TECHNICAL REPORT

Empirical Evaluation of Advanced Electromagnetic Induction Systems - Factors Affecting Classification Effectiveness in Challenging Geologic Environments
New Boston Air Force Station, NH

ESTCP Project MR-201314

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Acronyms

AFSCF	Air Force Satellite Control Facility
AFSPC	Air Force Space Command
BGS	below ground surface
cm	centimeter
DoD	Department of Defense
DSB	Defense Science Board
EMI	Electromagnetic Induction
ESTCP	Environmental Security Technology Certification Program
GIS	Geographic Information System
GPS	Global Positioning System
GRD	Geosoft grid
IDA	Institute for Defense Analyses
IMU	inertial measurement unit
ISO	Industry Standard Object
IVS	Instrument Verification Strip
JEP	Joe English Pond
JD	Julian Day
MEC	Munitions and explosives of concern
MOA	Memorandum of Agreement
mV/A	millivolts per ampere
mm	millimeter
MMRP	Military Munitions Response Program
MRS	Munitions Response Site
MRSIMS	Munitions Response Site Information Management System
NBAFS	New Boston Air Force Station
NRHP	National Register of Historic Places

NRL	Naval Research Laboratory
QC	quality control
RMS	root mean square
RTK	Real-time kinematic
SUXOS	Senior UXO Supervisor
Small ISO80	Industry standard object, 1.5-inch x 4-inch, schedule 80 thickness pipe nipple
TEMTADS	Time-domain Electromagnetic Multi-sensor Towed Array Detection System
TOI	Target of Interest
UXA	UX Analyze
UXO	Unexploded Ordnance
UXOSO	Unexploded Ordnance Safety Officer

EXECUTIVE SUMMARY

CH2M HILL performed an Environmental Security Technology Certification Program (ESTCP) Munitions Response Live Site Demonstration using a Time-domain Electromagnetic Towed Array Detection System (TEMTADS) at the Shooting Fields (MU705), located at New Boston Air Force Station (NBAFS), New Hampshire. The demonstration was designed to investigate the classification methodology at an Air Force site that is suspected to contain a large variety of munitions down to 20 millimeter (mm) projectiles. Approximately 6.1 acres were dynamically surveyed with a TEMTADS 2x2 system and 1500 anomalies from a subarea of the site were then interrogated (cued data collection) with the same system. A high density of metal was detected and a large percentage of the anomaly locations contained multiple metallic items under the instrument footprint. After several weeks of intrusive investigations yielding multiple items and a significant quantity of targets of interest identified in many of the anomaly locations, the project team, including ESTCP, NBAFS, and CH2M HILL, determined that enough information had been gathered to make a decision that classification at the site would not be financially beneficial (above intrusively investigating all anomalies) or effective (with respect to classification). Approximately 33% of the anomalies investigated resulted in more than three sources – and under these circumstances the inversion results do not appear to accurately represent the ground truth. Furthermore, the fact that 70% of the intrusive investigations resulted in TOI indicated that submission of a final prioritized list would add no value.

1.0 INTRODUCTION

This demonstration report details the Environmental Security Technology Certification Program (ESTCP) Munitions Response Live Site Demonstration at New Boston Air Force Station (NBAFS) performed in the summer of 2013.The Naval Research Laboratory (NRL) Man-Portable version of the Time-domain Electromagnetic Towed Array Detection System (TEMTADS), known as the TEMTADS 2x2, was demonstrated in both dynamic and cued modes.

1.1 BACKGROUND

CH2M HILL, Inc. (CH2M HILL) served as contractor to ESTCP under contract W912HQ-13-C-0039. This contract included emplacement of seed items, collection, processing, and analysis of dynamic and cued geophysical data using the TEMTADS 2x2, and intrusive investigation of anomalies at the Munitions Response Live Site Demonstration at the Shooting Fields (MU705), located at NBAFS, New Hampshire. This demonstration was designed to investigate the classification methodology at an Air Force site that is suspected to contain a large variety of munitions down to 20 millimeter (mm) projectiles.

1.2 OBJECTIVE OF THE DEMONSTRATION

The overall objective of the demonstration was to demonstrate the advanced sensor dynamic detection and cued classification technology at a site with a heavy density of metal and small munitions items (targets of interest [TOI]). CH2M HILL performed the following tasks in order to achieve this overall objective.

- Placement of subsurface 'blind' seeds within the demonstration site
- Establishment of an Instrument Verification Strip (IVS)
- Dynamic data collection using the TEMTADS 2x2
- Cued target interrogation using the TEMTADS 2x2
- Processing of dynamic and cued geophysical data
- Reacquisition and intrusive investigation of targets selected for cued interrogation

Approximately 6.1 acres of dynamic detection data were collected within the survey area at MU705 with the TEMTADS 2x2. CH2M HILL evaluated the dynamic TEMTADS data and selected 18,373 targets based on anomaly selection thresholds derived from IVS and dynamic test data.

CH2M HILL collected static cued data using the TEMTADS 2x2 in order to evaluate its performance in classifying anomalies. Of the 18,373 anomalies detected in MU705, 1,500 were reacquired for cued interrogation with the TEMTADS 2x2.

1.3 REGULATORY DRIVERS

The Military Munitions Response Program (MMRP) is charged with characterizing and, where necessary, remediating munitions response sites (MRS's). When an MRS is remediated, it is typically mapped with a geophysical system, based on either a magnetometer or electromagnetic induction (EMI) sensor, and the locations of all detectable signals are excavated. Many of these detections do not correspond to munitions, but rather to other 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. Current 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, all anomalies are currently treated as though they are intact munitions when they are dug. 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. 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 MRS's that are currently forecast to be untouched for decades.

2.0 TECHNOLOGY

This demonstration consisted of dynamic and cued data collection with the TEMTADS 2x2. Analysis of the data was performed using conventional and advanced data processing methods to select anomalies from advanced sensor dynamic data, and then extract features with the intent of performing anomaly classification on advanced sensor cued data; after review and analysis of the training data, however, classification was not pursued.

2.1 TECHNOLOGY DESCRIPTION

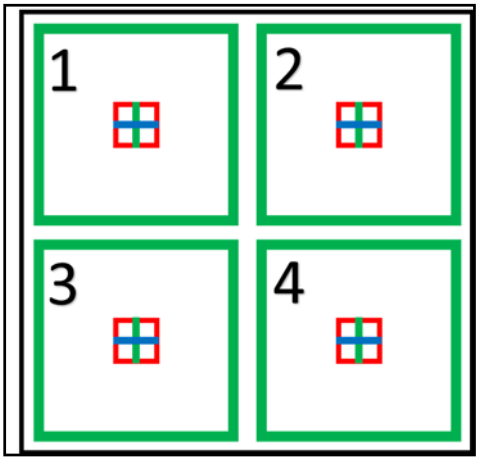
2.1.1 TEMTADS 2x2

The TEMTADS 2x2 is a man-portable system, shown in **Figure 2-1**, comprised of four of the TEMTADS EMI sensor elements arranged in a 2x2 array, as shown schematically by **Figure 2-2**. The array structure is fabricated from PVC plastic and Garolite fiberglass. The center-to-center distance between the coils is 40 centimeters (cm) yielding an 80 cm x 80 cm array. The array is

deployed on a set of wheels resulting in a sensor-to-ground offset of approximately 18 cm. The transmitter electronics and the data acquisition computer are mounted in the operator backpack, and a Global Positioning System (GPS) antenna and an inertial measurement unit (IMU) are mounted above the TEM array. The TEMTADS 2x2 can be operated in two modes; dynamic (or detection) mode, and cued mode. Data collection is controlled in dynamic mode using G&G Science's EM3D application suite, similar to that used for the Geometrics MetalMapper systems. In cued mode, the locations of previously-identified anomalies are flagged and surveyed with static measurements directly over the flag location. Custom software written by NRL is used to control the cued data acquisition.

Figure 2-1. TEMTADS 2x2 System

Figure 2-2. Schematic Diagram of TEMTADS 2x2 EMI Sensor Array



2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The original TEMTADS 5x5 Array was designed to combine the data advantages of a gridded survey with the coverage efficiencies of a vehicular system. The 5x5 Array was designed to collect data equal, if not better, in quality to the best gridded surveys (the relative position and orientation of the sensors will be better than gridded data) while prosecuting many more targets each field

day. The TEMTADS 2x2 is designed to offer similar production rates in difficult terrain and treed areas that the TEMTADS 5x5 Array cannot access.

With the upgraded 3-axis receivers, similar performance can be achieved with similar classification-grade data quality. The TEMTADS 2x2 array is 80 cm on a side and mounted on a man-portable cart. There are obvious limitations to the use of this technology. Terrain where the vegetation or topography interferes with passage of a cart of that size will not be amenable to the use of the system.

The other serious limitation is anomaly density. For all systems, there is a limiting anomaly density above which the response of individual targets cannot be isolated. Recent developments, including solvers designed for classification in multiple-object scenarios such as SAIC-ASAD's multi-target solver, have been shown to be effective at mitigating the effect of high anomaly densities on classification, but not overcoming this limitation entirely.

3.0 PERFORMANCE OBJECTIVES

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

4.0 SITE DESCRIPTION

The site description material reproduced here is taken from the NBAFS Draft Final Remedial Investigation Report (Shaw Environmental Inc., 2012). Additional details can be obtained in the report.

The NBAFS is a 2,826 acre site located within the towns of New Boston, Amherst, and Mont Vernon, NH. Outside of the active Operations Area, NBAFS consists of forests, fields, hills, wetlands, and ponds that provide a variety of camping and recreational opportunities. These opportunities are restricted to NBAFS personnel and guests. The Joe English Pond (JEP) was once the focal point of recreational activities at NBAFS. However, JEP was closed to all recreational activities in 1998 because of the probable presence of munitions and explosives of concern (MEC). The land immediately surrounding NBAFS is heavily wooded, rural, and consists primarily of low-density residential areas. There are several active farms in the area surrounding NBAFS, most of them situated on land adjacent to Chestnut Hill Road. The population and housing growth in the three surrounding communities is apparent from recent housing construction on the land surrounding NBAFS. The Joe English Conservation Area, Amherst, NH, is located immediately southeast of NBAFS.

NBAFS was nominated to the National Register of Historic Places (NRHP) in 2004 as the "New Boston Air Force Station Archaeological District". When it was nominated, the district included over 50 contributing properties representing thousands of years of human use. The district includes seven precontact sites of unknown cultural affiliation, including three small habitation areas and four isolated finds, 41 historic properties (ca. 1780-1940), and eight properties associated with the WWII- and Cold War-era use of the location by the U.S. military (ca. 1942-1956). The contributing properties include a wide range of resource types associated with cultural and social history, land use, and architecture important to the local, regional, state, and national history.

The ESTCP study was conducted on a subset of the MU705, the Shooting Fields, which is a 115 acre area located in the northwestern portion of NBAFS, directly southeast of Joe English Hill. The boundaries of MU705 were defined based largely on the 1995 UXO clearance boundary data obtained from NBAFS Geographic Information System (GIS). MU705 is a moderately sloped area with portions heavily forested with dense brush. Photographs from the site are provided as **Figure 4-1**.

Figure 4-1. Site Photographs

4.1 SITE SELECTION

This site was chosen as the next in a series of sites for demonstration of the classification process. The first site in the series, former Camp Sibert in Alabama, had only one Target of Interest (TOI) and item "size" was an effective discriminant. A hillside range at the former Camp San Luis Obispo in California was selected for the second of these demonstrations because of the wider mix of munitions, including 60-mm, 81-mm, and 4.2-in mortars and 2.36-in rockets. Three additional munitions types were discovered during the course of the demonstration. The third site chosen was the former Camp Butner in North Carolina, which is contaminated with items as small as 37-mm projectiles, adding yet another layer of complexity into the process.

The NBAFS site was chosen as one in a series of sites for demonstration of the classification process. Sites including this one provide opportunities to demonstrate the capabilities and limitations of the classification process on a variety of site conditions. This site presented the opportunity to demonstrate performance against 20-mm projectiles and high anomaly densities.

4.2 BRIEF SITE HISTORY

In the fall of 1941, the Federal Government acquired the 2,826 acres comprising the current configuration of NBAFS. This land was used as an active bombing range in support of Grenier Field at nearby Manchester, NH, until 1956. On 1 October 1959, the 6594th Instrumentation Squadron was activated at NBAFS. The squadron was assigned to the 6594th Aerospace Test Wing at Sunnyvale, California, and was a tenant of the 2235th Air Base Group, Grenier Field, where administrative and support facilities were maintained.

Satellite support operations began on 1 April 1960, using van-mounted equipment while permanent buildings were being constructed. By the summer of 1964, dual-satellite tracking, telemetry, and command capabilities were operating in permanent facilities at NBAFS. In March 1972, it was announced that Grenier Field would close in September of that year. All support facilities including supply, transportation, fire protection, and civil engineering were moved to NBAFS.

On 1 October 1979, the 6594th Instrumentation Squadron was re-designated as Detachment 2, Air Force Satellite Control Facility (AFSCF), Air Force Systems Command. On 1 October 1987, Detachment 2, AFSCF was re-designated as Detachment 2, 2nd Satellite Tracking Group and ownership was transferred from Air Force Systems Command to Air Force Space Command (AFSPC). On 1 November 1991, Detachment 2, 2nd Satellite Tracking Group was re-designated as the 23rd Space Operations Squadron. NBAFS currently provides launch, operation, and on orbit support for more than 170 DoD satellites. In addition, NBAFS supports NASA missions as well as NATO and other allied nation satellite operations.

NBAFS was used as an active bombing range in support of Grenier Field at nearby Manchester, NH, from the fall of 1941 until 1956. In addition to bombing activities, training and maneuver activities were performed on the property from 1956 until 2002, when the range officially closed.

The ESTCP study area, MU705, was one of the primary bombing/aerial targets used at NBAFS from 1942 to 1956. Unserviceable tanks, trucks, and half-tracks were used as strafing targets for machine guns, 20-mm cannons, and rockets.

4.3 MUNITIONS CONTAMINATION

MEC suspected to be present at MU705 include:

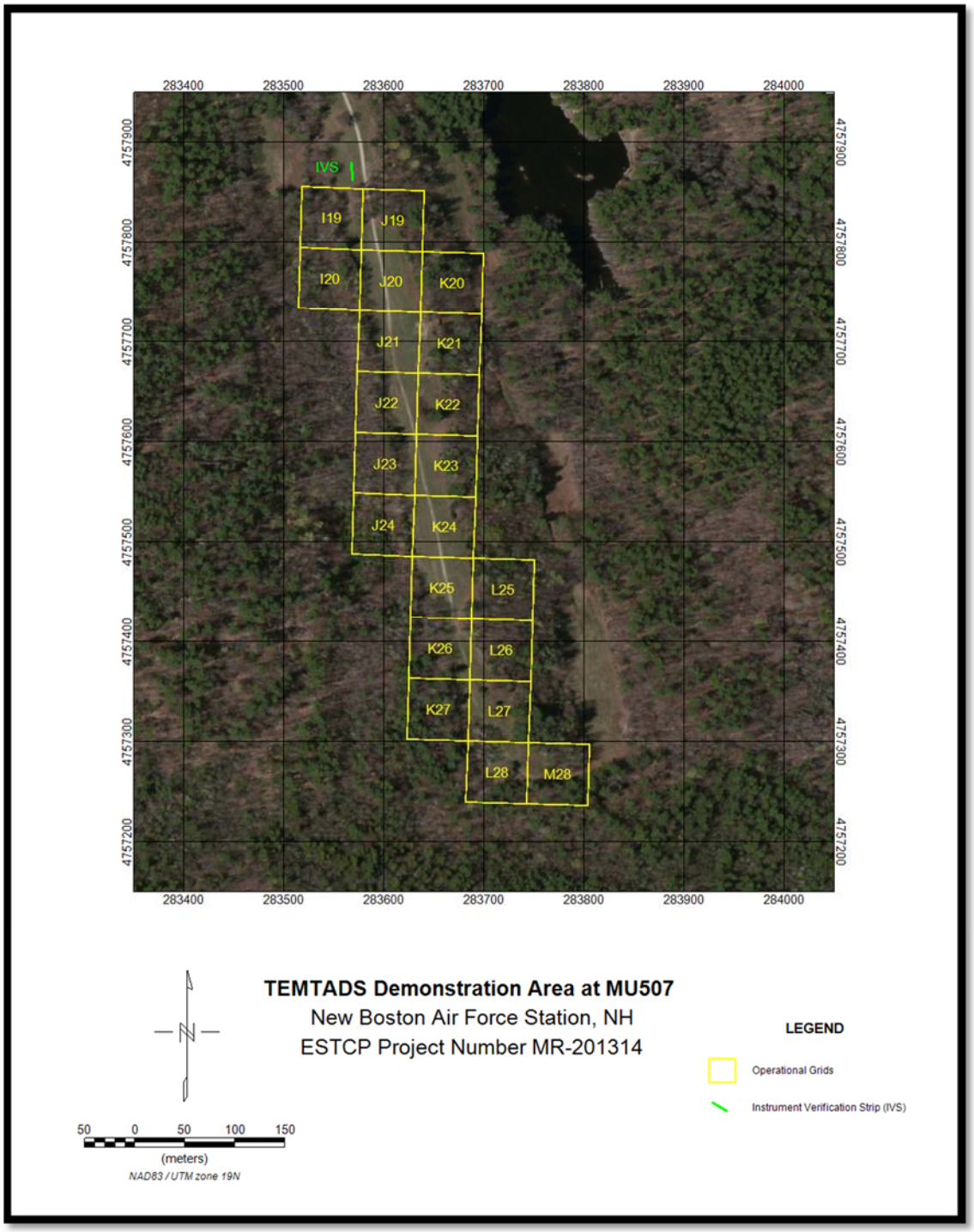
- 20-mm Projectile, Target Practice
- Practice Rockets, 2.25-inch and 5-inch
- HE Rockets, 5-inch
- Practice Bombs, 3-lb, 4.5-lb, 100-lb, 500-lb, and 1,000-lb
- General Purpose HE Bomb, 100-lb
- HE Depth Bomb, 325-lb and 350-lb
- M69 Incendiary Bomb

- Photoflash Bomb, M46

4.4 SITE CONFIGURATION

The general site setup and grid system where dynamic TEMTADS 2x2 surveys were performed at the site are shown on **Figure 4-1**. A total of approximately 6.1 acres were surveyed (the specific areas of which are shown on **Figure 5-2**). The cued investigations were only performed on a subset area of the site because of the high density of geophysical anomalies detected in the subsurface far exceeded the budgeted scope for cued investigations (1,500 anomalies).

Figure 4-2. TEMTADS Demonstration Area at MU507



5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The objective of this program was to demonstrate a methodology for the use of classification in the munitions response process. The three key components of this methodology were collection of high-quality geophysical data and principled selection of anomalous regions in those data, analysis of the selected anomalies using physics-based models to extract target parameters such as size, shape, and materials properties, and the use of those parameters to construct a ranked anomaly list. Each of these components was handled separately in this program.

Dynamic detection data were processed, and anomalies were selected and subsequently cued. Individual cued data sets were processed using existing routines in UX Analyze to extract target parameters.

5.2 PRE-DEMONSTRATION ACTIVITIES

Pre-demonstration activities included:

5.2.1 Survey of Historical Records

Historical information on this site has been referenced in the NBAFS Draft Final Remedial Investigation Report.

5.2.2 First-order Navigation Points

Two first-order survey monuments were established at the site by ESTCP prior to CH2M HILL's operations and were used by CH2M HILL for all positioning during the project. Their labels and coordinates are provided in **Table 5-1**.

Table 5-1. Geodetic Control Locations

ID	Latitude	Longitude	Elevation NAVD88 (m)	Northing (m)	Easting (m)	Ellipsoid Height (m)
ESTCP1	N42º56'21.11479	W71º39'05.78509	223.880	4757474.528	283653.228	196.375
ESTCP2	N42º56'29.14740	W71º39'07.71415	217.755	4757723.704	283617.324	190.252

5.2.3 Surface Clearance

A surface clearance of the demonstration area was conducted as part of the Remedial Investigation completed in 2012**.**

5.2.4 Seeding

CH2M HILL placed 110 seeds within the demonstration site area in accordance with the parameters laid out in the ESTCP Live Site Demonstration Seeding Plan (ESTCP, 2013). The seed locations and information were kept "firewalled" from the data collection and data processing teams. Each flagged location was swept with a Schonstedt to ensure anomaly avoidance and a clean area for emplacement. A hole was dug using a "plug" technique (removing a "plug" of topsoil for replacement upon filling the hole) to hide any visual indications of seed placement. Seeds were placed at the locations and depths provided by the ESTCP Program office. Physical characteristics of each seed were recorded onto a whiteboard and placed alongside the excavated hole and photographed. A professional land surveyor, GeoMetrics GPS, Inc., was employed to record the locations of the seeds using a Real-Time Kinematic (RTK) GPS. A comprehensive list of seed locations and burial information, including associated photographs, was provided to the ESTCP Program Office.

5.2.5 IVS and Training Pit

A geophysically 'quiet' area near the demonstration area was located by the UXO tech using handheld detectors. This location was used to establish an IVS for pre-survey and daily verification of proper sensor operation and functionality. 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**.

Figure 5-1. Schematic of IVS established at New Boston Air Force Station

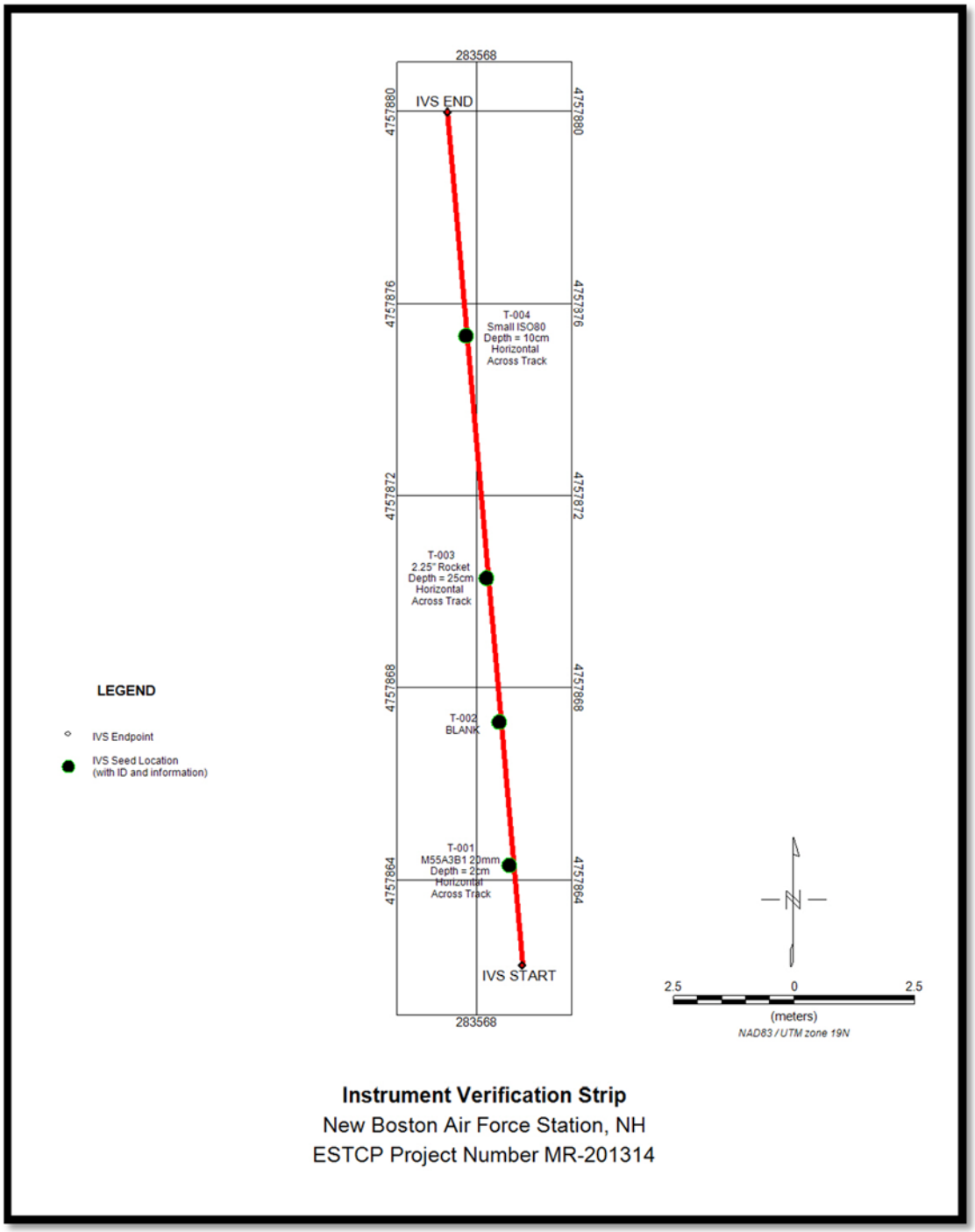


Table 5-2. Details of the Instrument Verification Strip

Item ID	Description	Easting (m)	Northing (m)	Depth (cm)	Inclination	Azimuth (° clockwise from N)
T-001	M55A3B1 20-mm	283568.673	4757864.312	2	Horizontal	Across Track
T-002	Blank Space	283568.46	4757867.286	N/A	N/A	N/A
T-003	2.25-inch Rocket	283568.197	4757870.292	25	Horizontal	Across Track
T-004	Small ISO80	283567.771	4757875.322	10	Horizontal	Across Track

A test pit / stand was established adjacent to the IVS and was used to collected signatures of a subset of TOI expected to be found at the site. Items for which static test data were collected are detailed in **Table 5-3**. The data from these measurements were added to the UX Analyze library used for the cued data analysis.

Table 5-3. Test Stand Items and Orientations

Item ID	Depths (cm)	Orientations
Small ISO80	2, 10, 20, 30	Horizontal, Vertical, 45°
20-mm ATC Projectile	2, 5	Horizontal, Vertical, 45°
2.25-inch Rocket	2, 5	Horizontal, Vertical, 45°
2-inch x 1/2-inch Pipe Nipple with Cap (20-mm surrogate)	5, 10, 15	Horizontal, Vertical, 45°
20-mm Shell Casing	5, 10	Horizontal, Vertical, 45°
Ground Signal Flare	5, 10, 15	Horizontal, Vertical, 45°
M102A1 Fuze	15	Horizontal, Vertical, 45°
M83 Smoke Grenade	10, 15	Horizontal, Vertical
M8 Practice Land Mine	10, 15	Horizontal, Vertical
M120 Fuze	10, 15, 20	Horizontal, Vertical
M103 Fuze	15, 20	Horizontal, Vertical
3-1/2-inch Rocket Warhead, Motor and Fuze	20	Horizontal
3-1/2-inch Rocket Warhead	15, 20	Horizontal, Vertical, 45°
3-1/2-inch Rocket Motor and Fuze	15	Horizontal, Vertical, 45°

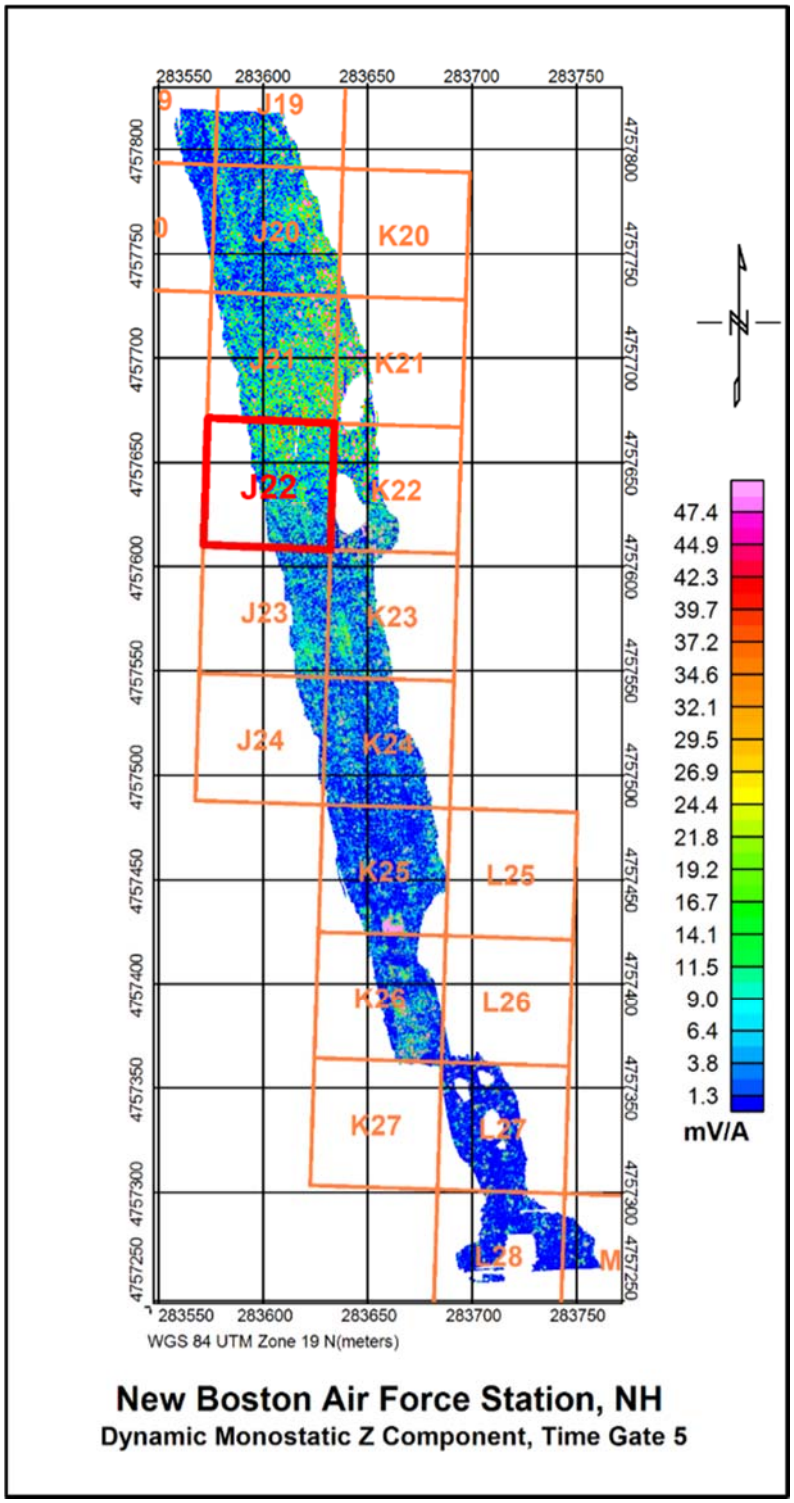
5.3 DATA COLLECTION ACTIVITIES

5.3.1 Dynamic Data Collection

Dynamic detection surveys were performed with the TEMTADS 2x2 over the course of 11 survey days during the time period from 18 July to 14 August 2013 (during this time period there were a

number of no-collection days due to equipment failures as well as weather delays and non-worked weekends). The positions of each measurement are determined using an RTK GPS antenna mounted at the center of the array, coil geometry relative to the GPS antenna, and the platform attitude (pitch, roll, and yaw) derived from the IMU. CH2M HILL's field team used ropes and flagging to perform data collection at a line spacing of 60 cm, which provided an overlap coverage of 20 cm to reduce the chance of data gaps. **Figure 5-2** shows a mosaic of the data collected at the site.

Figure 5-2. Overview of dynamic survey data collected at NBAFS and highlighted location of Grid J22 (the grid in which cued surveys were performed)

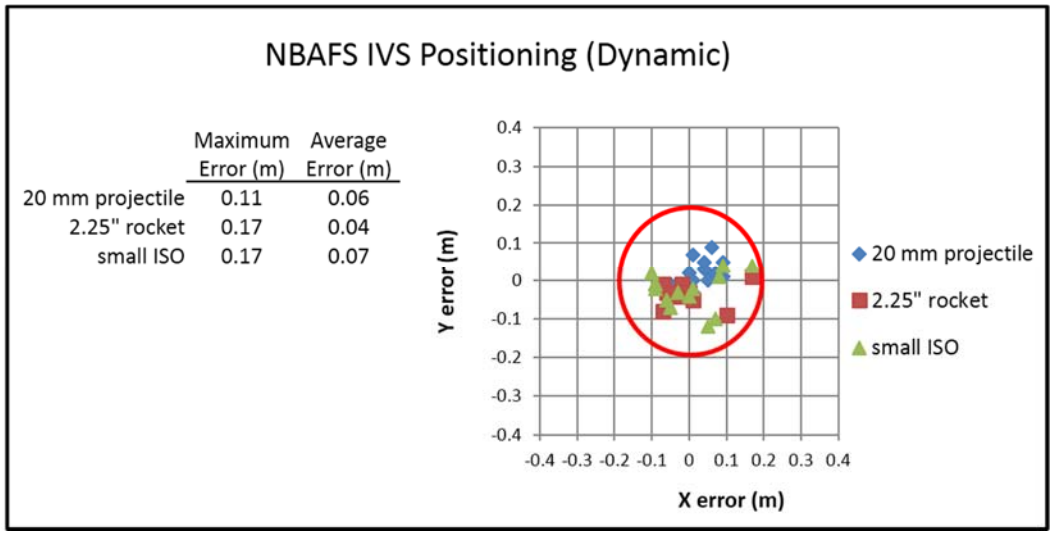


5.3.2 Dynamic Data QC

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.

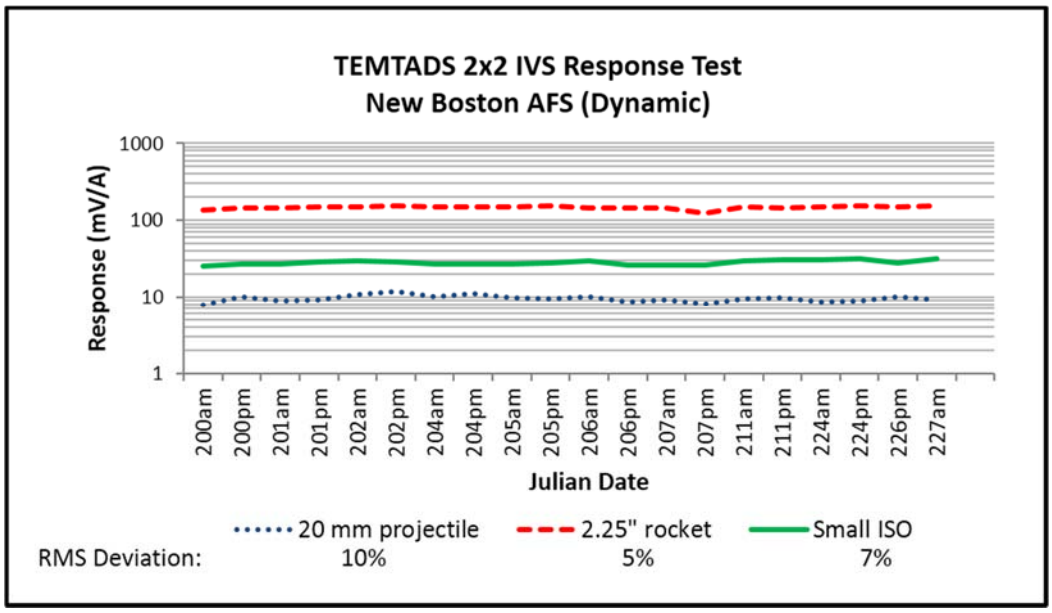
The positions were derived from the dynamic monostatic, Z-component response amplitude using Geosoft's automatic peak picking algorithm. **Figure 5-3** presents the position errors (relative to the ground truth) for each of the IVS items. The errors are within the stated objective of 0.2m (objectives presented later in **Table 6-1**).

Figure 5-3. Dynamic IVS survey positioning results



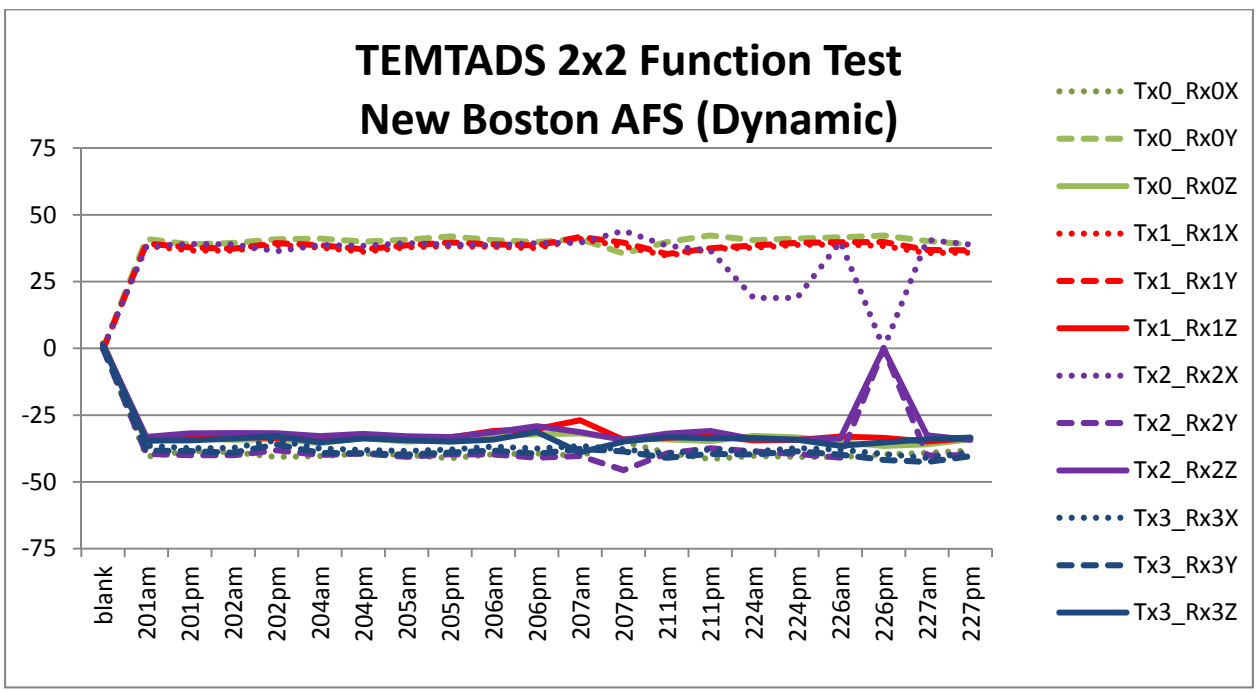
The response amplitude values were also derived using the automatic peak detection algorithm and are presented in **Figure 5-4**. The variability of these values were within the stated objective of 20% root mean square (RMS).

Figure 5-4. Dynamic IVS survey response amplitude results



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 an industry standard object, 1.5-inch x 4-inch, schedule 80 thickness pipe nipple (Small ISO80) on the top of the array housing. The function test results are presented on **Figure 5-5**.

Figure 5-5. Dynamic survey sensor function test results.



These tests identified a failure of the Rx2X coil on day 224 and failures of the Rx2 cube (X,Y and Z components) coil on day 226. The affected data were noted in the data delivery package. The decision was made to not re-acquire data because the effect on the results would be minimal.

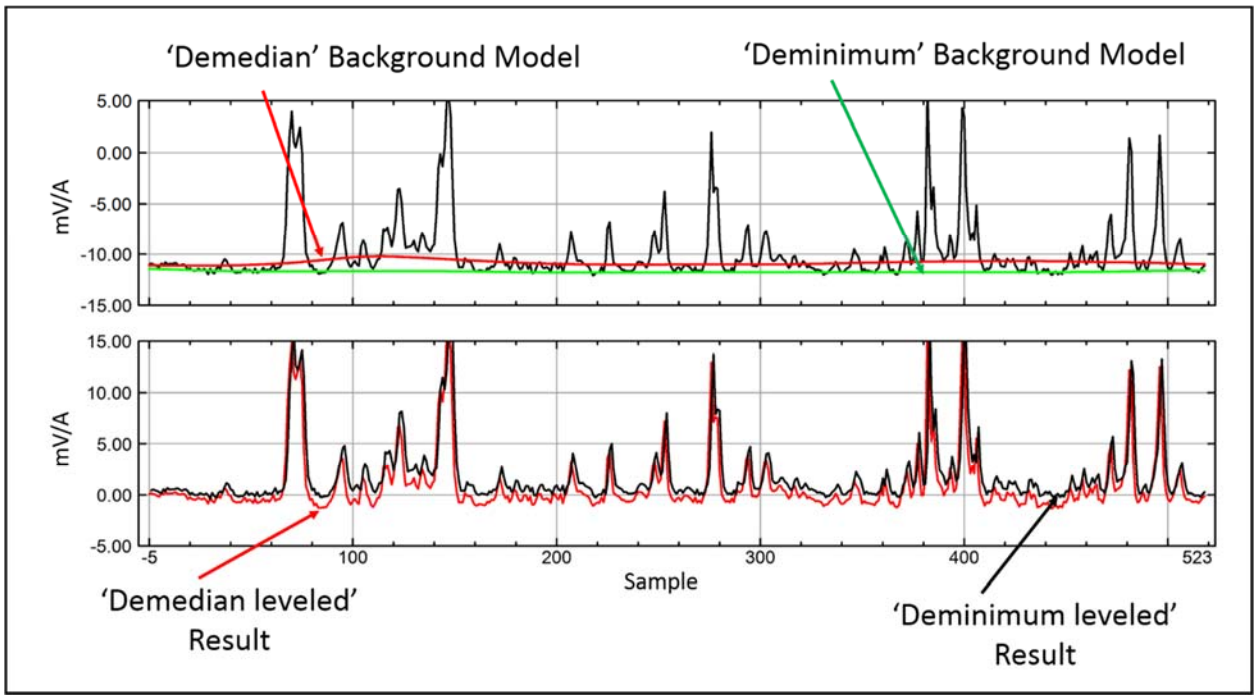
5.3.3 Dynamic Data Processing/Analysis

The raw instrument data files comprised of raw sensor data, RTK GPS data, and IMU measurement data converted to *.csv format using NRL's ConvertTEMTADS data conversion application for import into Geosoft UX Analyze (UXA) advanced analysis software environment. The *.csv file contains the sensor data merged with the RTK GPS and IMU data providing georeferenced positions for each TEMTADS 2x2 transmit/receive combination measurement.

The dynamic detection was performed using the amplitude response of the monostatic, vertical component measurements only. This approach is analogous to standard EM61 detection surveys with the main difference being that the data are much more dense and precise, providing a much higher resolution data set. Dynamic detection data were imported into the Geosoft UX-Analyze Advanced module for processing and analysis. Individual sensor data were assigned coordinates based on sensor offset and IMU data relative to the center mounted RTK GPS location. Positioned data were then exported to a located sensor database for data levelling and target selection.

Dynamic detection data were levelled by deriving a background model (comprised of long wavelength signals due to spatially stable soil response and sensor 'zero level' drift) and subtracting this model from the raw data to derive a levelled data set. Due to the anomaly density encountered, typical demedian filters used to derive the background model were not appropriate; as a result, the model was derived using a deminimum filter where the minimum over a large moving window is calculated and then low-pass filtered to remove high frequency artifacts. **Figure 5-6** shows example results of both filters on the raw data.

Figure 5-6. Dynamic survey background removal. Raw data are shown in black on top profile.



The final, leveled data for each grid were interpolated to grid nodes evenly spaced at 0.05 m using the Geosoft Oasis minimum curvature gridding routine. The interpolated Geosoft grid (GRD) files were mosaicked to create a full site GRD file from which anomaly selection was performed.

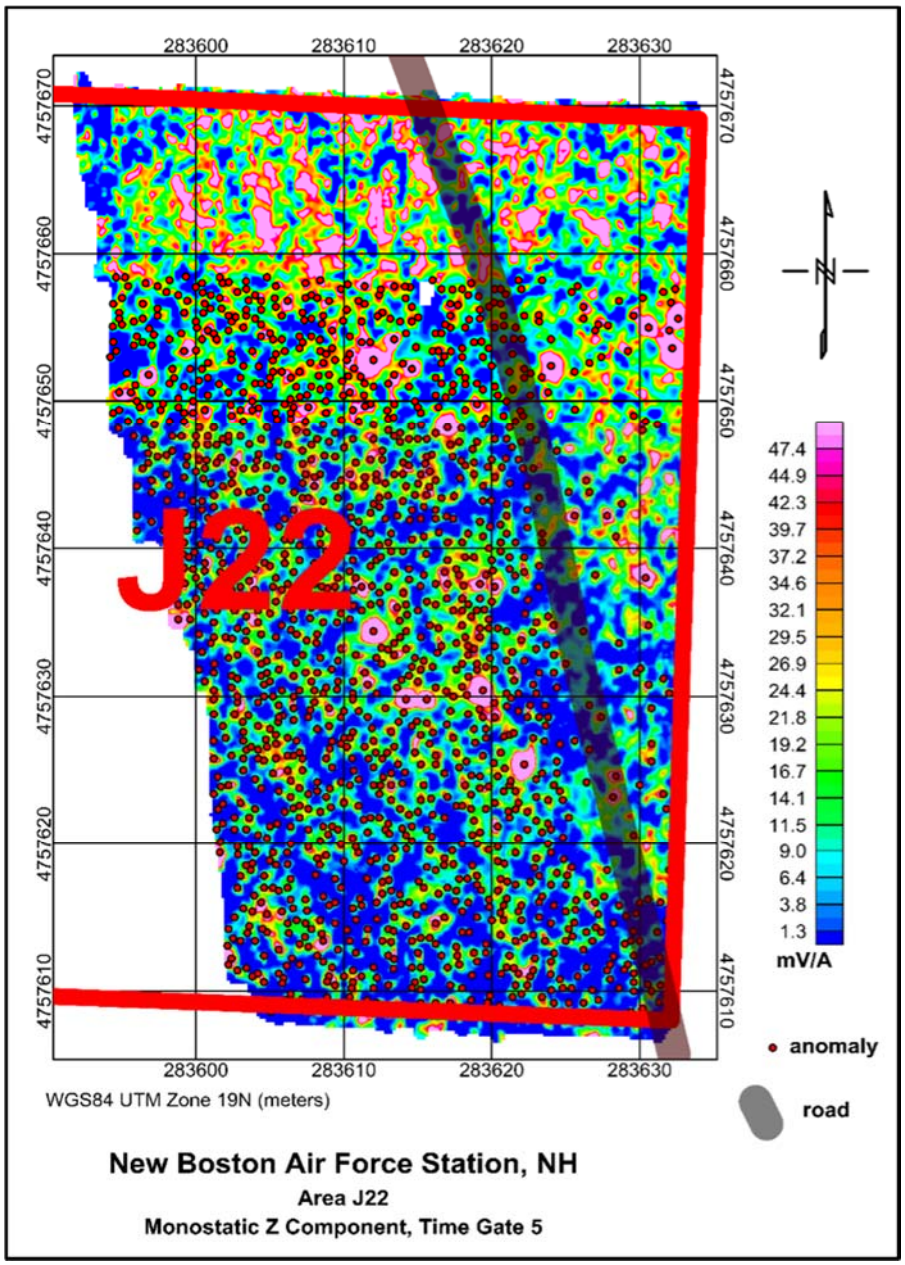
CH2M HILL provided raw and preprocessed data to the ESTCP Program Office for archiving in the form of *.tem, *.csv and Geosoft format databases (*.gdb). In consultation with the Program Office, CH2M HILL identified anomalies in the MU507 dynamic detection dataset. Response amplitude anomalies were selected from the full site GRD using the Geosoft Blakely grid peak detection algorithm. The cut-off threshold was 2.3 millivolts per ampere (mV/A). All anomaly selections were manually reviewed by the processing geophysicist and manual additions or deletions were performed where required. The threshold was validated by analyzing dynamic data collected over items buried in the test pit prior to the dynamic survey of the demonstration area. The test pit items included 20-mm projectiles (the smallest TOI expected at the site) at various depths and orientations to determine relevant system response values. Site- and system-specific noise information derived from sample survey data were used to validate the proposed anomaly selection amplitude threshold.

5.3.4 Cued Data Collection

After collection and analysis of the dynamic TEMTADS data were complete, the ESTCP Program office selected a subset of 1,500 anomalies (out of a total of 18,373 anomalies detected by the

dynamic survey) for cued interrogation. This down-selection was made to keep the project within its original scope (the anomaly density was an order of magnitude higher that was originally anticipated). The selected anomalies were located within Grid J22 (**Figure 5-7**). Most of the anomalies were within the region located west of the road and east of the forested region (the edge of the survey area). A small number of anomalies were located east of the road – these were selected primarily to include some blind seeds that otherwise would not be have been investigated.

Figure 5-7. Locations of anomalies selected for cued data collection.



Cued surveys were performed with the TEMTADS 2x2 over the course of 23 days from 1 August (Julian Day [JD] 213) to 23 August (JD 235), 2013. 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 data were transferred daily to the data analyst for quality control (QC)/analysis.

5.3.5 Cued Data QC

The quality control (QC) implemented throughout the cued data acquisition included the following:

- IVS measurements
- Function tests
- Transmit current and receiver decay monitoring
- Field inversion monitoring
- Recollection where horizontal target location was offset by more than 40cm

Throughout the course of the cued data acquisition, 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 parameter (source position) and intrinsic parameter (source betas) results were monitored and recorded. These results are presented in **Figures 5-8** and **5-9**. The values obtained were within the stated limits, with the exception of one of the IVS positions. On the final measurement of 8 August (JD 220) the GPS base station battery failed, resulting in an inaccurate position location for the last of the three emplaced items. Because this failure happened after the day's data collection, it had no adverse implications for the usability of the day's data.

Figure 5-8. Cued data IVS dipole fit position results.

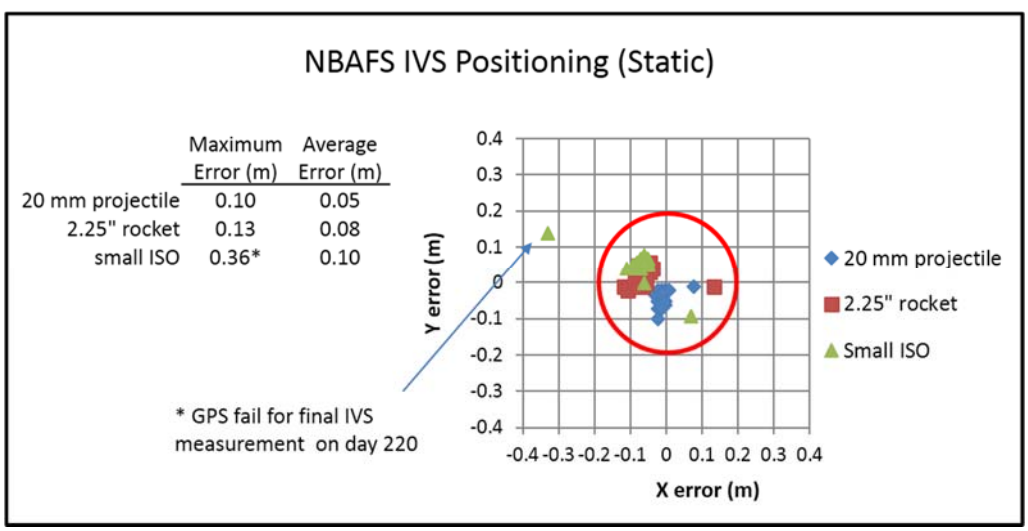
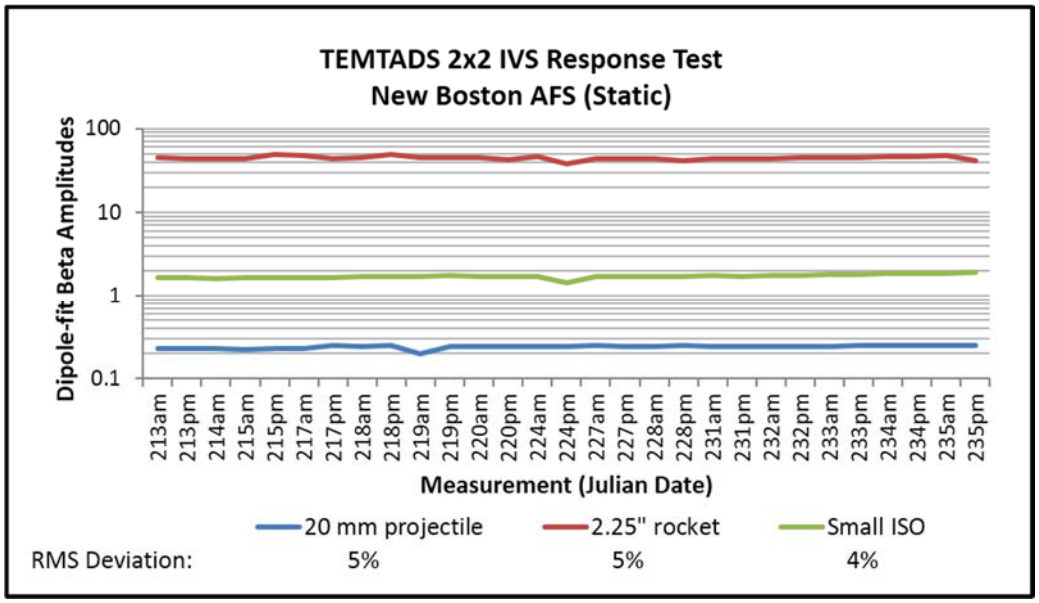
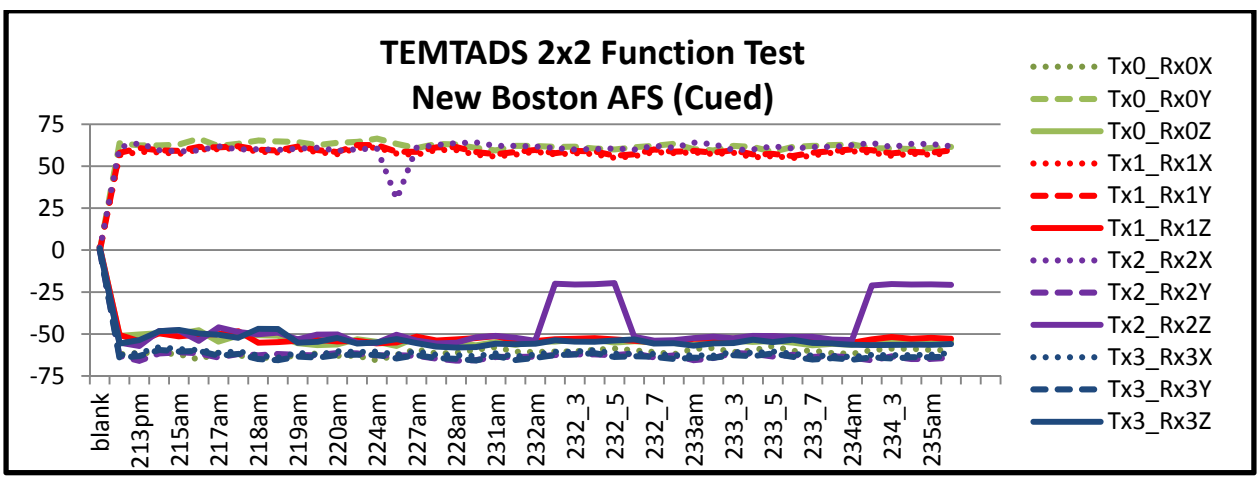


Figure 5-9. Cued data dipole fit β amplitude results



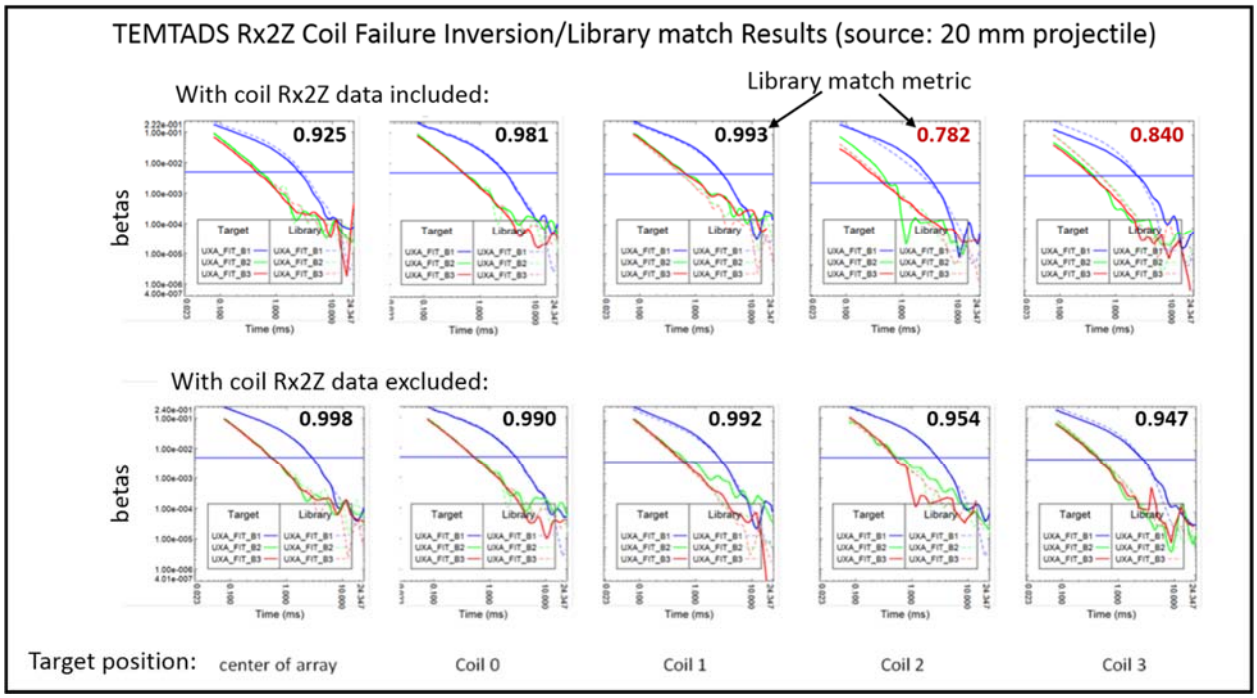
In addition to the twice-daily IVS, in-field sensor functionality tests were performed throughout each survey day to confirm that the TEMTADS system components were functioning within project specifications. Sensor function tests were performed during each background data collection event. The sensor function test results are shown on **Figure 5-10**. These tests identified a failure of the Rx2X coil on JD 224 and failures of the Rx2Z coil on JDs 232 and 234-235 (11, 13, 14 August 2013).

Figure 5-10. Cued data function test results.



The effect of the missing data was tested and assumed to be minimal as long as the failed data were rejected from the inversion. This is illustrated by **Figure 5-11**. This figure presents inversion results for a 20-mm target located at 5 positions under the sensor (center and under each coil) with the Rx2Z coil inoperable. On the top row the bad data are included in the inversion, and corrupt the inversion results as evidenced by the lower library match values. On the bottom row the Rx2Z data are excluded from the inversion and the inversion results are accurate. The affected data were noted in the data delivery package.

Figure 5-11. Effect of missing Rx2Z on inversion/classification results for a 20-mm projectile located at 5 different positions under the sensor (under the center of the array and under each coil).



5.3.6 Cued Data Processing/Analysis

Cued data were imported into the Geosoft UX-Analyze Advanced module for data QC and inversion modeling. The data were levelled using background data collected at frequent time intervals over a nearby anomaly-free background location. 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.

Parameter estimation was performed using the Geosoft UX-Analyze Advance module. Target data were inverted using both single-source and multi-source dipole response models to estimate target parameters. The principle parameters of interest for use in classification of the targets were the three polarizabilities (β_1, β_2, and β_3) estimated for each target by UX-Analyze. In addition to

estimates for the three βs for each target, an estimated location and depth was also returned by UX-Analyze for each target during inversion.

CH2M HILL provided the raw data (e.g. *.tem and *.gps), and digital as well and analog field notes to the ESTCP Program Office for archiving.

5.4 INTRUSIVE ACTIVITY AND PROCEDURES

CH2M HILL performed intrusive operations from 28 August through 24 September 2013. All prosecuted targets were investigated and documented according to the procedures outlined in the *Intrusive Investigation Data Collection Instructions*. These included the following:

- **Reacquisition of targets**. Targets selected for intrusive investigation were reacquired using a Trimble RTK GPS marked in the field using PVC pin flags.
- **Intrusively investigate the anomaly.** Anomalies were excavated to 30 cm below the expected depth below ground surface (BGS), within a 50 cm halo from the marked out anomaly location.
- **Identify recovered item**. All items recovered were inspected by the Unexploded Ordnance Safety Officer (UXOSO) and Senior UXO Supervisor (SUXOS) to ensure that each item was properly identified and properly documented.
- **Munitions Response Site Information Management System (MRSIMS) Data Entry/Whiteboard and photo**. Field observations of each recovered item were entered into CH2M HILL's MRSIMS field tablets. The exact location and depth of each item was recorded using a Trimble RTK GPS. Required information was written onto a whiteboard and a photo was taken with the item.
- **Bag and label item**. All recovered items were placed in ziplock bags and labeled.
- **Post-dig clearance**. Before declaring a dig complete, each area was swept with a Schonstedt magnetometer to determine if any additional items remained
- **Backfill hole**. Once the excavation was declared clear, the hole was backfilled to grade.

As NBAFS is included in the National Register of Historic Places (NRHP), all intrusive investigations were carried out in compliance with the Memorandum of Agreement (MOA) between the U.S. Air Force and the New Hampshire Historic Preservation Office (U.S. Air Force, 2013). Archaeological monitoring was performed by a certified archaeologist from CH2M HILL's Archaeology subcontractor, Landmark Archaeology, Inc., and any artifacts of significance that were recovered during intrusive investigations were properly documented and a report provided to the New Hampshire Division of Historic Resources (Landmark Archaeology, Inc., 2014).

5.5 INTRUSIVE INVESTIGATION RESULTS

The initial master dig list was comprised of the same 1,500 anomaly locations as were used for the cued TEMTADS investigations. After a review of several weeks of digs, the dig program was halted due to the fact that 70% of the intrusive investigations resulted in a TOI. Advanced classification is only useful if the costs associated with its implementation are less than the cost

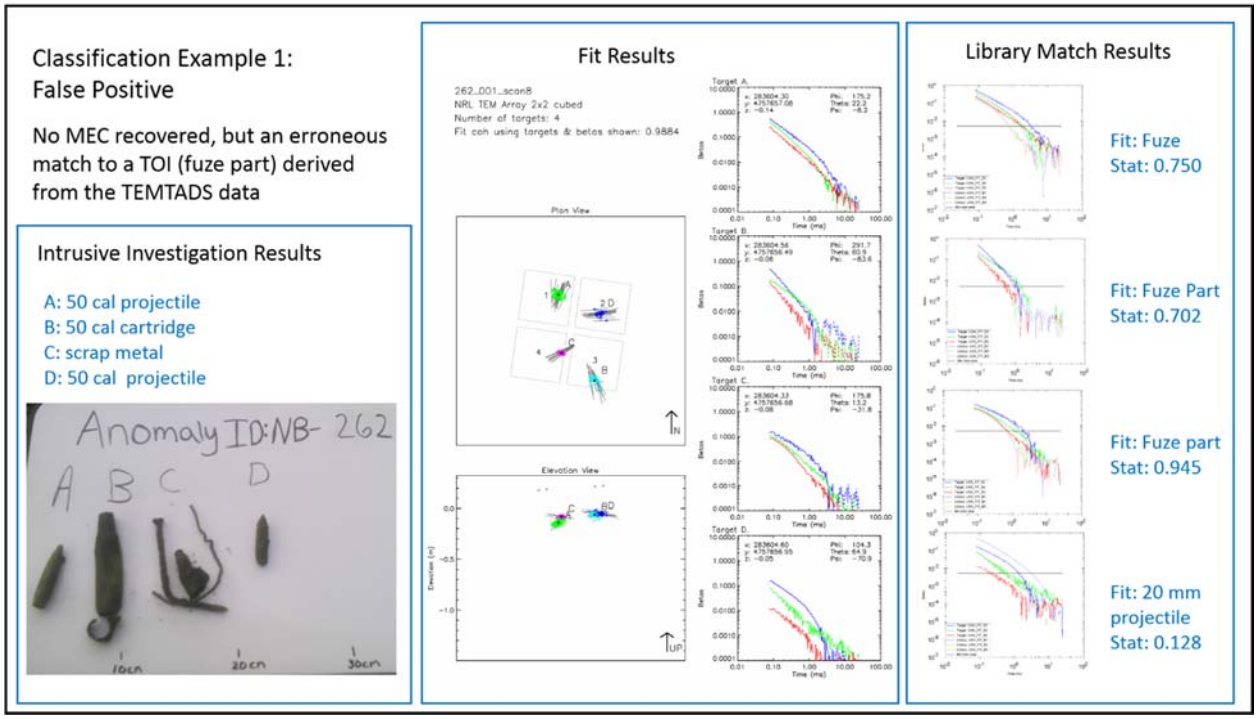
savings realized from the reduction in the required number of intrusive investigations. This condition is only met to the extent that the percentage of TOI relative to non-TOI buried at the site is small (unless the cost per dig is very high). With 70% of the digs resulting in TOI, the proposed classification methodology would not be cost effective. Accordingly the decision was made to end the intrusive investigations.

5.6 ANALYSIS OF TRAINING DATA

Upon initial review of the inversion results. A set of targets were selected for which the dig results would be requested to be used as 'training data' by the analyst. These data would be used to determine the source of any identified clusters of 'like signatures' as well as to inform the analyst with respect to the placement of decision thresholds in the prioritized list.

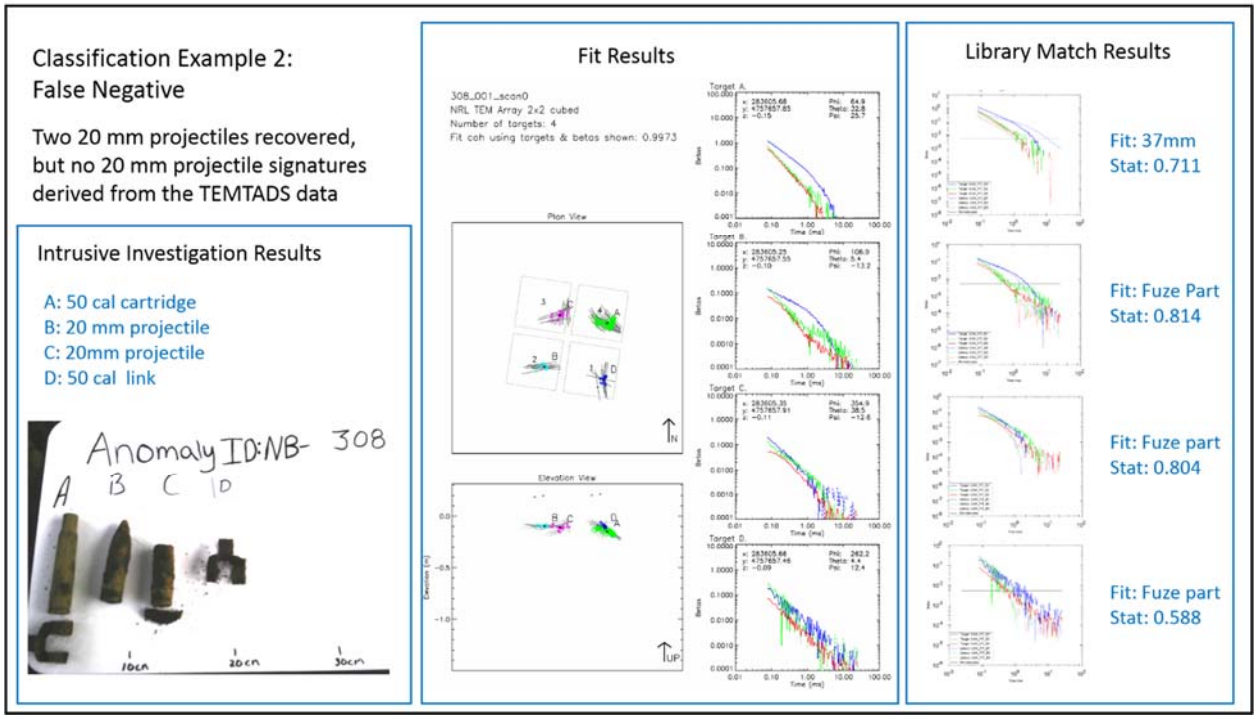
After receipt of the dig results for the requested flag locations, the decision was made to abandon attempts to classify the results. More than 40% of the training digs resulted in 4 or more discrete objects being found for a given flag location (a retrospective analysis of all of the dig results indicated that 33% of the digs resulted in 4 or more discrete objects). Comparison with the ground truth revealed that the multi-solver inversion routine was not able to consistently extract the correct signatures for the TOI at the site. **Figure 5-12** presents an example of a false positive finding where the derived signatures do not match the recovered sources, resulting in a non-TOI result being classified as a TOI. Although some percentage of false positives are expected, one of the goals of classification is to minimize these (and thus reduce the number of required intrusive investigations). The fact that the inversion results do not accurately represent the actual subsurface items is demonstrated by this figure.

Figure 5-12. Example of false positive classification results.



False negatives present a much more serious problem. An example of a false negative is shown on **Figure 5-13** where two 20-mm projectiles were recovered, but the inversion results for that flag location did not have a signature that was a good fit to these TOI. These signatures did fit to a 37mm but with a low fit metric that resulted in a non-TOI classification.

Figure 5-13. Example of 'False Negative' classification results.



In both of the examples shown, the multi-solver inversion fail to extract signatures consistent with the objects recovered. Qualitative analysis of the results indicates that the multi-solver results become unreliable when 4 or more targets are below the sensor. It bears mention that this was not a quantitative assessment nor does this observation support any generalized conclusions regarding the performance of the multi-solver. This observation only applies for the specific circumstances of this demonstration (sites with larger minimum TOI size might show a different result). Given that 33% of the intrusive investigations resulted in four or more recovered items and 70% of the excavations resulted in at least one TOI (thus the technology is assumed to be unsuitable at this site), further investigation into the performance of the multi-solver was not undertaken.

5.7 CLASSIFICATION

After review and analysis of the training data we were not able to find an approach that reliably derived accurate intrinsic parameters when there were more than three sources under the sensor; furthermore, the fact that 70% of the intrusive investigations resulted in TOI indicated that submission of a final prioritized list would add no value.

5.8 DELIVERABLES

The following deliverables resulted from the data collection at New Boston Air Force Station:

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.

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

Performance Objective	Metric	Data Required	Minimum Acceptable Criteria	Nominal Success Criteria	Result
Data Collection Performance Objectives					
Dynamic survey spatial coverage	Effective footprint coverage	Mapped survey data	95% coverage at line spacing of 60 cm with no gaps greater than 20cm (80 cm between adjacent line centers)	100% coverage at 60 cm line spacing	Pass – 100% of area surveyed at ≤ 60cm lane spacing
Along line measurement spacing	Point to point sample distance	Mapped survey data	95% ≤ 20 cm	98% ≤ 15 cm	Pass - >95% of mapped survey data < 20cm point to point sample distance
Detection of all targets of interest (TOI)	Percent of seed items detected	Seed item locations Geo-referenced anomaly list	100% of seeded items within a 50 cm halo	100% of seeded items within a 25 cm halo	Pass – 100% of seeded items detected within a 50 cm halo
Data positioning repeatability	Precision of dipole-fit derived extrinsic target features	Target fit positions from daily instrument verification strip (IVS)	Dynamic positions ± 20 cm	Dynamic positions ±10 cm	Pass
Sensor response repeatability (dynamic and cued surveys)	Precision of dipole fit derived intrinsic target features	Dipole-fit derived σs from daily IVS data	≤ 20% Root-Mean-Squared (RMS) variation in σ amplitudes	≤ 10% RMS variation in σ amplitudes	Dynamic: Pass – Amplitude RMS variation was <20% Cued: Pass –β Amplitude RMS variation was <20%

Performance Objective	Metric	Data Required	Minimum Acceptable Criteria	Nominal Success Criteria	Result
Cued interrogation anomaly coverage	Instrument position	Cued data	95% of anomalies where the center of the instrument is positioned within 40 cm of actual target location	100% of anomalies where the center of the instrument is positioned within 40 cm of actual target location	Pass
Data Analysis/Classification Performance Objectives					
Maximize correct classification of TOI	Number of TOI correctly identified	Ranked anomaly lists Scoring reports from Institute for Defense Analysis (IDA)	98% of all seeded targets 95% of all TOI	100% of all seeded targets 100% of all TOI	Fail – see discussion in section 5.2
Maximize correct classification of non-TOI	Number of false alarms eliminated	Ranked anomaly lists Scoring reports from IDA	Reduction of clutter digs required by >50% while retaining all TOI	Reduction of clutter digs required by >75% while retaining all TOI	In retrospect this was not achievable: 70% of all digs resulted in TOI.
Model results support classification decision	Number of anomalies classified as "Cannot Analyze"	Modeling fit coherence results	90% of targets have fit coherence > 0.80	95% of targets have fit coherence > 0.80	N/A – classification was not performed
Correct estimation of target parameters	Accuracy of estimated target locations for seed items	Modeled target parameters Results of intrusive investigation	X,Y < 15 cm (1σ) Z < 10 cm (1σ)	X,Y < 15 cm (1σ) Z < 10 cm (1σ)	Fail – see discussion

6.1 DYNAMIC SURVEY SPATIAL COVERAGE

The TEMTADS dynamic detection survey was designed to provide 100% coverage of the investigation area. A planned transect spacing of 60cm was used to ensure sufficient overlap of the 80 cm sensor swath footprint between traverses. Prior to the dynamic detection survey in each grid, 1 m wide survey lanes were established using ropes held in place by non-metallic tent stakes. This ensured consistent spacing between transects and even coverage of the investigation area.

The success criteria for this objective was 95% coverage of the investigation area with no gaps greater than 80 cm between adjacent lines. This objective was achieved, as no gaps greater than 80cm were observed in the data, and complete coverage of the investigation area was achieved.

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 criteria for this objective was for 98% of mapped data points to be within 15 cm of the along-line neighboring data point, and for no more than 5% of the data points to be outside of 20 cm from the along-line neighboring data point. This objective was achieved, as no along-line spacing greater than 15 cm was observed in the data.

6.3 DETECTION OF ALL TOI

This objective involved the detection of targets of interest during the dynamic detection survey. This objective was verified using a blind seeding program. Prior to the dynamic detection survey, 110 seed items were buried within the investigation area. These seed items consisted of Small ISO80s, ½-inch x 2-inch 20-mm simulants, ½-inch x 3-inch 20-mm simulants, and inert 20-mm projectiles. 20-mm and 20-mm simulants were buried at depths up to 15cm, and Small ISO (Schedule 80) were buried at depths up to 30cm as documented in the Demonstration Seed Plan.

6.4 DATA POSITIONING REPEATABILITY

This objective involved twice daily surveys of the seeded items in the IVS to show that the data positioning was repeatable to better than 0.2 m. The positions of the seeded items in the dynamic survey were determined as the locations of the amplitude response anomaly peaks associated with the seeded items. All detections were within the specified 0.2 m tolerance. The results are summarized in **Table 6-2**.

Table 6-2. Dynamic IVS positioning results

Seed Item	Maximum Error	Average Error
M55A3B1 20-mm	0.15	0.06
2.25-inch Rocket	0.17	0.04
Small ISO80	0.17	0.07

The positions of the seeded items surveyed during the cued investigation were derived from the dipole fit analysis of the measured data. These results are summarized in **Table 5-3**. One of the results exceeded the stated tolerance, but the cause for the exceedance was a base station battery failure that occurred just before the very last measurement of the day (and after the other two IVS items had been successfully surveyed at the end of the day). Thus the failure was deemed to have no adverse implications for the usability of the day's data.

Table 6-3. Static IVS positioning results

Seed Item	Maximum Error	Average Error
M55A3B1 20-mm	0.10	0.05
2.25-inch Rocket	0.13	0.08
Small ISO80	0.36	0.10

6.5 SENSOR RESPONSE REPEATABILITY

This objective involves the repeatability of sensor response amplitude over the course of the project for each seed item buried at the IVS. Consistent sensor responses can only be obtained if the sensor is functioning properly. Sensor response amplitudes for each IVS data collection event were tracked throughout the life of the project for both the dynamic and cued phases of data collection. The objective was considered to be met if there was <20% RMS deviation in response amplitudes for dynamic and cued IVS results.

Results for the dynamic data responses are detailed in **Table 5-4**. The largest RMS deviation was for the 20-mm, at 9.9%, which means that this objective was achieved for the dynamic data phase of the demonstration.

Table 6-4. Dynamic Data Sensor Response Results

Seed Item	Average Response (mV/A)	% RMS Deviation
M55A3B1 20-mm	9.58	9.90
2.25-inch Rocket	147.24	4.55
Small ISO80	28.42	6.50

Results for the cued β Amplitudes are detailed in **Table 5-5**. β amplitudes for each IVS seed item were within the 20% RMS tolerance established for this performance objective.

Table 6-5. Cued Data Sensor Response Results

Seed Item	Average β Amplitude	% RMS Deviation
M55A3B1 20-mm	0.24	4.75
2.25-inch Rocket	44.25	4.61
Small ISO80	1.69	3.25

6.6 CUED INTERROGATION OF ANOMALIES

This objective requires that 95% of anomalies result in having the target fit location within a 0.4 m horizontal radius from the center of the array. This is required to ensure that the target is properly

energized along its three principal axes. This metric was not achieved at NBAFS – only 75% of anomalies resulted in target fit locations within the stated radius. This was due to the fact that the majority of the measurements were made at locations with multiple targets in view. The field team used a single target inversion routine to reposition the sensor if the target was not within the specified radius. In a multi-target scenario, the real-time feedback is imprecise and there is no way to ensure that the most likely target of interest will be within the 0.4 m radius of the sensor.

6.7 MAXIMIZE CORRECT CLASSIFICATION OF TOI

Not applicable (see classification discussion above).

6.8 MAXIMIZE CORRECT CLASSIFICATION OF NON-TOI

Not applicable (see classification discussion above).

6.9 MODEL RESULTS SUPPORT CLASSIFICATION

This objective requires that the model derived during the inversion process must match the observed data to within a correlation of 0.8. This metric, provided by UX Analyze as the 'fit coherence' (UXA_fit_coh) is an output of the dipole analysis inversion routine. 98% of the inversion results resulted in fit coherence greater than 0.8.

6.10 CORRECT ESTIMATION OF TARGET PARAMETERS

This objective involved assessing the accuracy of the derived target parameters by comparing the seed ground truth with the positions derived from the inversion process. There were very few seeds that were investigated (due to the fact that the seeds were originally distributed over the entire site and only a small section of the site was subject to cued investigation). Given the failure of the derived signatures to accurately predict the anomaly sources when more than 3 sources were recovered and the fact that 33% of the flags had 4 or more sources recovered, it was determined that any analysis of performance against the few emplaced seeds that were measured would add no value to the demonstration.

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 was obtained during the demonstration that will aid in establishing realistic costs for implementing the technology and comparing it to potential alternative technologies. Because the technology demonstrated was found to be unsuitable for the site conditions encountered, a comparison against potential alternatives is moot (because the technology demonstrated is not a viable alternative). The cost to perform the surveys and intrusive investigations for the NBAFS site are far higher than other demonstration projects as a result of the high density of metallic items in the subsurface, on-site archaeological oversight required, and a high rate of quality control involvement in the project. The costs are not typical of other

geophysical classification demonstrations and projects and could likely be consider an outlier, but are nevertheless a useful point of reference for sites with challenging constraints.

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 HILL for this demonstration. The cost per acre (for dynamic data collection) and per anomaly (for cued data collection) do not include those costs.

Table 7-1. Costs for TEMTADS 2x2

Cost Element	Tracked Data	Cost/Quantity
Mobilization/Site Setup/Surface Sweep/Seeding/Surveyor/Archaeological Oversight/Demobilization		
Surface Sweep/ Seeding/ Archaeological Oversight	Costs for planning, mobilization, general site setup, shipping of equipment, surface sweep, QC seeding, surveyor services, onsite archaeologists, and demobilization.	$92,000
Dynamic TEMTADS Survey Costs		
Dynamic Survey Data Collection and Processing Costs	Dynamic detection survey (6 acres), including: Field labor (three geophysicists/geophysical technicians, one UXO technician), equipment setup, equipment rentals, Instrument Verification Strip setup and data collection, data processing, per diem, archaeological oversight	$57,000 ($9500/acre)
Cued TEMTADS Survey Costs		
Cued Survey Data Collection	Reacquisition of anomalies for cued surveys, cued surveys (1500 anomalies), including: Field labor (three geophysicists/geophysical technicians, one UXO technician), equipment setup, equipment rentals, Instrument Verification Strip setup and data collection, per diem, archaeological oversight	$110,000 ($73.31/anom)
Cued Survey Data Processing	Processing of cued data, including several site visits for task kickoff and quality control purposes	$64,000 ($42.66/anom)
Intrusive Investigation		
Intrusive Investigation Costs	Reacquisition of anomalies and all UXO team related costs related to the intrusive investigation and documentation of discoveries per the ESTCP intrusive investigation instructions	$228,000 ($598.16/anom)

8.0 IMPLEMENTATION ISSUES

The underlying premise of geophysical classification is that remediation costs can be reduced by classifying an anomaly source as TOI or non-TOI, and limit the intrusive investigations to those anomalies that are potentially TOI. This premise assumes that the percentage of anomalies that are potentially TOI is sufficiently small and the cost savings associated with reducing the number of required excavations is greater than the cost of implementation of classification. Using generic assumptions of $50 per anomaly for classification (more typical than the costs experienced on the NBAFS project) and $200 per excavation (also more typical) as a starting point, a minimum dig reduction of 25% is required to offset the cost of classification (obviously any benefit realized would require more than a 25% reduction and would be directly proportional to the percent reduction). The intrusive results indicate that, even with perfect classification, the maximum dig reduction at the NBAFS site could only be 30%. Clearly classification does not offer the potential for cost savings at this site if 20-mm projectiles are included in the TOI list.

In addition to the percent of TOI, the number of sources encountered for each anomaly significantly impacted the usability of the results. Approximately 33% of the anomalies investigated resulted in more than three sources – under these circumstances the inversion results do not appear to accurately represent the ground truth. Additionally, there currently is no way to use the inversion results to reliably determine the number of sources, so there is no way to prove that the inversion results are valid when the anomaly density (and, by implication, source density) is this high.

9.0 REFERENCES

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Landmark Archaeology, Inc. 2014. Archaeological Monitoring in Support of ESTCP Program Demonstration Project, New Boston Air Force Station, Hillsborough County, New Hampshire. December.

U.S. Air Force. 2013. Memorandum of Agreement for Recovery of Significant Information Between the U.S. Air Force and the New Hampshire Historic Preservation Officer Pursuant to 36 CFR 800.6 Regarding the Interim Removal Action Clearance at New Boston Air Force Station, New Hampshire. 2008 & 2013.

APPENDIX A: POINTS OF CONTACT

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
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Dave Wright	CH2M HILL 18 Tremont Street #700, Boston, MA 02108	(978) 356-3962	Lead Geophysicist