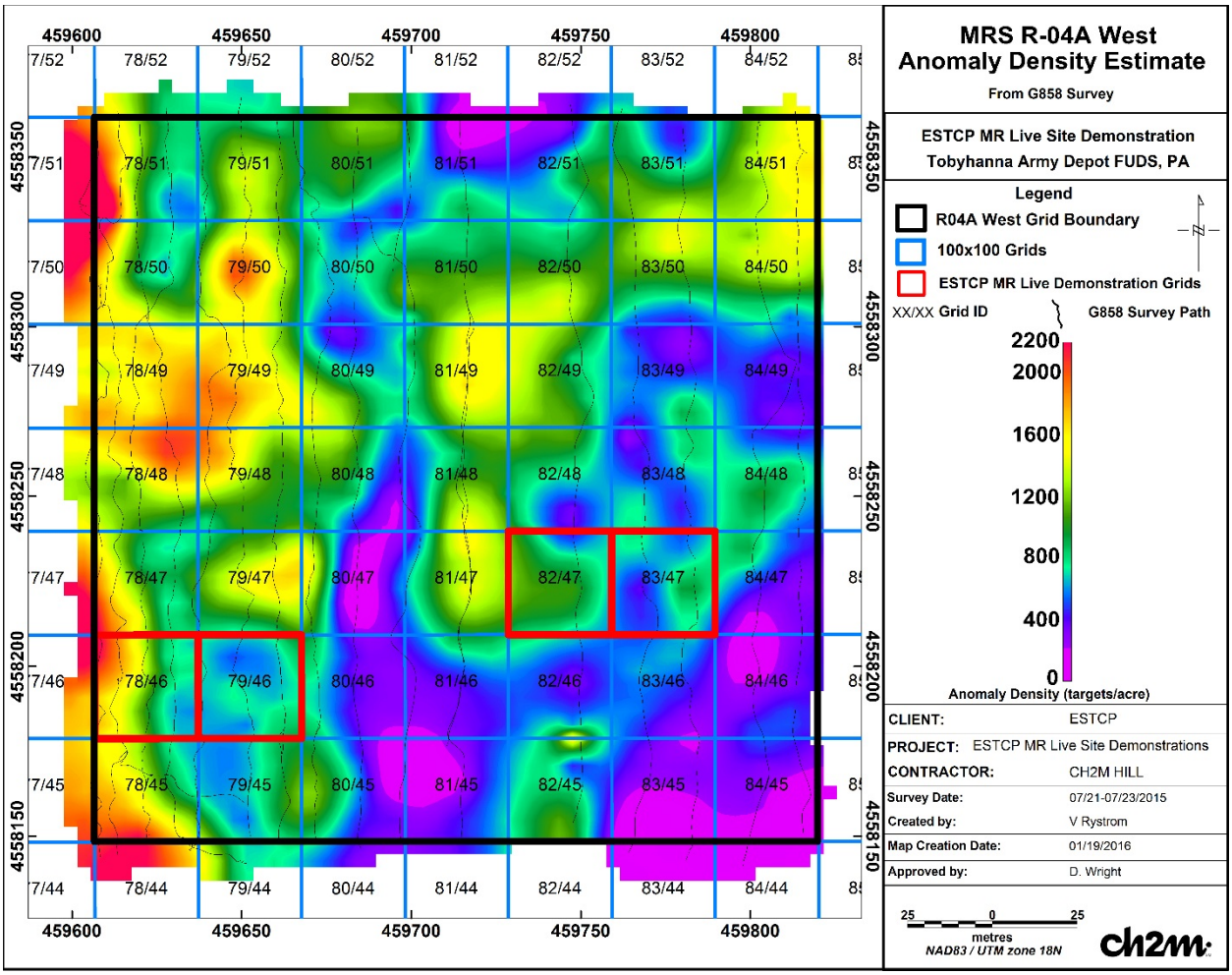


Figure 4-3. MRS-R04A (West) Anomaly Density Estimates and Selected Demonstration Grids

4.2 Brief Site History

TOAR was established as Camp Sumerall when the United States purchased 33 square miles of property in Monroe County in 1909. The facility was used for a variety of missions throughout the years.

The site was first used for machine gun and artillery training during 1913. The Army and National Guard used the facility from 1913 until 1949 for field artillery practice. Camp Sumerall was also used as a training area for tanks from July through October 1918. The ranges were the only areas in Pennsylvania where live cannon fire was permitted from 1919 to 1932. During this timeframe, the rounds were mainly 75-mm French artillery. The range area between Warnertown and Route 611 became a temporary Headquarters Explosives Depot. An estimated 4 million pounds of high explosives was stored from February 1919 through October 1919. Bunkers were constructed in the current State Game Lands 127. The storage designation only lasted 10 months.

4.3 Munitions Contamination

Suspected munitions within MRS-R04A (West) include primarily 75-mm and 155-mm high explosives (HE) and shrapnel projectiles; however, during the remedial investigation conducted within MRS-R04A (West), 37-mm HE projectiles were reportedly recovered along with 75-mm and 155-mm HE projectiles.

4.4 Site Geodetic Control Information

CH2M subcontracted Taylor Wiseman & Taylor, a Professional Land Surveyor (PLS) licensed in Pennsylvania, to establish temporary benchmarks for use as control for the RTS during the demonstration. CH2M did not have information on current benchmarks that may be onsite and in use by other contractors working at the site. New temporary benchmarks were established to a third-order (1:10,000) accuracy. Universal Transverse Mercator (UTM) Zone 18 North is used as the projection and the horizontal datum is North American Datum 1983 (NAD83), CONUS; the vertical datum is North American Vertical Datum 1988 (NAVD88). All geodetic measurements and reported information are in units of meters. Additional locations were established by the PLS throughout the survey grids, as needed, to maintain line of sight for the RTS during the TEMTADS and MPV surveys.

4.5 Site Preparation

Vegetation reduction was performed in the grids selected to be surveyed with the TEMTADS and the MPV. A brush reduction team removed vegetation smaller than 6 inches (in.) in diameter. Low branches were cleared to 8 feet above ground to reduce obstruction of the RTS prism; large logs and fallen timber were not removed.

CH2M also performed a surface clearance of the selected demonstration grids prior to collection of dynamic TEMTADS and MPV data. The surface clearance was performed with the objective of leaving no more than five pieces of exposed or partially exposed metallic objects exceeding 2 in. in any dimension within any 0.2-acre area.

5.0 TEST DESIGN

5.1 Calibration Activities

5.1.1 Navigation Control

Two control monuments were used by the PLS to gain control of the site: #7 MON FP5 and #31 IRC FP5 AZ. New control stakes were set for the work area grids known as MRS-RO4A West, grids 78/46–79/46 and 82/47–83/47. These points were set by establishing a pair of real time kinematic (RTK) GPS control points in the open (no tree canopy), outside of the grid areas, running a conventional survey traverse to the grids, then rough-checking the traverse point position with GPS under the heavy tree canopy. Due to the heavy woods and terrain, control point recover sheets were not produced. From these control points 16 additional control points were established within the four grids. Their labels and coordinates are provided in **Table 5-1**.

Table 5-1. Geodetic Control Locations

ID	Easting (m) NAD83/UTM18 N	Northing (m) NAD83/UTM18 N	Elevation NAVD88 (m)
1000	459500.8	4558192.63	557.831
1001	459543.96	4558291.43	559.57
1002	459576.81	4558229.49	557.356
1003	459631.14	4558194.27	554.828
1004	459736.93	4558215.96	557.885
1010	459612.62	4558212.64	555.64
1011	459642.42	4558175.84	554.351
1012	459668.17	4558209.79	555.821
1013	459637.54	4558211.29	555.246
1014	459731.49	4558208.47	558.007
1015	459750.17	4558244.65	557.887
1016	459791.55	4558239.09	560.63
1017	459779.14	4558208.38	560.294
1018	459728.9	4558227	557.984
1019	459609.2	4558176	554.539
1020	459731.4	4558241	557.627
1021	459761.3	4558225	558.549
1022	459760.8	4558209	558.837

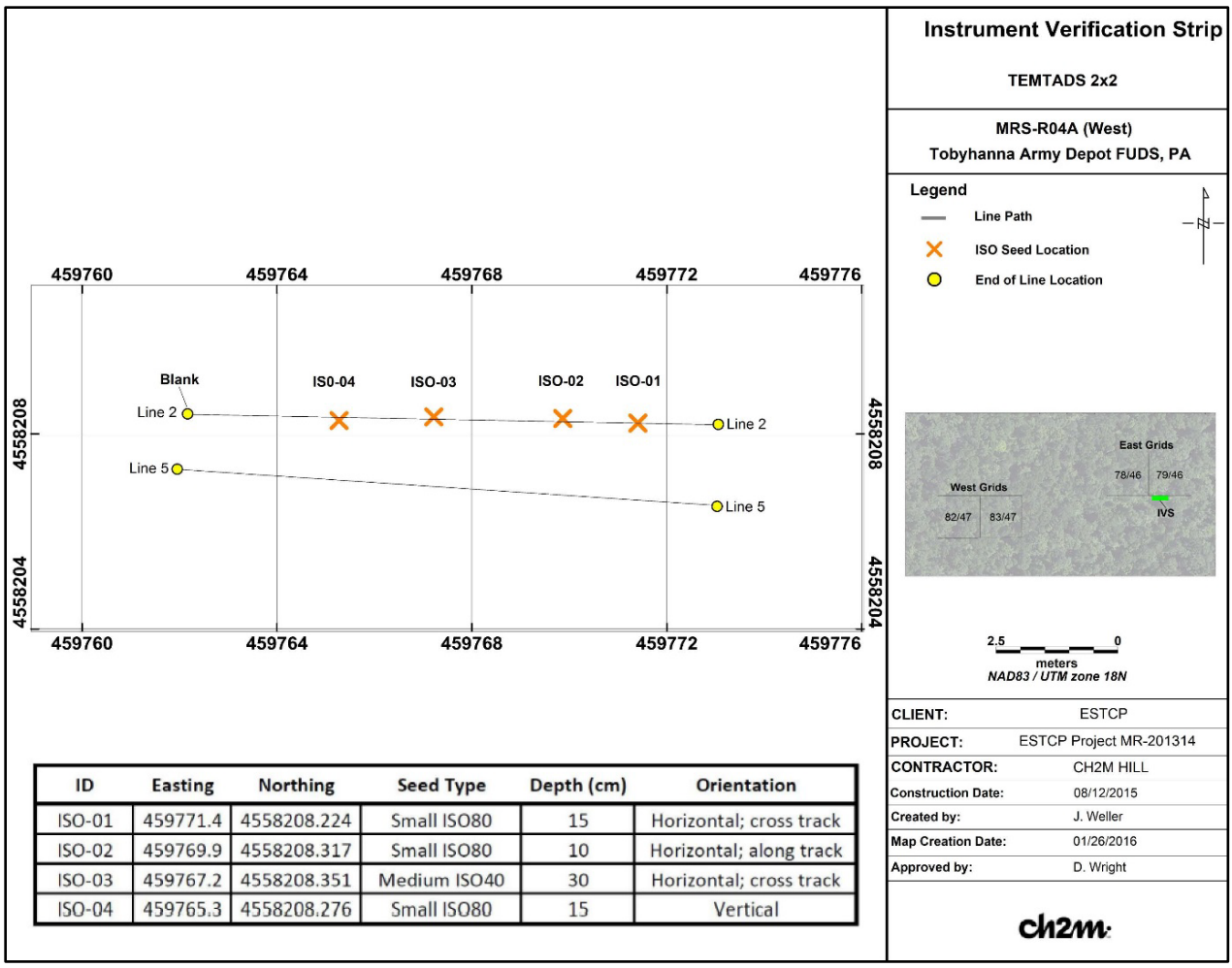
To set up the RTS system, three control points were used: a base location, a back-sight, and a check point. For the IVS, point #1017 was used as the base. The checkpoint was recorded and submitted as part of the daily quality control (QC) position check.

5.1.2 Seeding

After vegetation reduction and prior to conducting the dynamic TEMTADS and MPV surveys, CH2M seeded the selected demonstration grids. CH2M UXO personnel buried 20 seed items consisting of industry standard objects (ISOs). ISOs are commonly available pipe sections that have been well-characterized through data measurements and modeling. A combination of small schedule 80 ISOs (diameter = 1.315 in., length = 4 in.) and medium schedule 40 ISOs (diameter = 2.375 in., length = 8 in.) were used and buried between 1 and 17 cm. The PLS recorded the locations of the blind seeds at the time of emplacement. All seeds locations were blind to data collection and analysis personnel.

5.1.3 Instrument Verification Strip

An area near the demonstration grids was located to establish an IVS for daily verification of proper sensor operation. An initial background (i.e., preseeded) survey was conducted using the TEMTADS to identify a suitable location for the IVS, so that burial of seed items was sufficiently far from existing geophysical anomaly locations (so the response from the seed items were not impacted by responses from metallic objects of unknown nature in the subsurface). A schematic of the IVS is shown as **Figure 5-1** and details of seed items placed in the IVS are listed in **Table 5-2**.



ID	Easting	Northing	Seed Type	Depth (cm)	Orientation
ISO-01	459771.4	4558208.224	Small ISO80	15	Horizontal; cross track
ISO-02	459769.9	4558208.317	Small ISO80	10	Horizontal; along track
ISO-03	459767.2	4558208.351	Medium ISO40	30	Horizontal; cross track
ISO-04	459765.3	4558208.276	Small ISO80	15	Vertical

Figure 5-1. As-built IVS

Table 5-2. Details of the Instrument Verification Strip

Item ID	Description	Easting (m)	Northing (m)	Depth (cm)	Inclination	Azimuth
ISO-1	Small ISO80	459771.40	4558208.22	15	Horizontal	Across Track
ISO-2	Small ISO80	459769.86	4558208.31	10	Horizontal	Along Track
ISO-3	Medium ISO40	459767.21	4558208.35	30	Horizontal	Across Track
ISO-4	Small ISO80	459765.27	4558208.27	15	Vertical	Vertical
ISO-5	N/A	459762.10	4558208.44	N/A	Blank	Blank

ISO = Industry Standard Object
N/A = not applicable

5.1.4 Sensor Calibration

The TEMTADS sensor was calibrated during the initial commissioning of the system at the NRL facility at Blossom Point, Maryland. The system calibration was verified on a regular basis via function tests and daily IVS surveys. The function tests involve measurement of the system response to an ISO placed in a known location relative to the sensor. Function tests were performed a minimum of twice per day to verify the proper operation of all of the sensor transmit and receive components. Results of the function tests and IVS surveys are provided in the discussion of QC testing in Section 5.2.2 (Dynamic Data QC) and Section 5.2.5 (Cued Data QC).

5.2 Data Collection Activities

5.2.1 Dynamic Data Collection

Dynamic detection surveys were performed with the TEMTADS over the course of 11 survey days, from 12 August to 4 September 2015 (during this period there were a number of no-collection days due to equipment failures as well as weather delays and non-worked weekends). There were a total of 8 days of initial data collection and an additional 3 days of effort filling gaps in coverage. The positions of each measurement were determined using an RTS prism mounted at the center of the array, coil geometry relative to the RTS prism, and the platform attitude (pitch, roll, and yaw) derived from the IMU. CH2M's field team used ropes and flagging to perform data collection at a line spacing of 50 cm, which provided an overlap coverage of 30 cm to reduce the chance of data gaps. **Figures 5-2** and **5-3** show mosaics of the data collected at 78/46 and 79/46 (the western) and 82/47 and 83/47 (the eastern) grid sites, respectively.

Dynamic data collection was hindered by the rough terrain (boulders, swamp, felled trees, and standing trees) and the need to reestablish position control on a separate control point once the angle from the RTS "gun" became not optimal or a tree blocked too much of the "gun" site.

Due to site access time constraints, it was decided with the input from the ESTCP Program Office to focus on a 100% completion of one grid. Grid 82/47 (**Figure 5-3**) had gaps identified by CH2M and the data were collected until only physical obstacles (not RTS "gun" shadows) inhibited data collection. Because it took an additional 3 days to complete the gap fill on one grid (¼ of the planned survey area), by extrapolation it is estimated that an additional 9 days would have been required to fill all of the gaps in the planned survey areas.

Of the 0.89-acre footprint cleared, approximately 0.71 acre of dynamic detection data were collected with the TEMTADS. CH2M evaluated the dynamic TEMTADS data and selected 429 targets based on anomaly selection thresholds derived from IVS and dynamic test data.

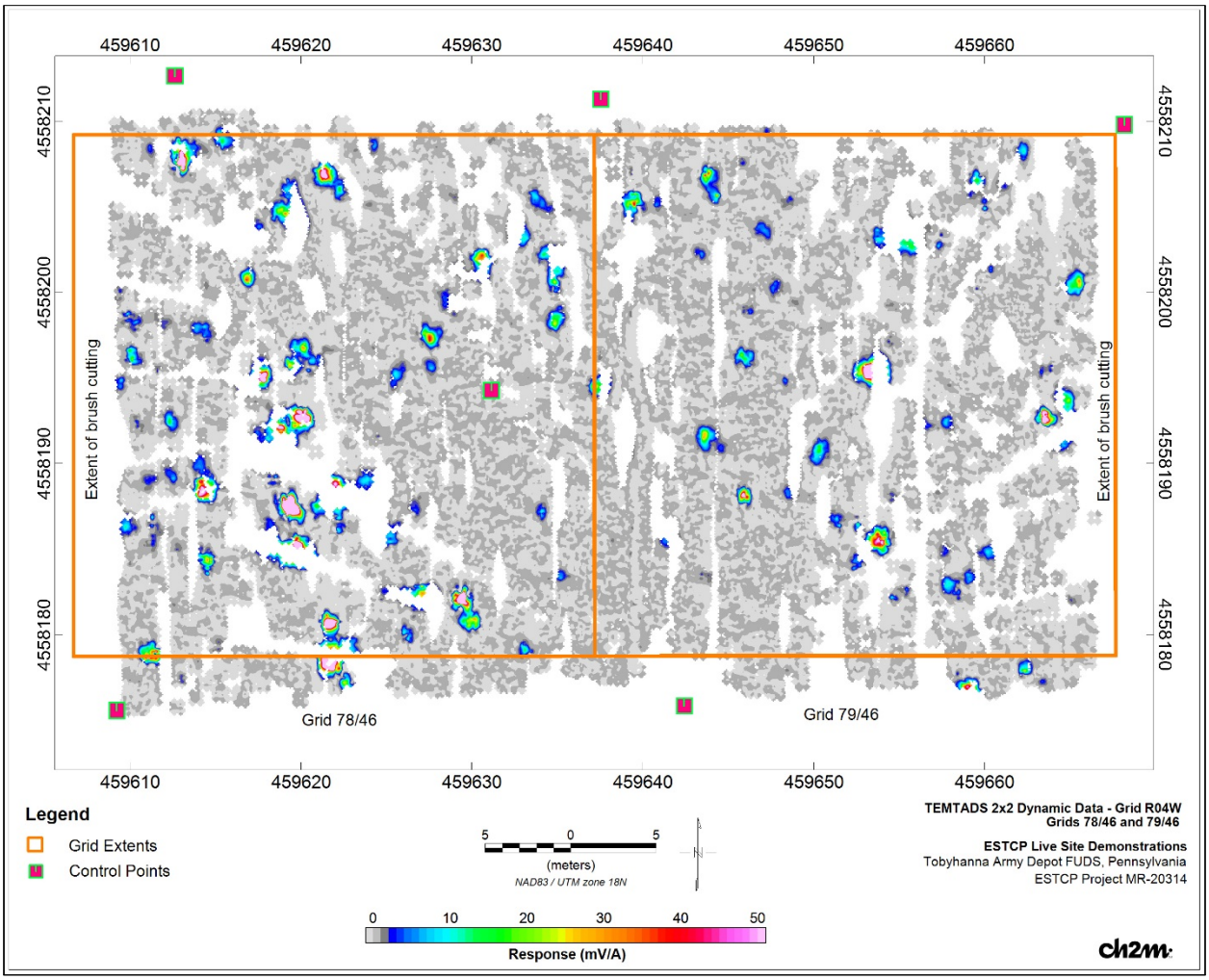


Figure 5-2. Dynamic TEMTADs 2×2 Survey in Grids 78/46 and 79/46 (Western)

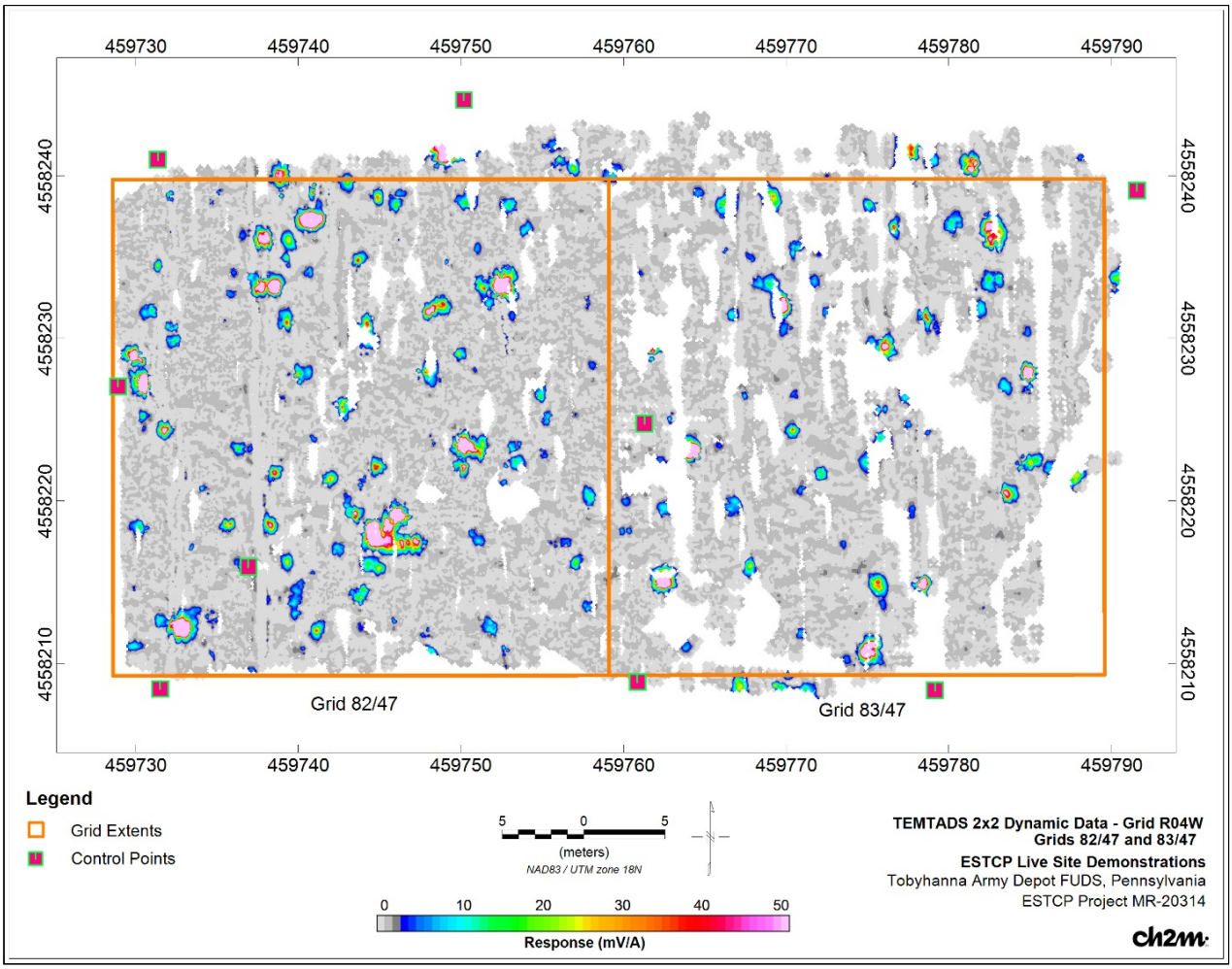
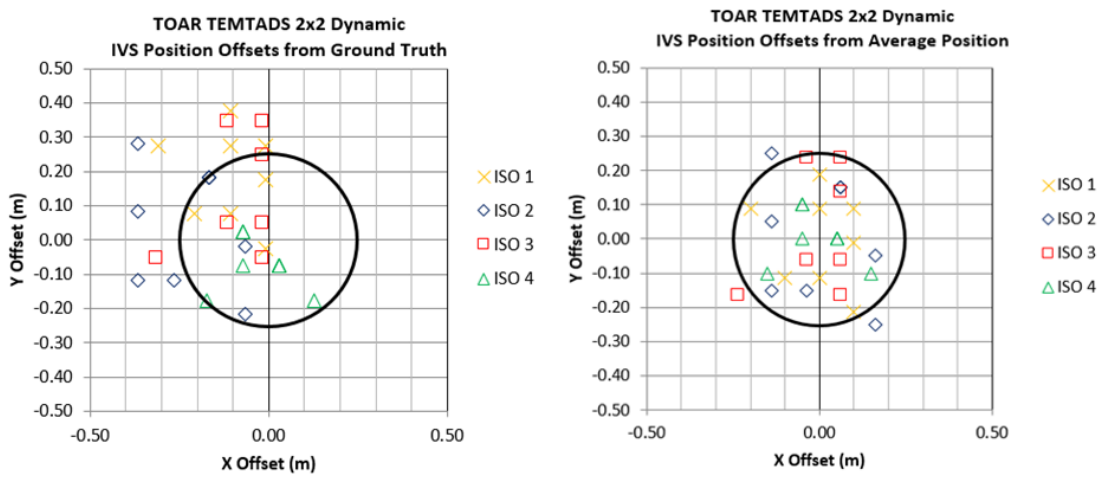


Figure 5 3. Dynamic TEMTADS 2×2 Survey in Grids 82/47 and 83/47 (Eastern)

5.2.2 Dynamic Data QC

Throughout the course of the dynamic detection survey, the TEMTADS system was tested at the IVS on a twice-daily basis to verify proper system operation. In order to measure precision of the system, ongoing analysis was performed on the IVS detection results, with each successive day's results compared to the averaged results of all previous IVS surveys for detection offset and amplitude response of each seed item.

The positions were derived from the dynamic monostatic, *Z*-component response amplitude anomaly peaks using Geosoft's automatic peak picking algorithm. **Figure 5-4** (left) presents the position offsets (relative to the ground truth) for each of the IVS items. **Figure 5-4** (right) presents the position offsets from average position. The errors were outside the stated objective of 0.25 m (objectives presented in **Table 6-5**).

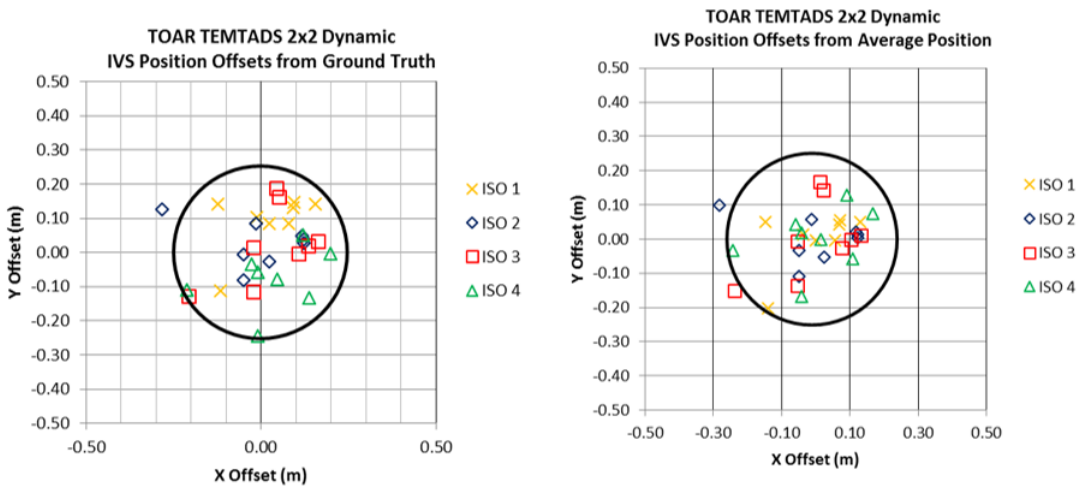


	Maximum Error (m)	Average Error (m)
ISO 1	0.39	0.24
ISO 2	0.46	0.29
ISO 3	0.37	0.20
ISO 4	0.25	0.12

	Maximum Error (m)	Average Error (m)
ISO 1	0.23	0.15
ISO 2	0.29	0.20
ISO 3	0.29	0.18
ISO 4	0.18	0.10

Figure 5-3. Dynamic TEMTADs 2×2 IVS Survey Position Results (Initial Processing)

During the field operations, the lack of positioning accuracy was assumed to be a function of the RTS operating in the wooded environment. After the project was completed, a review of the processing approach revealed that the data processor had failed to account for the extended height of the RTS prism above the TEMTADS array. Because of this, the pitch and roll positioning corrections were not accurate, and the accuracy of the results was compromised. The data were reprocessed using the correct positioning approach, and the results are provided in **Figure 5-5**. While these results indicate considerable improvement, there remains very little difference between the accuracy (results against ground truth) and the precision (variability in the results). This indicates that the positioning methodology used does not have the same precision as a typical GPS-enabled approach. However, the precision in the results is comparable to that of a GPS-enabled EM61-MK2 survey, and the dig radius of 1 m used during the intrusive investigation was sufficient to mitigate the effects of these increased errors on locating the anomaly sources.



	Maximum Error (m)	Average Error (m)
ISO 1	0.21	0.15
ISO 2	0.31	0.12
ISO 3	0.24	0.15
ISO 4	0.25	0.15

	Maximum Error (m)	Average Error (m)
ISO 1	0.25	0.10
ISO 2	0.30	0.12
ISO 3	0.28	0.14
ISO 4	0.24	0.13

Figure 5-4. Dynamic TEMTADs 2×2 IVS Survey Position Results (after Reprocessing)

In addition to the daily IVS measurements, the functionality of the TEMTADS sensor was assessed daily using a system "function test" whereby the system response was challenged by placing a small schedule 80 ISO on the top of the array housing. The function test results are presented on **Figure 5-6**.

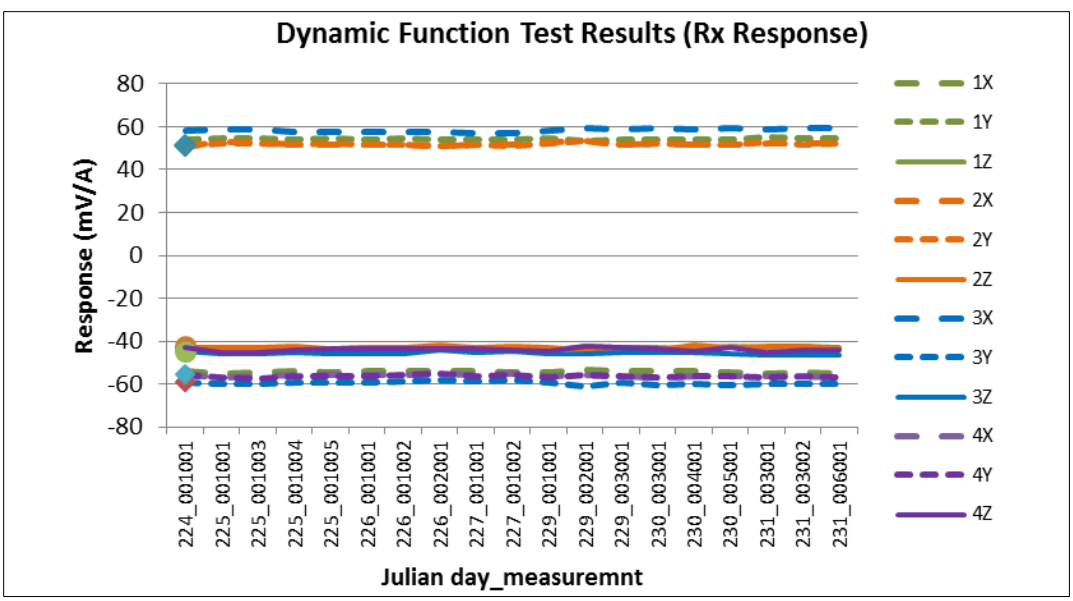


Figure 5-5. Dynamic TEMTADS IVS Survey Sensor Function Results

5.2.3 Dynamic Data Processing/Target Selection

Data Processing

The raw data files, comprising raw sensor, RTS, and IMU data, were loaded into the UX-Analyze (UXA) advanced analysis software environment. The RTS and IMU data were merged with the sensor data to provide georeferenced positions for each TEMTADS transmit/receive (Tx/Rx) combination measurement. The monostatic *Z*-component Rx coil measurements were used as the basis for amplitude response anomaly detection.

The background monostatic *Z*-component responses were removed using a de-median filter in which long wavelength signals (due to spatially stable soil response and sensor "zero level" drift) were modeled and removed by calculating the median over a large moving window and subtracting the median from the unleveled data. The final (leveled) data for each grid were interpolated to grid nodes evenly spaced at 5 cm using the Geosoft Oasis minimum curvature gridding routine. The interpolated Geosoft grid files were mosaicked to create a full-site Geosoft grid file from which anomalies were selected.

Dynamic TEMTADS Target Selection

Targets were selected using amplitude response detection by applying Geosoft's peak detection function to the interpolated monostatic, *Z*-component responses at time gate 5 (0.137 ms). This is similar to conventional EM61-MK2 target detection, with the only difference being the higher resolution of the TEMTADS sensor due to the smaller Tx/Rx coil footprints and more densely sampled data set.

Detection performance is a function of the signal-to-noise ratio of the detection method, where signal is derived as the peak anomaly response and the noise is calculated as the root mean square of the non-anomalous responses. Typically, a signal-to-noise ratio of 5 is used to maximize detection of real targets while minimizing false detections due to noise in the data. The site-specific noise levels were estimated by calculating the standard deviation of the leveled data (assuming perfect leveling, root mean square noise is equivalent to the standard deviation of the signal) in non-anomalous regions. Noise levels of 0.46 millivolts per ampere (mV/A) resulted in a detection threshold of 2.3 mV/A. This threshold provides a maximum reliable detection depth (assuming worst case orientation) of 0.3 m for small ISOs (small ISOs are similar in response to 37-mm projectiles). Note that optimally oriented small ISO's and 37-mm projectiles will be detected at greater depths. Using this threshold, anomalies were automatically selected from the gridded data using Geosoft's peak detection algorithm. All anomaly selections were manually reviewed by the processing geophysicist, and manual additions or deletions were performed where required.

CH2M selected a total of 429 anomaly locations for cued interrogation. There were 165 selections in the western grids (**Figure 5-7**) and 264 selections in the eastern grids (**Figure 5-8**). In addition to these, 68 MPV targets selected by Black Tusk Geophysics were added to the cued interrogation and intrusive investigation lists. These targets were MPV targets located in the 100% coverage area (eastern grids) that did not have a corresponding TEMTADS anomaly location (due primarily to the fact the MPV could access locations that the TEMTADS could not).

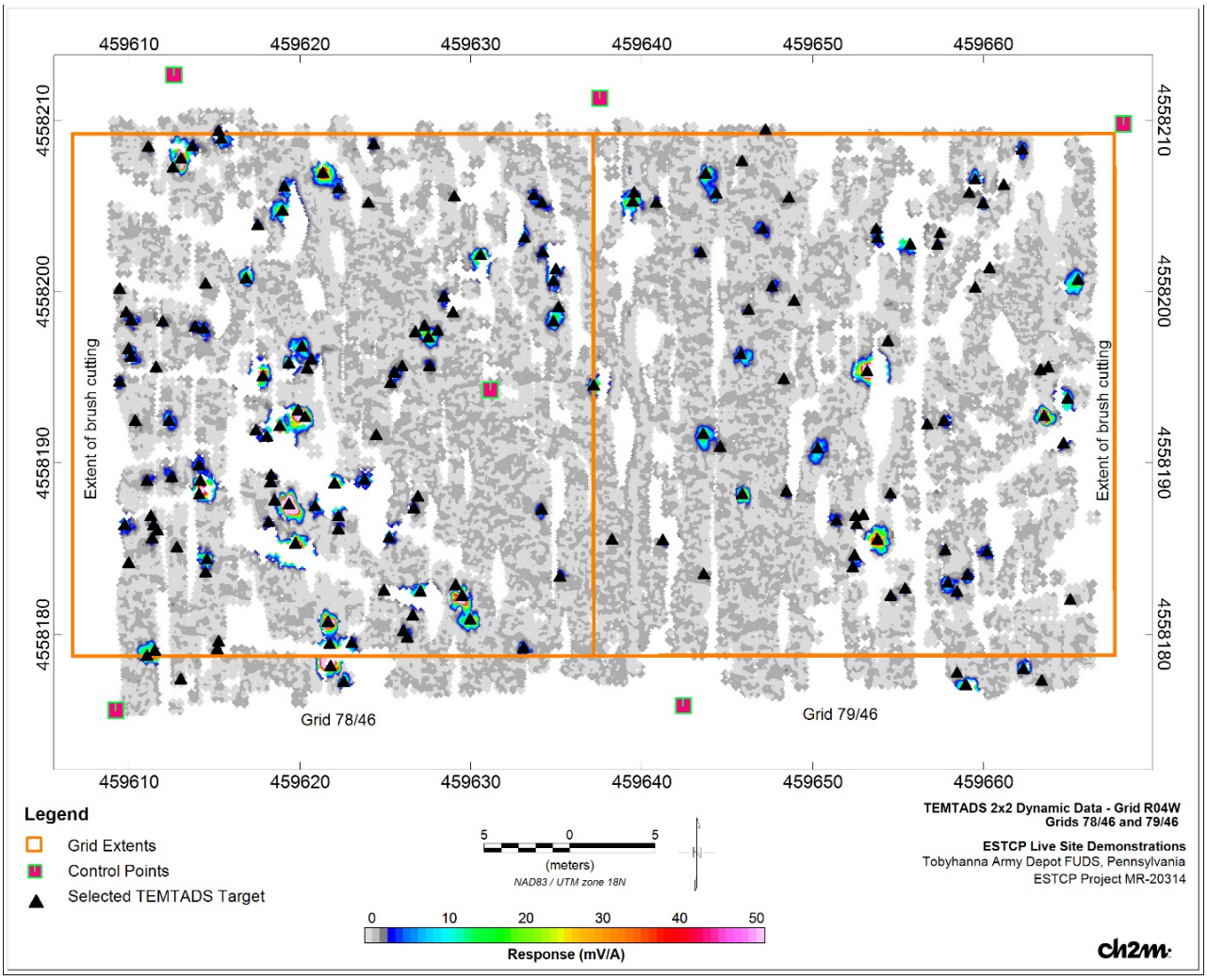


Figure 5-6. Dynamic TEMTADS Data with Locations of Anomalies Selected for Cued Data Collection, Grids 78/46 and 79/46 (Western Grids)

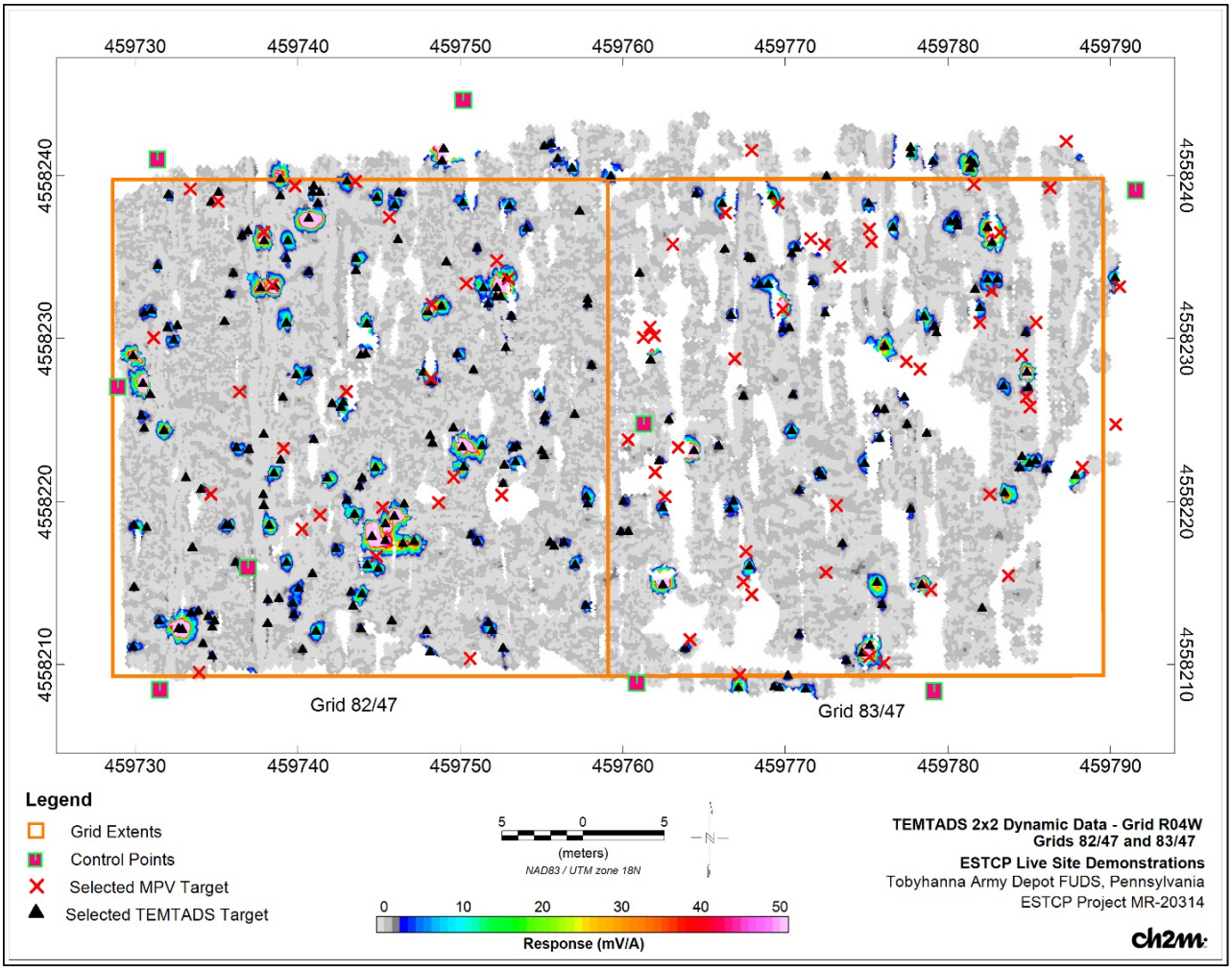


Figure 5-7. Dynamic TEMTADS Data with Locations of Anomalies Selected for Cued Data Collection, Grids 82/47 and 83/47 (Eastern Grids)

5.2.4 Cued Data Collection

Cued surveys were performed with the TEMTADS over the course of 7 days, from 4 September (Julian day 247) to 17 September (Julian day 260), 2015. Data were recorded electronically as collected on the TEMTADS backpack data acquisition computer hard drive. The collected data were copied and backed up daily onto removable media and transferred daily to the data analyst for QC analysis.

All of the 429 targets detected by the TEMTADS were reacquired for cued interrogation with the TEMTADS. Cued measurements at the 68 MPV target locations that were not selected by the TEMTADS were also collected, resulting in a total of 497 reacquired targets.

5.2.5 Cued Data QC

The QC implemented throughout the cued data collection included the following:

- IVS measurements before and after each day of production measurements
- Function tests collected whenever background measurements were collected
- Transmit current and receiver decay monitoring
- Field inversion monitoring
- Re-collection where horizontal target location was offset by more than 40 cm

Throughout the course of the cued data collection, the TEMTADS system was tested at the IVS on a twice daily basis to verify sensor functionality. The daily IVS measurements were inverted, and the extrinsic parameters (source location) and intrinsic parameters (source polarizabilities [βs]) results were monitored and recorded.

These results for the source locations are presented on **Figures 5-8**. All but one of the source position results obtained were within the measurement quality objective (MQO)of 25 cm for accuracy (position relative to the ground truth) and all of the results were within the 20-cm MQO for precision (offset from the average position). Because the accuracy results for ISO 1 exhibit a bias, and this bias is not present in the remaining ISOs, it is assumed that the MQO failure is attributable in part to inaccuracy in the ground truth for ISO 1.

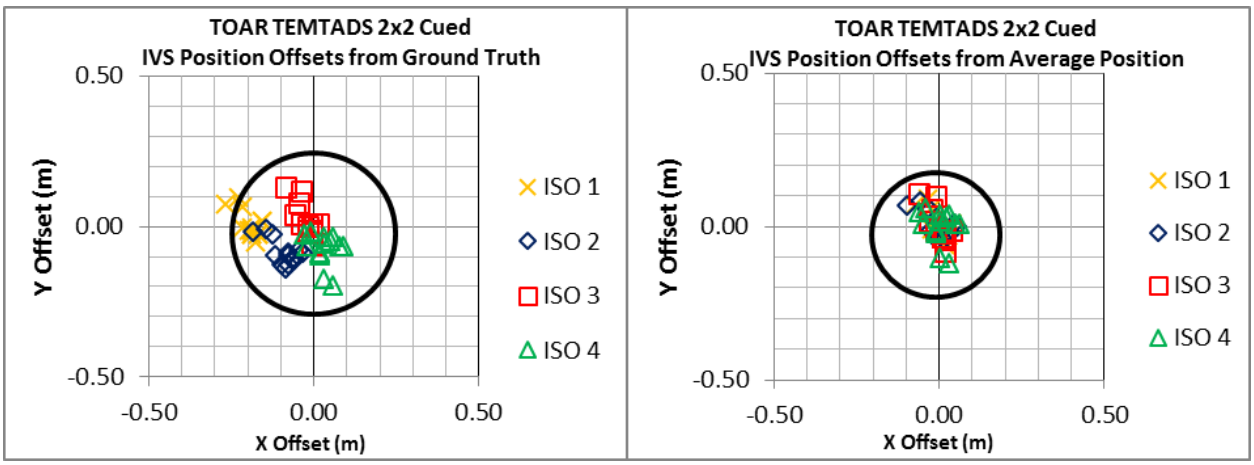


Figure 5-8. TEMTADS Cued Data IVS Dipole Fit Position Results: (Left) Offset from Ground Truth and (Right) Offset from Average Position

The derived source βs were assessed by performing a library match to derive decision metrics (described below in section 5.3.1) for each measurement and the results are presented on **Figure 5-9**. All measurements resulted in very good fits to their respective library entries, indicating proper operation of the system.

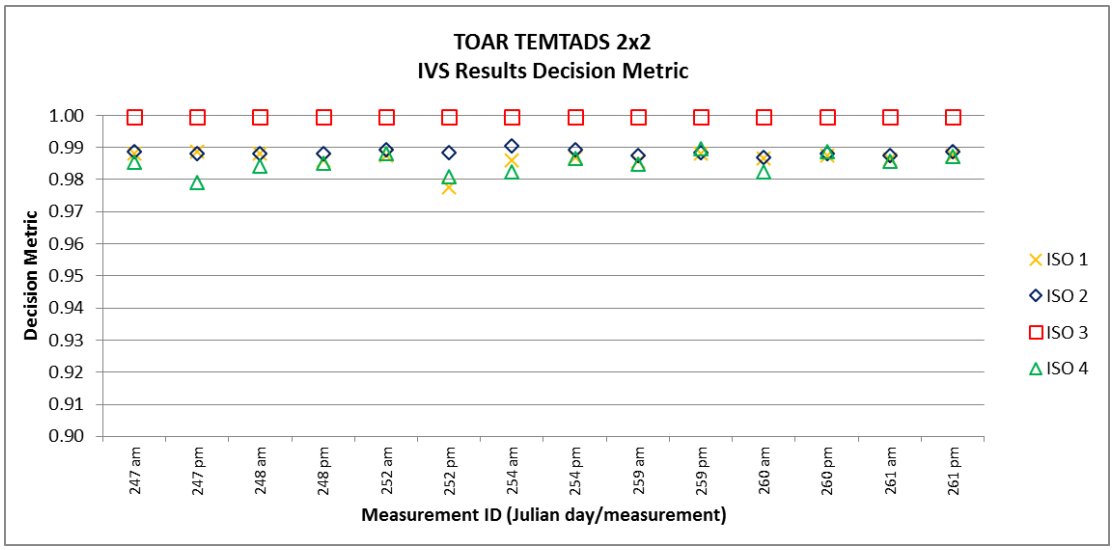


Figure 5-9. TEMTADS Cued IVS Decision Metric (Library Match) Results

In addition to the twice-daily IVS, in-field sensor functionality tests were performed throughout each survey day to confirm that the TEMTADS system components were functioning within project specifications. Sensor function tests were performed during each background data collection event. The sensor function test results are shown on **Figures 5-10**, **5-11,** and **5-12**.

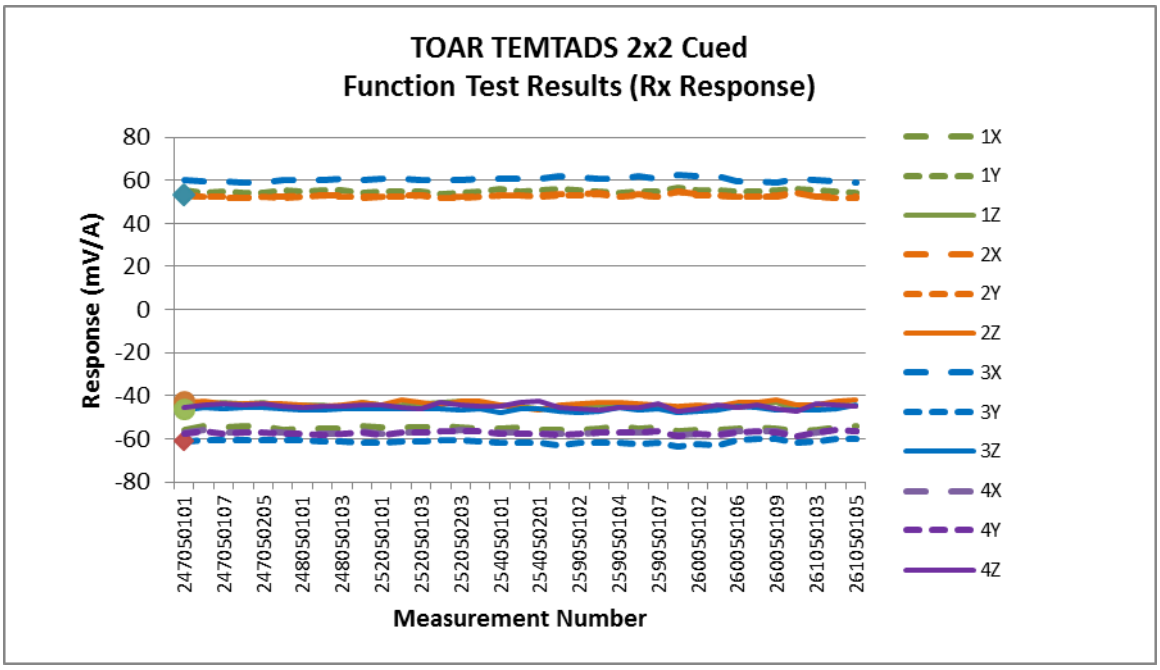


Figure 5-10. TEMTADS Cued Data Sensor Function Test Results Rx Response

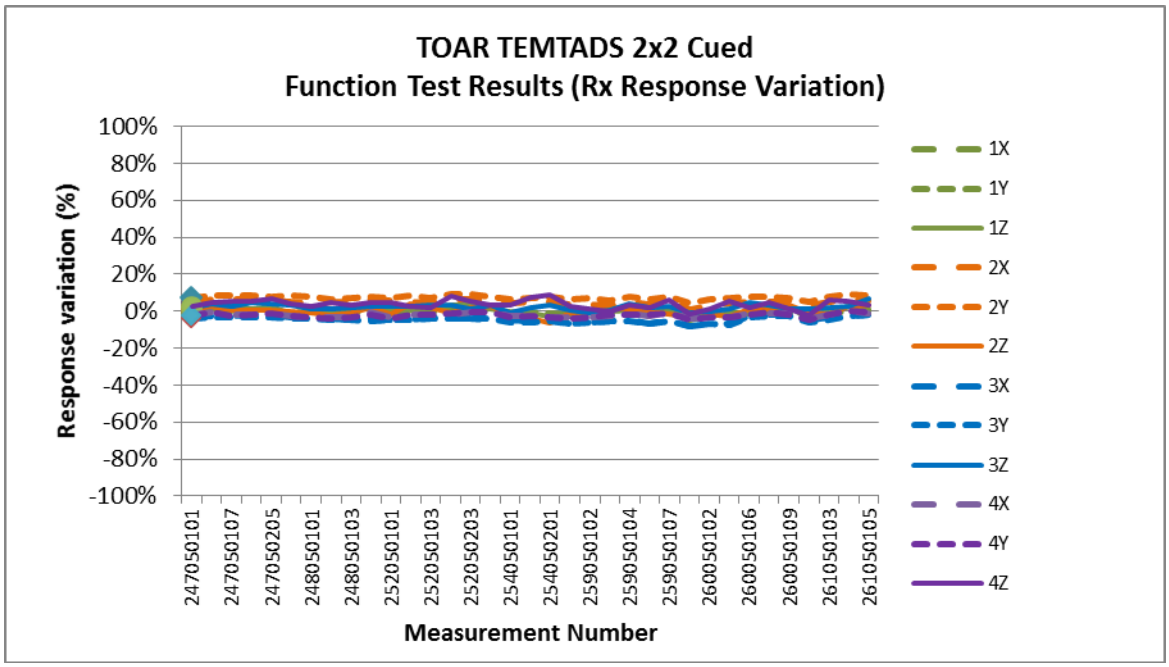


Figure 5-11. TEMTADS Cued Data Sensor Function Test Results Rx Response Variation

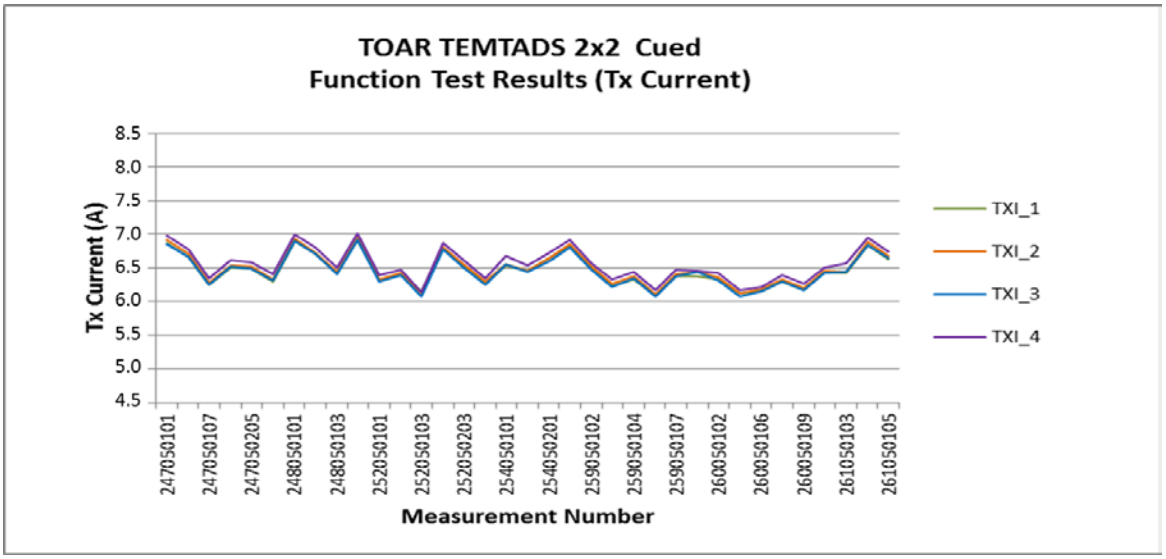


Figure 5-12. TEMTADS Cued Data Sensor Function Test Results Tx Current

5.3 Classification

The data processing, analysis, and classification steps undertaken to generate a dig/no-dig decision for each target are described below. These steps were performed for the TEMTADS data using the UXA module within the Geosoft Oasis Montaj processing platform.

Cued data were imported into the Geosoft UXA Advanced module for data QC and inversion modeling. The data were levelled using background data collected at frequent time intervals over

nearby, anomaly-free background locations. The measurements used for background correction were reviewed for variability and to identify any outliers which may correspond to measurements over subsurface metal. To minimize errors in the background removal process, spatial and temporal distance between the background and target measurements were minimized.

Target data were inverted using both single-source and multisource dipole response models to estimate target parameters. The principle parameters of interest for use in classification of the targets were the three polarizabilities ($\beta 1$, $\beta 2$, and $\beta 3$) estimated for each target by UXA. In addition to estimates for the three βs for each target, an estimated location and depth and fit coherence (i.e., the correlation between the observed responses and the model predictions) was also returned by UXA for each target during inversion.

Classification of each target was performed using the intrinsic features (βs) derived from the single-source and multisource inversion processes. Classification was based primarily upon how well the derived βs matched the library of candidate TOI types. The final composition of the library was informed by a set of analyst calibration digs (ACDs) (described in detail in section 5.3.2).

5.3.1 Library Match Decision Metric

Classification is based primarily on the goodness-of-fit metric (values from 0.0 to 1.0) generated by UXA during a comparison of the β values estimated for each surveyed target and the β values in the site-specific library of candidate munitions. This comparison is performed via the library match utility in UXA. The goodness-of-fit metric is a measure of the fit correlation between a target and the library entry that best fits that target, with higher values indicating a better fit between the target and the corresponding item in the library. The library fit analysis matches the following four combinations of βs to those of the candidate library TOIs:

- $\beta 1$, $\beta 1/\beta 2$, $\beta 1/\beta 3$
- $\beta 1$, $\beta 1/\beta 2$
- $\beta 1/\beta 2$, $\beta 1/\beta 3$
- $\beta 1$

The confidence metrics for each fit combination are averaged to derive a “decision metric.” This library matching process is performed for each single-solver model and every target in each of the multisource solver candidate realization models. For each flag position, the best library fit from the single-solver and multisolver targets is used as the decision metric, which is subsequently used to rank and classify the target list. Values below the analyst threshold (nominally 0.825) are considered non-TOI. The analyst threshold was refined using results from a set of ACDs.

5.3.2 Analyst Calibration Digs

Because all identified anomalies were intrusively investigated, ACDs were not performed separately from the intrusive investigation phase. Instead, the ACDs were simulated through requests for ground truth from the ESTCP program office. The following sections describe the rationale for the ACD selections.

Cluster Analysis

A “cluster analysis” designed to identify signatures that are ubiquitous to the site was performed using the UXA signature matching/cluster identification routines. For identified clusters that were not already represented in the library, representative samples were selected for addition to the set of ACDs (in this case, “selections” provided on request by the ESTCP Program Office to simulate the ACD process) to confirm that they are not due to an unexpected TOI.

Feature Space Analysis

In addition to the library match decision metric described above, a feature space analysis was also performed to identify any targets that did not match a specific library entry but had the combined characteristics of being large, rotationally symmetric, and thick-walled. Targets identified with these characteristics were selected and added to the ACD selection list.

Dig/No-dig Threshold Calibration

The ACDs were also used to finalize the analyst threshold (i.e., the decision metric cutoff value separating the prioritized list into dig/no-dig classifications). These targets were selected by sampling each library match munition type above and below the initial starting metric of 0.825. Because the analyst threshold must be set low enough to identify TOIs that have noisy polarizabilities as TOIs, where possible targets that looked qualitatively like a TOI were preferentially selected. Although final classification is based upon objective numeric criteria, qualitative selection of these threshold calibration digs is required to preferentially select those targets that are likely to be TOIs, thus calibrate the threshold appropriately.

Library Entry Verification

The initial library contained a comprehensive list of munitions including entries that were not in the list of munitions expected to be onsite but were conservatively left in as a representative size/shape sample. Where one or more of these entries resulted in a significant number of matches, they were sampled to determine if they were actual TOIs. Where these samples did not result in the recovery of a TOI, these entries were removed from the final site-specific list. Selection of targets with noise-free polarizabilities does not inform the threshold calibration because if they are near the threshold they will not be TOIs.

5.3.3 Candidate TOI library

The initial candidate library consisted of a comprehensive range of munitions that are delivered with the UXA installation files (listed on the left side of **Figure 5-13**). The final site-specific library of candidate TOIs comprised munitions expected to be onsite, as confirmed by the results of the ACDs. The site-specific library had one or more entries for each item listed on the right-hand side of **Figure 5-13.**

Comprehensive Library (all UXO)			
Type	Size	Decay	Symmetry
Small ISO	0.21	0.031	1.02
rifle grenade	0.79	0.009	1.03
medium ISO	0.98	0.046	1.06
large ISO	1.54	0.054	1.02
81mm	1.36	0.032	1.05
75mm	1.08	0.057	1.01
60mm	0.79	0.038	1.01
5in proj	1.70	0.058	1.05
57mm	0.68	0.056	1.02
40mm grenade	0.28	0.092	1.01
3in stokes mortar	1.38	0.070	1.15
3in proj	1.14	0.052	1.02
37mm	-0.08	0.092	1
2.36in rocket	1.17	0.075	1.19
155mm_proj	2.10	0.050	1.13
105mm proj	1.59	0.059	1.14
20mm	-0.30	0.022	0.98
MK2 Hand grenade	0.32	0.001	1.04
Fuze Piece/part/component	-0.45	0.009	1.1

TOAR Library Entries			
Munition	Size	Decay	Symmetry
Small ISO	0.21	0.030	1.02
Medium ISO	0.98	0.050	1.06
Large ISO	1.54	0.050	1.02
37-mm projectile	0.20	0.060	1.00
75-mm projectile	1.08	0.057	1.01
155-mm projectile	2.10	0.050	1.13

Figure 5-13. Initial (left) and Final, Site-specific TOI Library (Right) for TOAR

5.4 Intrusive Activity and Procedures

CH2M performed intrusive operations from 13 September through 1 October 2015. All prosecuted targets were investigated and documented according to the procedures outlined below.

5.4.1 Intrusive Investigation Procedures

- **Reacquisition of targets**. Targets were previously reacquired by the PLS for the cued interrogation using RTS. The pin flag was located approximately 50 cm north of the paint mark denoting the target location.
- **Intrusively investigate the anomaly.** Anomalies were excavated to 30 cm below the expected depth below ground surface, within a 50-cm radius from the marked-out anomaly location.
- **Identify recovered item**. All items recovered were inspected by the Unexploded Ordnance Safety Officer and Senior UXO Supervisor to ensure that each item was properly identified and documented.
- **Munitions Response Site Information Management System (MRSIMS) data entry/whiteboard and photo**. Field observations of each recovered item were entered into CH2M's MRSIMS field tablets. The exact location and depth of each item was recorded by a CH2M field geophysicist using the RTS. Required information was written onto a whiteboard, and a photo was taken with the item.
- **Postdig clearance**. Before declaring a dig complete, each area was swept with a Schonstedt magnetometer and a White's All Metal detector to determine if any additional items remained.

- **QC check**. Approximately 10 percent of all excavations were checked by UXO Quality Control personnel with the Schonstedt magnetometer and a White's All Metal detector to ensure the hole was clear.
- **Backfill hole**. Once the excavation was declared clear, the hole was backfilled to grade.

5.4.2 Intrusive Investigation Results

All of the TEMTADS cued targets were intrusively investigated as well as a set of MPV targets located in the 100% coverage area. Time constraints imposed by site access limitations did not allow for all of the MPV targets outside the 100% coverage area to be investigated. During the intrusive investigation, all of the QC seeds were located within the 0.4-m MQOs and recovered. The results of the intrusive investigations were provided to the ESTCP Program Office and are not presented in this report.

5.5 Deliverables

The following deliverables resulted from the data collection at TOAR:

1. **Dynamic detection data:** Raw and processed dynamic detection data were provided to the ESTCP Program Office, along with a final target list based on the established detection threshold

2. **Cued data:** Raw sensor data (*.tem) and associated GPS/IMU data (*.gps)

3. **Cross-reference list**: A text readable table that associates TEMTADS filenames with each Target ID, and provides any applicable collection notes

4. **Intrusive results:** The intrusive results were provided to the ESTCP Program Office in the form of a table listing the results for each location identified for intrusive investigation as well as photos detailing the metallic items that were removed from each location. Note that all of the intrusive results were firewalled from the data analyst until after the analysis was completed (with the exception of the ACD selections described above)

6.0 PERFORMANCE ASSESSMENT

The performance objectives for this classification survey and the corresponding results are summarized in **Table 6-1**. Details on the results for each objective are subsequently discussed in the following sections.

TABLE 6-1. Performance Objectives and Results for this Demonstration

Performance Objective	Metric	Data Required	Minimum Acceptable Criterion	Result
Dynamic survey spatial coverage	Effective footprint coverage	Mapped survey data	100% at ≤ 75 cm cross-track measurement spacing with intended spacing of 50 cm	Fail (pass for 100% coverage area)
Along-line measurement spacing	Point to point sample distance	Mapped survey data	98% ≤ 25 cm; no gaps > 40 cm unless obstruction or hazard is present	Fail (pass for 100% coverage area)
Detection of all TOIs	Percent of seed items detected	Seed item locations Georeferenced anomaly list	100% of seed items within a 40-cm radius of ground truth	Fail (all seed items were detected but two were not within the specified distance due to gaps in coverage)
Initial dynamic survey data positioning	Accuracy of derived target positions	Derived target positions from initial measurements at the IVS	Derived positions within 25 cm of the ground truth	Fail (one outlier from horizontal targets–at 31 cm)
Ongoing dynamic survey data positioning	Precision of derived target positions	Derived target positions from daily measurements at the IVS	Derived positions within 25 cm of the average positions during ongoing daily measurements	Fail (two outliers from horizontal targets—all within 30 cm)
Initial cued survey data positioning	Accuracy of dipole-fit-derived target positions	Target fit positions from initial measurements at the IVS	IVS item fit locations within 25 cm of ground truth locations	Pass
Ongoing cued survey data positioning	Precision of dipole-fit-derived target positions	Target fit positions from daily measurements at the IVS	IVS item fit locations within ±20 cm of average fit locations during ongoing daily measurements	Pass
Initial cued sensor polarizability accuracy	Accuracy of dipole-fit-derived intrinsic target features	Dipole-fit-derived polarizabilities from initial measurements at the IVS	Library match metric ≥0.9 to initial polarizabilities for each set of inverted polarizabilities	Pass
Ongoing cued sensor polarizability precision	Precision of dipole-fit-derived intrinsic target features	Dipole-fit-derived polarizabilities from daily measurements at the IVS	Match metric ≥0.95 to initial polarizabilities at the IVS for each set of inverted polarizabilities from daily measurements	Pass

TABLE 6-1. Performance Objectives and Results for this Demonstration

Performance Objective	Metric	Data Required	Minimum Acceptable Criterion	Result
Cued interrogation anomaly coverage	Instrument position	Cued data	100% of anomalies where the center of the array is positioned within 30 cm of anomaly location	Pass
Correct classification of TOIs	Number of TOIs correctly identified	Ranked anomaly lists Scoring reports from ESTCP Program Office	100% of all seed targets 100% of all TOIs categorized as "dig" or "cannot analyze"	Pass
Model results support classification decision	Number of anomalies classified as "cannot analyze"	Modeling fit coherence results	≥90% of targets have fit coherence > 0.80	Pass

6.1 Dynamic Survey Spatial Coverage

The TEMTADS dynamic detection survey was designed to provide 100 percent coverage of the investigation area. A planned transect spacing of 50 cm was used to ensure sufficient overlap of the 80-cm sensor swath footprint between traverses. Data were collected continuously with an even walking pace; this consistent pace allowed the RTS base to reestablish contact with the RTS prism on the TEMTADS after it emerged from behind an obstacle. Using this approach, two types of gaps exist in this data set: one caused by the RTS "gun" shadow created when the TEMTADS is carried behind a tree, and one created by obstacles such as downed trees, upright trees, and boulders. For the case of the RTS shadow, data were not interpolated even though the dynamic TEMTADS data were still being collected and there were positioning data on either side of the tree, the positioning data were not interpolated in processing. As in any survey, obstacles such as trees and boulders precluded coverage. To achieve the stated goal of 100% coverage, gaps due to interruption of the RTS data required re-collection, whereas gaps due to physical obstructions were documented as such.

Due to time constraints, the gap fills required to achieve the 100% coverage goal were performed on only one of the four grids (grid 82/47). This grid had a coverage of 81.2% prior to gap fill and 94.1% after gaps due to RTS coverage were eliminated. The remaining 5.9% was due to physical obstacles; thus the 100% coverage metric was achieved for this grid. Grids 78/46 and 79/46 (western grids) combined had an overall coverage of 72.4% with no gap re-collection. The gap percentage due to obstacles was not calculated because the locations of these objects were not recorded. Grids 82/47 and 83/47 (eastern grids) combined had 71.2% coverage, not accounting for obstacles.

6.2 Along-line Measurement Spacing

The TEMTADS dynamic detection survey was designed to have an along-line measurement spacing of 15 cm or less so as to provide a dense detection dataset. The success criterion for this objective was for 98% of mapped data points to be within 25 cm of the along-line neighboring data point. This objective was not achieved, as gaps created by the RTS "gun" shadow were not interpolated across these gaps. The heavily wooded site inhibited the continuous contact between the base RTS and the prism located on the TEMTADS.

6.3 Detection of All TOI

This objective involved the detection of TOIs during the dynamic detection survey using the blind seeding program. Prior to the dynamic detection survey, 20 seed items were buried within the investigation area. These seed items consisted of small schedule 80 ISOs and medium schedule 40 ISOs buried at depths up to 17 cm. The minimum acceptable criterion of 100 percent of seed items' locations being predicted within a 40-cm radius of ground truth was not met (**Table 6-2**). All of the seed items were detected within the 40-cm radius from the recorded PLS position with the exception of Seeds 1 and 4. The detection distance for these seeds was outside of the MQO due to the gaps in coverage discussed in Section 6.1. All of the seeds in the 100% detection grid passed the 40-cm MQO.

Table 6-2. TEMTADS QC Seed Detection

Seed ID	Delta X (m)	Delta Y (m)	Distance (m)
1	-0.56	0.00	0.56 [a]
2	0.03	0.21	0.22
3	-0.13	-0.20	0.24
4	-0.17	-0.39	0.43 [a]
5	0.34	-0.10	0.35
6	0.08	0.03	0.09
7	-0.11	0.05	0.13
8	0.12	-0.16	0.20
9	0.13	-0.06	0.14
10	-0.31	-0.06	0.32
11	0.10	-0.28	0.30
12	0.16	0.28	0.32
13	0.18	-0.01	0.18
14	-0.05	-0.06	0.08
15	0.07	-0.13	0.14
16	-0.24	-0.02	0.24

Table 6-2. TEMTADS QC Seed Detection

Seed ID	Delta X (m)	Delta Y (m)	Distance (m)
17	0.13	-0.11	0.17
18	0.08	0.16	0.18
19	0.08	-0.06	0.10
20	0.29	0.12	0.32

[a] Outside the MQO.

6.4 Initial Dynamic IVS Survey Data Positioning

This objective was to demonstrate positioning accuracy during initial dynamic data collection over the IVS with the TEMTADS by deriving positions within 25 cm of ground truth. The metric was assessed by evaluating the derived target positions from the initial data collection at the IVS as determined by the amplitude response anomaly peaks associated with the seeded items. Results for the dynamic data responses are provided in **Table 6-3**. The largest deviation was 39 cm for ISO-1, which means that this objective was not achieved for all ISOs.

Table 6-3. TEMTADS Initial Dynamic IVS Survey Positioning Results

Seed Item	Error (m)
ISO-1	0.39
ISO-2	0.25
ISO-3	0.25
ISO-4	0.08

6.5 Ongoing Dynamic Survey Data Positioning

This objective involved the repeatability of sensor response amplitude over the course of the project for each seed item buried at the IVS. The minimum success criterion was that the derived positions of the IVS targets would be within 25 cm of the average positions derived from the ongoing daily IVS measurements. This approach gives an estimate of the precision of the positioning and is independent of any ground truth errors. Results for the dynamic data responses are detailed in **Table 6-4**. The largest deviation was 30 cm for ISO-2, which means that this objective was not fully achieved for the dynamic data phase of the demonstration.

Table 6-4. TEMTADS Dynamic IVS Positioning Results

Seed Item	Maximum Error (m)	Average Error (m)
ISO-1	0.23	0.15
ISO-2	0.30	0.20
ISO-3	0.29	0.18
ISO-4	0.18	0.10

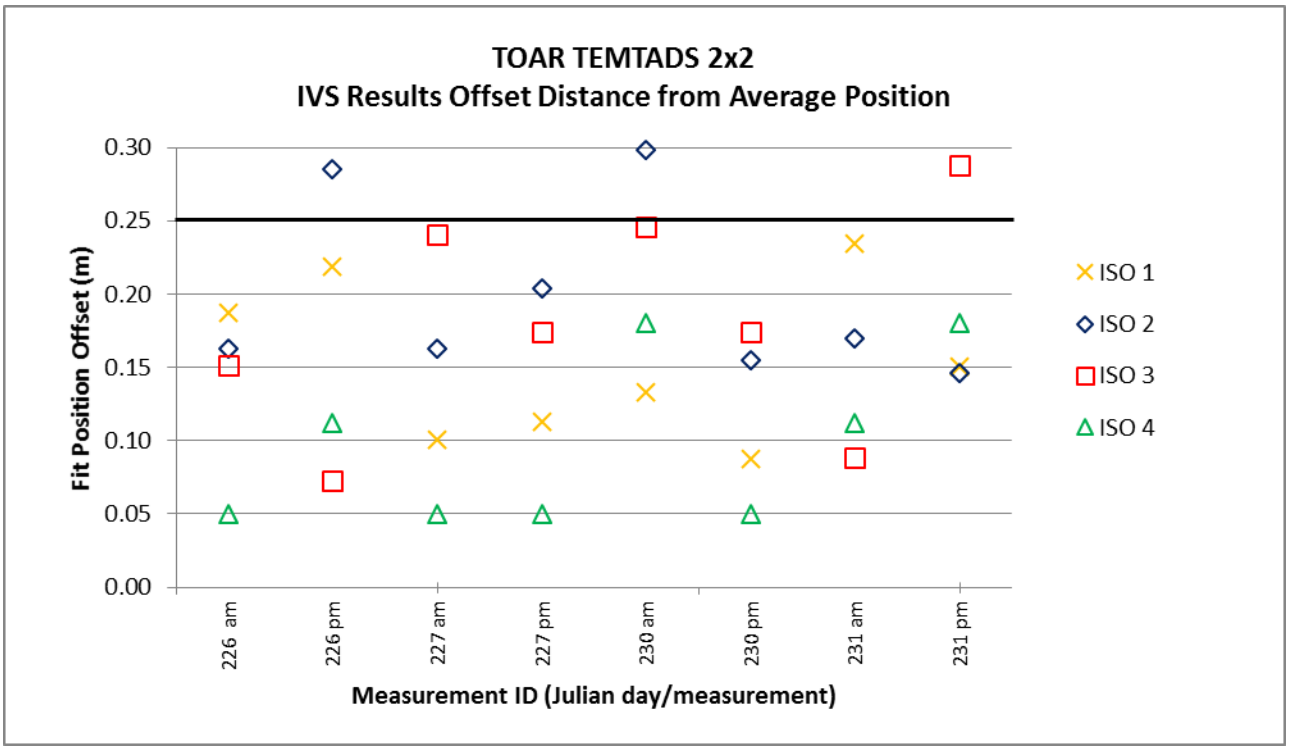


Figure 6-1. Dynamic IVS Position Precision (Errors Relative to Average Derived Positions)

6.6 Initial Cued Survey Data Positioning

This objective was to demonstrate positioning accuracy during initial cued data collection with the TEMTADS. The metric was assessed by evaluating the dipole-fit-derived target positions from initial measurements at the IVS. The minimum success criterion was that 100 percent of the fit-derived positions of the IVS targets would be within 25 cm of the ground truth location for the initial IVS measurements. This objective was achieved for the initial IVS cued survey (**Table 6-5**).

TABLE 6-5. TEMTADS Initial Cued IVS Survey Positioning Results

Seed Item	Error (m)
ISO-1	0.19
ISO-2	0.16
ISO-3	0.06
ISO-4	0.18

6.7 Ongoing Cued Survey Data Positioning

This objective was to demonstrate positioning precision during ongoing cued data collection with the TEMTADS. The metric was assessed by evaluating the dipole-fit-derived target positions from daily measurements at the IVS. The minimum success criterion was that the derived positions of the IVS targets be within 20 cm of the average positions derived from the ongoing daily IVS measurements. As expected, the precision of the measurements was better than the initial accuracy assessment because the initial accuracy assessment factors in ground truth measurement error. The performance criterion for this metric was met (**Table 6-6**). Results for the cued data responses are detailed in **Figure 6-2**.

TABLE 6-6. TEMTADS Cued IVS Positioning Results

Seed Item	Maximum Error (m)	Average Error (m)
ISO-1	0.10	0.04
ISO-2	0.12	0.05
ISO-3	0.12	0.05
ISO-4	0.12	0.05

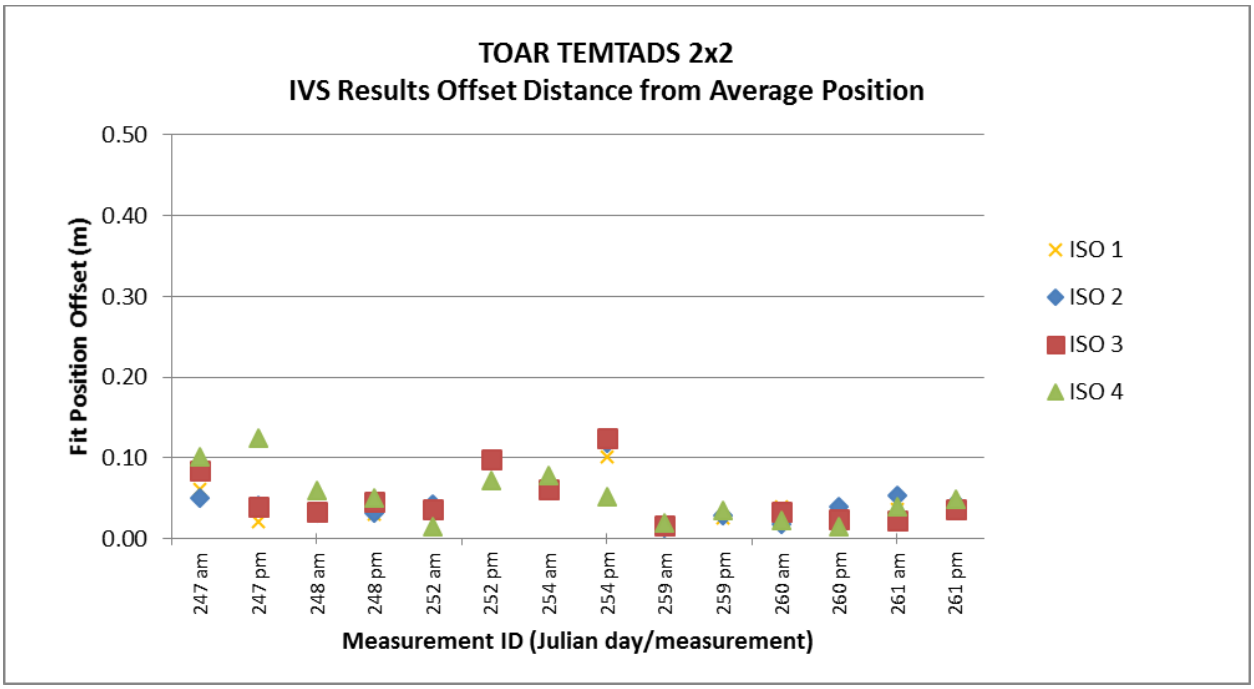


Figure 6-2. Cued IVS Position Precision (Errors Relative to Average Derived Positions)

6.8 Initial Cued Measurement Polarizabilities

This objective was to demonstrate that the derived polarizabilities of the IVS targets matched the polarizabilities in the library during the initial IVS measurements. The minimum success criterion was met, as the dipole-fit-derived polarizabilities for the IVS targets during initial IVS measurements exhibited a decision metric of ≥0.9 for all IVS ISOs. These results are provided as the first day's data points on **Figure 6-3**.

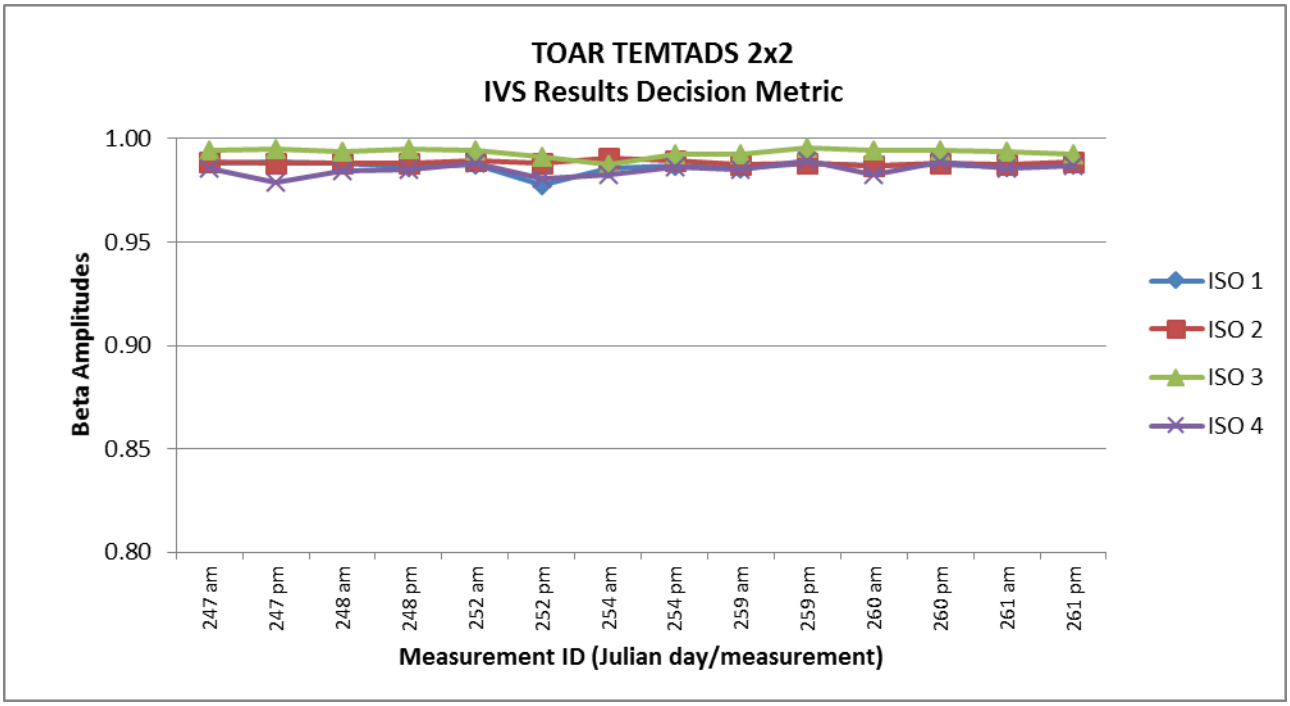


Figure 6-3. Decision Metric for IVS ISOs

6.9 Ongoing Cued Sensor Polarizability Precision

This objective was to demonstrate that the derived polarizabilities of the IVS targets from ongoing daily IVS measurements matched the polarizabilities derived from the initial IVS measurements. The minimum success criterion was that the ongoing daily decision metric for the IVS targets was better than ≥0.95. Although the initial IVS signature for each ISO can be used for this test, the matches to the existing library entry were sufficient to pass the MQO, so it was not necessary to use the initial IVS-derived signatures.

6.10 Cued Interrogation Anomalies

To collect data that support classification, the source of the anomaly must be illuminated along its three principle axes. To ensure this, the sensor array must be positioned directly over the center of the item. The metric for this objective was to demonstrate that the center of the array was within sufficient distance of the anomaly source's location during cued interrogation. Positions of the array center were derived from the RTS and IMU data along with the derived target locations for comparison against each other. The array center positions were compared against the supplied target coordinates as part of the daily QC process during data collection. The minimum and nominal success criterion for this objective was that 100% of the final derived targets be positioned within 40 cm of the center of the array. Exceptions include targets that are considered "cannot analyze" (e.g., saturated response area) and multitarget sources. Thirty-six targets were classified as "cannot analyze" because the source was too far from the center of the array to support classification. All of the targets not considered "cannot analyze" had a valid measurement within this metric.

6.11 Correct Classification of Targets of Interest

Meeting this objective was a primary key measure of the effectiveness of the classification approach. By collecting high-quality data and analyzing those data with advanced parameter estimation and classification algorithms, targets would be classified with high efficiency. The metric for this objective demonstrates that TOIs are correctly classified as TOIs on the final ranked anomaly list. The ranked anomaly list was submitted to ESTCP for scoring against the emplaced seed items and the intrusive results. The minimum success criterion was correct classification of 100 percent of the seed items and native TOIs as TOIs. Successful achievement of this metric would include seed items and other TOIs categorized as "dig" or "cannot analyze" on the final ranked anomaly list. A pseudo receiver operating characteristic (ROC) curve presenting the classification performance is shown in **Figure 6-4.** The ROC curve is derived by moving down the prioritized list and adding 1 to the *y* axis for each recovered TOI and 1 to the *x* axis for each non-TOI recovery. A ROC curve representing perfect classification rises vertically until all TOIs are identified, then horizontally for the remaining non-TOI results. A diagonal ROC curve indicates no classification performance. The results presented in **Figure 6-4** indicate good classification performance. All TOIs were correctly categorized as "dig"; six TOIs were initially selected as Category -1 (ACDs), and the remaining 26 TOIs were all selected as Category 1 (high likelihood TOI).

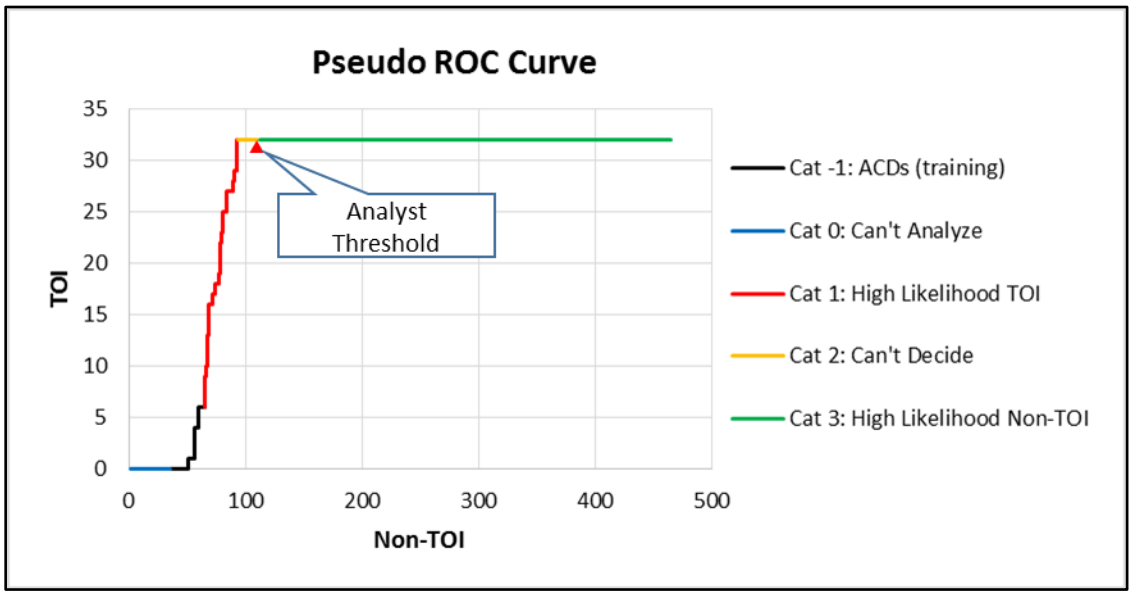


Figure 6-4. Classification Results for Cued Investigations of 497 Targets

6.12 Model Results Support Classification Decision

This objective was to demonstrate that data gathered exhibit a measure of the correlation between the model and the observed data, which is used to determine whether the model will support classification. The metric used to validate that the model responses support classification is the percentage of targets that cannot be classified as well as the fit coherence between the model response and observed data. The targets that cannot be classified were identified as having a "fit coherence" of less than 0.8. (Fit coherence is an output of the UXA dipole fit routine indicating the correlation of the modelled data with the observed responses). The minimum success criterion

for the number of targets with responses that support classification was that ≥90 percent of the targets meet the fit coherence requirement. Two targets were categorized as “can’t analyze” due to fit coherence, resulting in 99.6 percent of the targets meeting this metric.

7.0 COST BENEFIT ANALYSIS

ESTCP projects are required to develop and validate, to the extent possible, the expected operational costs of the technology. The intent of this section is to identify the information that was tracked or the data that were obtained during the demonstration that will aid in establishing realistic costs for implementing the technology and comparing it to potential alternative technologies.

The tracked costs are provided in **Table 7-1**, and discussion on the cost elements provided in the following subsections. Note that the TEMTADS system was provided by NRL at no cost to CH2M for this demonstration. The costs per acre (for dynamic data collection) and per anomaly (for cued data collection) do not include those costs.

Table 7-1. Costs for TEMTADS

Cost Element	Tracked Data	Cost/Quantity
Site Setup		
Costs for planning, mobilization, general site setup, shipping of equipment, instrument aided visual surface sweep, QC seeding, surveyor services, and demobilization		$63,000
MPPEH management and MEC disposal for the instrument-aided visual surface clearance was de-scoped from CH2M and passed along to the removal action MEC contractor		$5,300
Dynamic TEMTADS Survey Costs		
Dynamic detection survey (0.89 acre), including field labor (three geophysicists/geophysical technicians, one UXO technician), equipment setup, equipment rentals, instrument verification strip setup and data collection, data processing, and per diem		$77,500 ($87,078/acre) [a]
Dynamic detection survey data processing		$8,300
Cued TEMTADS Survey Costs		
Reacquisition of anomalies for cued surveys (497 anomalies), including field labor (three geophysicists/geophysical technicians, one UXO technician), equipment setup, equipment rentals, instrument verification strip setup, data collection, and per diem		$40,000 ($80.48/anom)
Processing of cued data, including several site visits for task kickoff and quality control purposes		$6,400 ($12.88/anom)
Intrusive Investigation		
Reacquisition of anomalies and all UXO team-related costs related to the intrusive investigation and documentation of discoveries per the ESTCP intrusive investigation instructions		$173,200 ($348.49/anom)
Management of material potentially presenting an explosive hazard and MEC disposal for the intrusive investigation was de-scoped from CH2M and passed along to removal action MEC contractor		$11,600

[a] See implementation issues section for explanation of high per-acre cost.

8.0 IMPLEMENTATION ISSUES

While the RTS can be used for positioning in open areas or narrow corridors, the TEMTADS unit cannot be carried in such a way that it is always moving perpendicular to the RTS base station, thus avoid being shielded from the base by the operators. In order to facilitate positioning in a heavily wooded area using RTS, the RTS prism located above the TEMTADS unit had to be raised above the heads of the operators. This allowed free movement by the operators and increased the data production rate; however, the added height of the prism more than likely caused dynamic IVS measurement MQO failures due to the oscillation of the prism while walking. Additionally, dynamic data with a lower prism height were not collected, so it is not possible to rule out that just walking in litter mode with the RTS was not the issue. Prior experience using the RTS with the TEMTADS in wheeled mode had no positioning MQO failures.

Data collection production rates were hindered for the following reasons:

- Approximately 1.5 hours of travel time was needed after reaching the site each day to access the collection grids.
- Daily reassembly and breakdown were required, as there was no secure storage facility. A temporary carport was installed for a partial breakdown area; however, cables needed to be secured nightly due to animal activity.
- Setting up the RTS base stations in multiple locations took more time than a standard RTK GPS set up. There was also a steep learning curve for speedy assembly of the RTS; this often delayed the start of production.
- Due to the experimental nature of the NRL TEMTADS, several days of production were lost due to software issues and a hard drive failure, which resulted in several trips to NRL for solutions.

9.0 CONCLUSIONS

CH2M performed an ESTCP Munitions Response Live Site Demonstration at MRS R-04A West at TOAR FUDS, Pennsylvania. The demonstration involved the participation of two advanced EMI sensors and was designed to investigate the use of these advanced EMI sensors at a densely wooded site with challenging microterrain features (e.g., impact craters, rocks, boulders, gullies) for detection of munitions down to the size of 37-mm projectiles. The NRL TEMTADS was demonstrated in both dynamic and cued modes in a two-person litter carry configuration. Collection and processing of dynamic and cued data with an MPV was performed by Black Tusk Geophysics, the results of which are addressed under separate cover by Black Tusk Geophysics. Both instruments were coupled with a Trimble RTS for positioning.

Approximately 0.71 acre was dynamically surveyed with the TEMTADS system. Production was significantly hindered by the remote location and site conditions, and only one of the four grids initially selected for investigation achieved 100% coverage (not including gaps due to physical obstructions). Based upon this effort, production rates under less challenging conditions are estimated to be much higher.

A total of 429 anomalies were identified by the TEMTADS dynamic data analysis. These anomaly locations and an additional 68 targets selected by the MPV survey were interrogated (cued data collection) and classified with the TEMTADS system. The cued data were used to classify the targets as being a potential TOI (dig) or high-likelihood non-TOI (do not dig). The TEMTADS successfully detected and classified all known TOIs (seeds and native TOI).

10.0 REFERENCES

Battelle Memorial Institute. 2015. *Visual Sample Plan.*

ESTCP. 2015. *Live Site Demonstrations TEMTADS Demonstration Plan MRS-R04A (West), Tobyhanna Army Depot FUDS, Pennsylvania, ESTCP Project MR-201314.* August.

APPENDIX A: POINTS OF CONTACT

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Tamir Klaff	CH2M 2411 Dulles Corner Park Suite 500 Herndon, VA 20171	(202) 596-1199 tamir.klaff@ch2m.com	Principal Investigator
Dave Wright	CH2M 18 Tremont Street #700, Boston, MA 02108	(978) 356-3962 david.wright@ch2m.com	Lead Geophysicist