

FINAL REPORT

Marine Towed Array
Underwater EMI Sensor Platform for Metallic Item Detection

ESTCP Project MR-201610

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ACRONYMS AND ABBREVIATIONS

1PPS	The 1-pulse-per-second synchronization signal output by GPS receivers
AGC	Advanced Geophysical Classification
AWG	American Wire Gauge
cDAQ	Compact Data Acquisition System
CONUS	Continental United States
DAQ	Data Acquisition System
EM3D	AGC data acquisition software from G&G Sciences
EM61	Cart-based, EMI geophysical sensor
EM68	Array EMI geophysical sensor
EMI	Electromagnetic Induction
EMI-SIB	EMI Sensor Interface Bottle
ESTCP	Environmental Security Technology Certification Program
GPS	Global Positioning System
GUI	Graphical User Interface
IMU	Inertial Measurement Unit
ISO	Industry Standard Object
IVS	Instrument Verification Strip
L1	Original GPS signal at the frequency 1575.42 MHz
LISO	Large ISO, Schedule 40, surrogate for a 105mm projectile
MagLog	Data acquisition software from Geometrics
miniMTA	A half-scale mockup of the proposed EMI array for the MTA
MPV	Man-Portable Vector, a man-portable G&G Sciences AGC system
MR	Munitions Response
MTADS	Multi-sensor Towed Array Detection System
MTA	Marine Towed Array
NRL	Naval Research Laboratory
QC	Quality Control
RDP	Microsoft Remote Desktop Protocol
RMS	Root-Mean-Square
R/V	Research Vessel
Rx	Receive
SERDP	Strategic Environmental Research and Development Program
sISO80	Small ISO, Schedule 80, surrogate for a 37mm projectile
SNR	Signal to Noise Ratio
TEM	Transient Electromagnetic
TEMTADS	Transient Electromagnetic – Multi-sensor Towed Array Detection System
TOI	Target of Interest
Tx	Transmit
UXO	Unexploded Ordnance
VIMS	Virginia Institute of Marine Science
XLISO	Extra-Large ISO, Schedule 40, surrogate for a 155mm projectile

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We would like to Dr. Douglas E. Humphreys and his team at Vehicle Control Technologies, Inc. for assistance in reactivating the MTA wing's inertial measurement unit and autopilot subsystem. David Wright of AGCPro provided important continuity of knowledge from the previous research and operation team. Dave George of G&G Sciences provided invaluable assistance in the modification of the G&G Science's cDAQ system to our application.

ABSTRACT

INTRODUCTION AND OBJECTIVES

The technological focus of this project is to replace the electromagnetic induction (EMI) sensor array originally designed for the Marine Towed Array (MTA), developed under Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) funding, with one based on advanced EMI electronics and sensor designs.

TECHNOLOGY DESCRIPTION

The MTA provides both marine electromagnetic and marine magnetic sensors for detection and mapping of underwater UXO. The MTA platform operates as an underwater, flying wing sensor array towed by a triple-hull pontoon boat. The MTA's EMI sensor array is based on older technology and additionally has never reached the full potential of the technology. We have replaced the MTA's original EMI electronics with modern, advanced EMI electronics and sensor loops to provide advanced geophysical classification (AGC) grade data to evaluate object detection and UXO / clutter classification performance in the underwater environment.

PERFORMANCE AND COST ASSESSMENT

The upgraded EMI array performs as well in salt water as it does on land. Transmit currents are lower than planned (8.3 vs 20 A), due to limitations in the plan to modify the original transmitter. Additionally, York River noise levels encountered experimentally are 2-3x larger than those seen in air, on land during our testing at Blossom Point. To improve SNR to the levels required to meet the project's design goals would require either or both: a) new transmitter loops with heavier gauge wire, or b) a new bipolar transmitter capable of using higher supply voltages.

IMPLEMENTATION ISSUES

The MTA's EMI array was successfully upgraded to incorporate a more modern, AGC-grade EMI data acquisition system, transmitter loops, and tri-axial receiver cubes. All existing MTA systems were successfully reactivated or replaced after years of storage. Notionally, there are no new implementation issues for the MTA. The MTA was and remains ideally suited for deployment in relatively flat-bottoms, open areas such as bays where munitions transfers occurred ship to ship.

PUBLICATIONS / PRESENTATIONS

1. "Dynamic Classification with the Marine Towed Array," Daniel A. Steinhurst; Glenn R. Harbaugh; Thomas H. Bell; Dean A. Keiswetter; Grace M. Massey; and David J. Wright, presented at the SERDP – ESTCP Symposium, December 3-5, 2019, Washington, DC.
2. "Advanced Geophysical Classification with the Marine Towed Array," Daniel A. Steinhurst; Glenn R. Harbaugh; Thomas H. Bell; Dean A. Keiswetter; Grace M. Massey; and David J. Wright, presented at the Fall 2017 AGU Meeting, December 15, 2017, New Orleans, LA.
3. "Updating the Marine Towed Array for Advanced Geophysical Classification," as part of the "Platforms for Underwater and Near-Shore Munitions Survey" Webinar, SERDP and ESTCP Webinar Series, #64, November 2, 2017.

EXECUTIVE SUMMARY

INTRODUCTION

Unexploded ordnance (UXO) is known to exist at a large number of underwater sites, and represents a significant and previously unresolved risk to human health and safety. Hindered by the combination of unfriendly survey conditions and other technological limitations, the Marine Towed Array (MTA) was originally developed with funding from the Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) to establish analogous capabilities to proven land-based UXO detection and classification systems to be applied to the underwater environment. The MTA prototype represented the foundation for the routine and systematic detection/classification of UXO in underwater environments. This effort was focused upon the design and integration of significant upgrades to the original MTA, whose performance metrics were projected to be significantly improved through innovative sensor designs and advanced electromagnetic induction (EMI) electronics.

OBJECTIVES

The objective of this project is demonstrate the UXO / clutter classification ability of an advanced EMI sensor system for underwater UXO sites. To achieve this objective, we have replaced the existing industry-standard EMI sensor array currently in the MTA with one based on advanced EMI electronics and sensor elements. The existing large transmitter loop was replaced with an interleaved array of three transmitter loops. The receiver loops were replaced with triaxial receiver cubes. Once installed, the performance of the new EMI system was demonstrated on two sets of emplaced targets of interest (TOI), where the TOI had been selected to explore the operational envelope of the new array.

TECHNOLOGY DESCRIPTION

Triaxial Receiver Cubes

The design of the TEMTADS/3D EMI sensors is based on the advanced Electromagnetic Induction (EMI) sensor developed by the U.S. Naval Research Laboratory (NRL). The single, vertical-axis receiver coil of the original sensor was replaced with a three-axis receiver cube. For this project, the triaxial receiver cubes are individually and separately packaged in waterproof enclosures, as shown in Figure E-1.

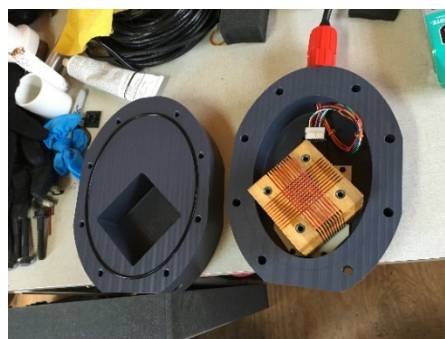


Figure E-1. Triaxial Receiver Cube Being Installed in Waterproof Housing.

Transmitter Loops

Full-sized EMI transmitter loops were designed to fit in the MTA wing while maximizing the generated transmit current. Based on the lessons learned from SERDP Projects MR-2409 and MR-2500, and from ESTCP Project MR-201313, a buffer area of non-conducting epoxy as insulation was added around each transmitter coil. This buffer is necessary to limit noise generated from the interactions of the loops with a conductive media (e.g., sea water). The fabrication process used for the coils is shown for a small-scale example in Figure E-2.



Figure E-2. (Upper Left) Sample EMI Coil Winding, (Upper Right) Sample EMI Coil Suspended in Form, (Lower Left) Waterproof Epoxy Being Mixed, (Lower Right) Final Sample Coil Released from Mold.

Each loop consists of 20 turns of 14 AWG copper wire. Individual turns were carefully wound on structural forms. A sealant was then poured into the molds around the forms and wires. Final coil dimensions were: Main loop: 4.63 m x 1.07 m; Inner loops: 2.26 m x 0.97 m.

cDAQ Data Acquisition System

The EMI data acquisition system is based on the G&G Sciences cDAQ system. Originally designed for G&G Science's MPV, the system is capable of driving up to 4 transmitter loops of the TEMTADS/3D type and receiving from four (4) triaxial receiver cubes. The transmitter is operated in a bipolar mode where magnetic charging effects are minimized by alternating the polarity of the transmit current on consecutive transmits. Decay data are collected after turn off of the excitation pulse with sample rates of up to 500 kHz for up to 25ms. Data from negative transmit current excitations are inverted prior to summing with the positive transmit current excitations. This data collection configuration can result in raw decays of up to 12,500 points; too many to be used practically. These raw decay measurements are typically grouped into logarithmically-spaced "gates" with center times ranging from 25 μ s to 24.35 ms with proportional widths and are saved to disk.

Our unit was modified to support an additional 4 triaxial receiver cubes by replacing the National Instruments chassis with a larger-capacity unit, adding additional analog input modules, and adding a second cDAQ receiver board in a second cDAQ enclosure. An additional benefit of the larger-capacity chassis is access to the chassis timing inputs which can be used for synchronization with GPS via the 1PPS signal.

The transmitters used in the TEMTADS family of AGC systems operate in a bipolar transmission mode to suppress 60 Hz noise. The overall transmitted current first contains a positive-going current pulse, followed by a decay period, followed by a negative-going current pulse, and a second decay period. The stacking process then inverts the response from the “negative” decay, and adds it to the “positive” decay. Three supply voltages are input to the transmitter electronics to support this mode of operation: a ground for reference and two equal but opposite signed voltages, +V and -V. The nomenclature +/-V will be used for the remainder of this document, for example, +/-15 VDC corresponds to the standard TEMTADS 2x2 supply voltages of +15 VDC, ground, and -15 VDC.

To support the larger transmit coils, the capacitors in the transmit circuit were swapped out for larger ones and the drive voltage increased from +/-12 V to +/-24 V.

Application of the Technology

Application of this technology is evaluated for ‘dynamic classification.’ In this application, the wing is “flown” at a stable altitude above the bottom surface with the EMI array continually acquiring data. These data are then collectively preprocessed and anomalies detected. A data chip around each detection is then fit to a dipole model (or “inverted”) and fit parameters extracted (both intrinsic and extrinsic). Intrinsic parameters provide size and shape information which is then used to classify the anomaly as a target of interest (TOI) or as clutter. The data are transferred to the analyst several times each day for near real-time analysis.

PERFORMANCE ASSESSMENT

The performance objectives for the MTA test flights are summarized in Table E-1. The performance objectives and results are discussed further in Sections 3.0 and 7.0 of this report. The success criteria for this project’s objectives were lowered relative to levels which would have otherwise been specified in accordance with the projected MTA performance shown in Figure E-3. The levels specified here reflect the expected performance of the system as actually fielded on the York River in 2019. Based on this, the expected SNR for these tests should have been roughly 35 times smaller than what was used for the MTA prediction in Figure E-3. The stated success levels for the objectives that follow were correspondingly lowered.

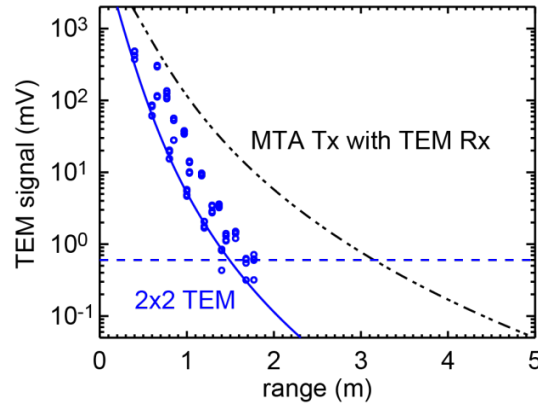


Figure E-3. TEMTADS 2x2 Signal vs. Range Response Curve for a 105 mm Projectile (0.3 ms Following the Primary Field Cutoff) Compared with the Corresponding Response Curve Calculated Using the MTA Transmit Coil Parameters.

Symbols are Measured TEMTADS Signals, and the Horizontal Dashed Line is a Representative Survey Mode Noise Level.

With the upgraded MTA, we get good estimates of the target polarizabilities with fit qualities of about 0.75 and higher. Figure E-4 shows examples. Figure E-4 (a)-(d) are for the hollow steel ball at nominal array heights of 0.75 m, 1.0 m, 1.25 m and 1.5 m above the bottom. The symbols show the polarizabilities determined by inverting the array data and the curves are the expected polarizabilities calculated using a conductivity of 5×10^6 S/m and a relative permeability of 100. Deviations between the data-derived and actual (calculated) polarizabilities are less than 15% for the first three (with fit quality greater than 0.8), but 88% for the final one which has a fit quality less than 0.7.

Table E-1. Performance Results for this Demonstration

Performance Objective	Metric	Data Required	Success Criteria	Success? (Yes/No)
Quantitative Performance Objectives				
Detection of Anomalies	Detection of emplaced seed items	Detection of anomalies as a function of reconstructed trajectory and altitude	All seed items detected when overflown by array at or below expected altitude	Yes
Correct Classification	Number of seed items correctly identified	Classification results from Data Analyst	100% correct classification of seed items with peak signal > 0.1V	Yes
Positional Accuracy	Reproducibility of reconstructed seed item locations from pass to pass	Similar results as from previous magnetometer surveys with the MTA	Reproducibility within 20% of previously demonstrated 1 m	Yes
Qualitative Performance Objective				
Implementation	Upgraded system was assembled, deployed, and data collected	Team and Data Analyst feedback	EMI data were collected in the marine environment	Yes
Robustness & Reliability	Number of significant technical issues	Field logs of significant technical issues	≤ 1 significant technical issue per day	Yes

Figure E-4 (e) and (f) show results for the large industry standard object (LISO). Here the curves are library polarizabilities. The nominal array heights are 0.75 m and 1.0 m above the bottom, respectively. Fit quality and signal strength are as noted on the plots. The target passed under the starboard edge of the array in Figure E-4 (e) and near the center in Figure E-4 (f). Deviations of the data-based polarizabilities from the library polarizabilities are 17% and 15% in these cases.

The root mean square (RMS) noise level during the tests was 2.3 mV at the 0.216 ms time gate. This is just slightly smaller (~25%) than noise levels observed at other stations along the York River in the summer of 2016 using a standard TEMTADS transmit coil – receive cube pair encased in a Delrin pressure housing and a second receive cube (offset horizontally by 35 cm) in a pressure housing. The data were collected during a study of background EMI response in marine environments conducted as part of SERDP project MR-2409. The MTA EMI array design study used a noise model based on in-air data collected with a one-half scale model at the Blossom Point test site and an assumed transmit current of 20 A. The corresponding RMS noise level for these data was 0.69 mV.

In conclusion, the upgraded EMI array performs as well in salt water as it does on land. Transmit currents are lower than planned (8.3 vs 20 A), due to limitations in the plan to modify the original transmitter. Additionally, York River noise levels encountered experimentally are 2-3x larger than those seen in air, on land during our testing at Blossom Point. For reference, noise levels were 2.3 vs 0.7 mV at the 0.216 ms time gate. To improve SNR to the levels required to meet the project's design goals would require ~800 A·t versus the original design 480 A·t, or the obtained 110 A·t. This could be achieved by either or both: a) new transmitter loops with heavier gauge wire (*e.g.*, 80 turns of 6 AWG wire), or b) a new bipolar transmitter capable of using higher supply voltages (*e.g.*, +/- 48 Volts).

COST ASSESSMENT

For the purposes of assessing the costs of implementing this technology, a cost model was developed, which is presented in the next section in Table E-2. The cost drivers and cost benefits are discussed in the following sections.

The four-week deployment would survey approximately 415 hectares, or 1025 acres at a total cost of \$212k. At the expected survey rate or 20.7 hectares/day, the survey costs would be roughly \$310/hectare and data analysis costs would be roughly \$65/hectare.

Cost Model

A four-week deployment to the opposite coast of CONUS is used as the basis for this model. A team of three (two-person survey team and one-person data analysis team). The rental of a vessel of opportunity for towing the MTA is included along with the use of a local dive team for emplacement of an IVS strip. The model is shown in Table E-2. As a production rate has not been demonstrated for this array at a significant scale, the average of the coverage rates given in Section 5.3, 20.7 ha/day, used in the cost model.

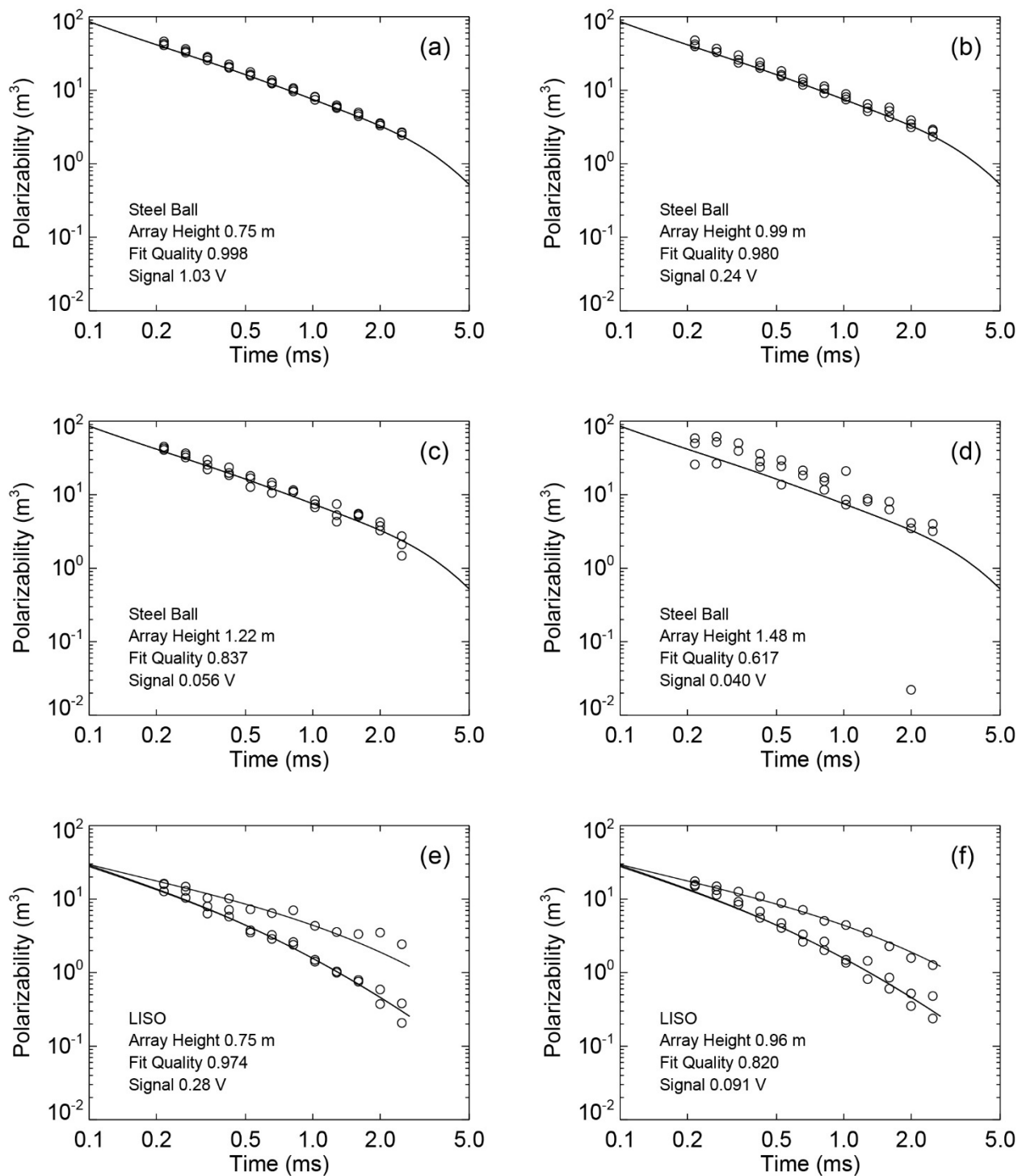


Figure E-4. Examples of Polarizabilities Determined by Inverting Array Data.

Symbols are measured polarizability, curves are calculated (sphere) or library polarizability (LISO).

Cost Drivers

Two factors were expected to be strong drivers of cost for this technology as demonstrated. The first is the number of hectares which can be surveyed per day. Higher productivity in data collection equates to more area (and therefore anomalies) investigated for a given period of time in the field. The time required for analyzing individual anomalies can be significantly higher than for other, more traditional methods and could become a cost driver due to the time involvement. The thoughtful use of available automation techniques for data processing and analysis with operator QC support can help moderate this effect.

Cost Benefit

The main benefit to using a UXO classification process is cost-related. The ability to reduce the number of non-hazardous items that have to be reacquired and remediated as presumptively-hazardous items directly reduces the cost of a remediation effort. The additional information for anomaly classification provided by these sensor systems provides additional information for the purposes of anomaly classification. If there is buy-in from the stakeholders to use these techniques, this information can be used to reduce costs.

IMPLEMENTATION ISSUES

The MTA's EMI array was successfully upgraded to incorporate a more modern, AGC-grade EMI data acquisition system, transmitter loops, and tri-axial receiver cubes. All existing MTA systems were successfully reactivated or replaced after years of storage. Notionally, there are no new implementation issues for the MTA. The MTA was and remains ideally suited for deployment in relatively flat-bottoms, open areas such as bays where munitions transfers occurred ship to ship.

Due to limitations of the specific transmitter / transmitter loop implementation, the maximum transmit moment which can be generated by the EMI array is significantly smaller than was anticipated in the original design. Additionally, measurements of environmental noise during the two test flights indicate that the original estimates of noise levels were optimistic. Therefore, transmit moments on the order of 1000 A·t would be needed to reach the design goal of correctly classifying a 105mm projectile at a survey altitude of 1.4m.

Table E-2. Tracked Costs

Cost Element	Data Tracked	Cost
Data Collection Costs		
Pre/Post Survey Activities	Component costs and integration costs Spares and repairs (/week)	\$3,250
	Cost to pack the array and equipment, mobilize to the site, and return - Personnel required to (re)pack (Re)packing hours - Personnel to (de)mobilize (De)mobilization hours - MTA transportation (one way)	\$42,800 1 40 3 8 \$10,000
	Cost to emplace IVS - Personnel required - Hours required - Boat hours required	\$2,200 4 4 4
	Cost for initial IVS - Personnel required - Hours required - Boat hours required	\$1,525 3 2 2
	Cost per survey day Cost per hectare Production Rate (ha/day) - Boat Rental (hour/day) - Survey personnel required - Daily IVS (hour/day) - Survey hours (/day) - Break-down and setup (hours/day) - Team per diem (/day)	\$6,425 / day \$310 / ha 20.7 ha/day 10 2 1 8 1 2
Processing Costs		\$1,350 / day \$65 / ha
Preprocessing	Time required to perform standard data clean up and to merge all data streams.	4 hr/day
Parameter Estimation	Time required to extract parameters for all anomalies in data set.	2 hr/day
Dig List Preparation	Time to assemble ranked dig list	2 hr/day

1.0 INTRODUCTION

1.1 BACKGROUND

Unexploded ordnance (UXO) is known to exist at a large number of underwater sites, and represents a significant and previously unresolved risk to human health and safety. Hindered by the combination of unfriendly survey conditions and other technological limitations, the Marine Towed Array (MTA) was originally developed with funding from the Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) to establish analogous capabilities to proven land-based UXO detection and classification systems to be applied to the underwater environment. The MTA prototype represented the foundation for the routine and systematic detection/classification of UXO in underwater environments. This effort was focused upon the design and integration of significant upgrades to the original MTA, whose performance metrics were projected to be significantly improved through innovative sensor designs and advanced electromagnetic induction (EMI) electronics.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objective of this project is demonstrate the UXO / clutter classification ability of an advanced EMI sensor system for underwater UXO sites. To achieve this objective, we have replaced the existing industry-standard EMI sensor array currently in the MTA with one based on advanced EMI electronics and sensor elements. The existing large transmitter loop was replaced with an interleaved array of three transmitter loops. The receiver loops were replaced with triaxial receiver cubes. Once installed, the performance of the new EMI system was demonstrated on two sets of emplaced targets of interest (TOI), where the TOI had been selected to explore the operational envelope of the new array. This demonstration replaced the original one planned to compare against the MTA's magnetometer array using a 93-acre area located off the shore of our facility at ARL Blossom Point, MD which was previously surveyed with the MTA in magnetometer mode in 2007.

1.3 REGULATORY DRIVERS

Stakeholder acceptance of the use of classification techniques on real sites will require demonstration that these techniques can be deployed efficiently and with high confidence classification results. The first step in this process is to demonstrate acceptable performance on seeded test strips and later synthetic test sites such as Underwater Test Site at Sequim Bay, WA. Later steps would include demonstration in more real-world scenarios. Further demonstration at live sites with more extensive ground-truth validation will further facilitate regulatory acceptance of the UXO classification technology and methodology.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

2.1.1 Triaxial Receiver Cubes

The design of the TEMTADS/3D EMI sensors is based on the advanced Electromagnetic Induction (EMI) sensor developed by the U.S. Naval Research Laboratory (NRL). The single, vertical-axis receiver coil of the original sensor was replaced with a three-axis receiver cube. A TEMTADS/3D coil under construction is shown in Figure 2-1. For this project, the triaxial receiver cubes are individually and separately packaged in waterproof enclosures, as shown in Figure 2-2.

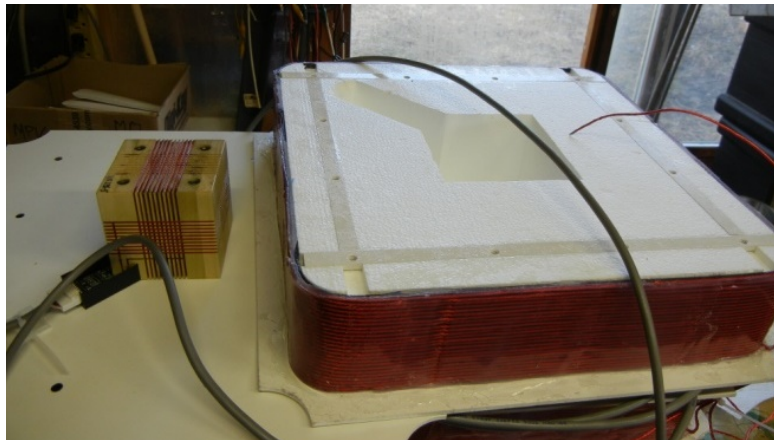


Figure 2-1. Individual TEMTADS/3D EMI Sensor with 3-axis Receiver Under Construction.

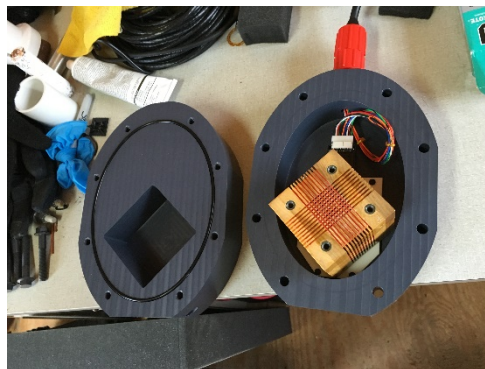


Figure 2-2. Triaxial Receiver Cube Being Installed in Waterproof Housing.

2.1.2 Transmitter Loops

Full-sized EMI transmitter loops were designed to fit in the MTA wing while maximizing the generated transmit current. Based on the lessons learned from SERDP Projects MR-2409 and MR-2500, and from ESTCP Project MR-201313, a buffer area of non-conducting epoxy as insulation was added around each transmitter coil. This buffer is necessary to limit noise generated from the interactions of the loops with a conductive media (e.g., sea water). The fabrication process used for the coils is shown for a small-scale example in Figure 2-3.



Figure 2-3. (Upper Left) Sample EMI Coil Winding, (Upper Right) Sample EMI Coil Suspected in Form, (Lower Left) Waterproof Epoxy Being Mixed, (Lower Right) Final Sample Coil Released from Mold.

Each loop consists of 20 turns of 14 AWG copper wire. Individual turns were carefully wound, like was done with the mini-MTA, on structural forms. A sealant was then poured into the molds around the forms and wires. Final coil dimensions were: Main loop: 4.63 m x 1.07 m; Inner loops: 2.26 m x 0.97 m.

2.1.3 cDAQ Data Acquisition System

The EMI data acquisition system is based on the G&G Sciences cDAQ system. Originally designed for G&G Science's MPV, the system is capable of driving up to 4 transmitter loops of the TEMTADS/3D type and receiving from four (4) triaxial receiver cubes. The transmitter is operated in a bipolar mode where magnetic charging effects are minimized by alternating the polarity of the transmit current on consecutive transmits. Decay data are collected after turn off of the excitation pulse with sample rates of up to 500 kHz for up to 25ms. Data from negative transmit current excitations are inverted prior to summing with the positive transmit current excitations. This data collection configuration can result in raw decays of up to 12,500 points; too many to be used practically. These raw decay measurements are typically grouped into logarithmically-spaced "gates" with center times ranging from 25 μ s to 24.35 ms with proportional widths and are saved to disk.

Our unit was modified to support an additional 4 triaxial receiver cubes by replacing the National Instruments chassis with a larger-capacity unit, adding additional analog input modules, and adding a second cDAQ receiver board in a second cDAQ enclosure. An additional benefit of the larger-capacity chassis is access to the chassis timing inputs which can be used for synchronization with GPS via the 1PPS signal as will be discussed later.

The transmitters used in the TEMTADS family of AGC systems operate in a bipolar transmission mode to suppress 60 Hz noise. The overall transmitted current first contains a positive-going current pulse, followed by a decay period, followed by a negative-going current pulse, and a second decay period. The stacking process then inverts the response from the “negative” decay, and adds it to the “positive” decay. Three supply voltages are input to the transmitter electronics to support this mode of operation: a ground for reference and two equal but opposite signed voltages, +V and –V. The nomenclature +/-V will be used for the remainder of this document, for example, +/-15 VDC corresponds to the standard TEMTADS 2x2 supply voltages of +15 VDC, ground, and -15 VDC.

To support the larger transmit coils, the capacitors in the transmit circuit were swapped out for larger ones and the drive voltage increased from -12 V / Ground / +12 V (+/-12 V) to +/-24 V.

2.1.4 Application of the Technology

Application of this technology is evaluated for ‘dynamic classification.’ In this application, the wing is “flown” at a stable altitude above the bottom surface with the EMI array continually acquiring data. These data are then collectively preprocessed and anomalies detected. A data chip around each detection is then fit to a dipole model (or “inverted”) and fit parameters extracted (both intrinsic and extrinsic). Intrinsic parameters provide size and shape information which is then used to classify the anomaly as a target of interest (TOI) or as clutter. The data are transferred to the analyst several times each day for near real-time analysis.

2.2 TECHNOLOGY DEVELOPMENT

The MTA tow body (shown on a trailer to NRL’s Blossom Point test facility in the photograph on the left in Figure 2-4) is a 4.8 m wide wing-shaped fiberglass structure designed to be towed from a medium size (~30 ft) utility vessel or larger. Elevators on the trailing edge are driven by a control system to maintain a fixed height above the bottom during normal operations. The diagram on the right in Figure 2-4 shows the original MTA EMI array configuration. The transmit coil is 4.6 m wide and 1.0 m long and has 24 turns carrying a nominal current of 20 A. There are four 1.1 m by 0.5 m receiver coils, each with 56 turns.

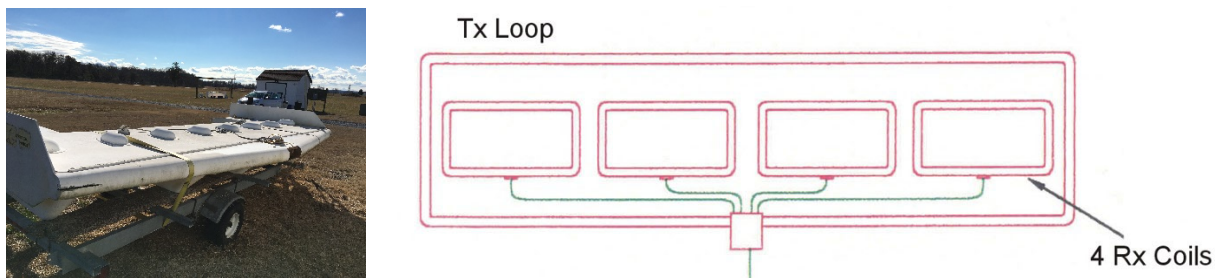


Figure 2-4. (Left) The Marine Towed Array Tow Body on a Trailer at NRL’s Blossom Point Test Facility. (Right) Diagram of Existing MTA EMI Array Configuration.

The electronics are based on the Geonics model EM38 transient electromagnetic (TEM) sensor. The transmitter is operated in a bipolar mode at 7.5 Hz and data are recorded from each of receiver coils into 26 log-spaced, time-delay bins spanning the range from 0.1 ms to 32 ms after the transmit current cutoff.

The existing EMI sensor array is based on 1990's EMI technology with analog electronics which has proven to be inadequate for reliable classification work. SERDP- and ESTCP-sponsored work over the last fifteen years has shown that arrays which combine single axis transmitter coils with multi-axis receivers and are controlled using modern digital electronics can be used to reliably detect and classify UXO. The objective of this project is to replace the MTA's original EMI array with modern EMI sensors and electronics and use the new system to evaluate detection and classification performance in the underwater environment.

The MTA typically flies 1 – 1.5 m above the bottom [1]. With the standard cart-based TEMTADS 2x2 system developed in ESTCP project MR-200909, [2] the sensors are nominally 20 cm above the ground. All things being equal, increased standoff translates directly to decreased signal levels, degrading performance. Due to its larger size the MTA transmit coil has a larger transmit moment than the TEMTADS 35 cm transmit coils. This increases signal strength, compensating for the loss due to increased standoff distance. The performance dividend which results from a large transmit coil was recognized during the development of the MTA [3,4]. The effect is illustrated in Figure 2-5. The solid blue curve shows how the amplitude of the TEMTADS signal (at 0.3 ms following primary field cutoff) decays with range for a target (in this case a 105 mm projectile) in its minimum signal orientation. The points are measured signals for various target orientations, and the horizontal dashed line is a representative (Camp Spencer [5]) RMS noise level for the TEMTADS 2x2 in survey mode. Results of a similar calculation using MTA transmit coil parameters are shown by the chain-dashed black line. The larger MTA transmit coil extends the range at which the signal drops to noise level by more than the increased standoff range of the MTA sensor array relative to the TEMTADS array.

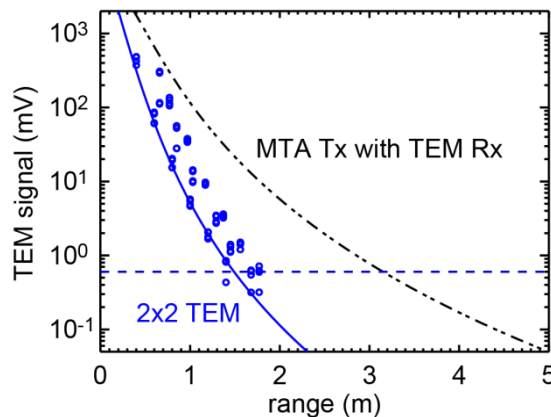


Figure 2-5. TEMTADS 2x2 Signal vs. Range Response Curve for a 105 mm Projectile (0.3 ms Following the Primary Field Cutoff) Compared with the Corresponding Response Curve Calculated Using the MTA Transmit Coil Parameters.

Symbols are measured TEMTADS signals, and the horizontal dashed line is a representative survey mode noise level.

EMI-based classification uses target features (principal axis polarizabilities) extracted from data collected with an array of receiver coils and multi-axis target illumination by some arrangement of transmitter coils. In general, a single large transmit coil passing over a target does not illuminate that target along three orthogonal axes.

Previously in this project, we have examined the classification performance of different MTA transmit coil configurations using a half-scale model array which is shown in the photograph on the left in Figure 2-6. The diagram on the right shows the configuration of transmit and receive coils. There are three transmit coils: a pair of 0.5 m by 1.14 m coils (Tx2 and Tx3) inside of a 0.53 m by 2.34 m outer coil (Tx1). Each has 14 turns. The current is nominally 4 A for the inner coils and 3.5 A for the outer coil. There are six 8-cm, 3-axis receive cubes spaced across the array, which is controlled with a G&G Sciences cDAQ electronics package. We refer to this as the miniMTA. All of the target signal data were collected using 2.77 ms decays with 20% gate width. Noise data were collected in full wave mode (2 μ s sampling interval) with 2.77 ms decays.

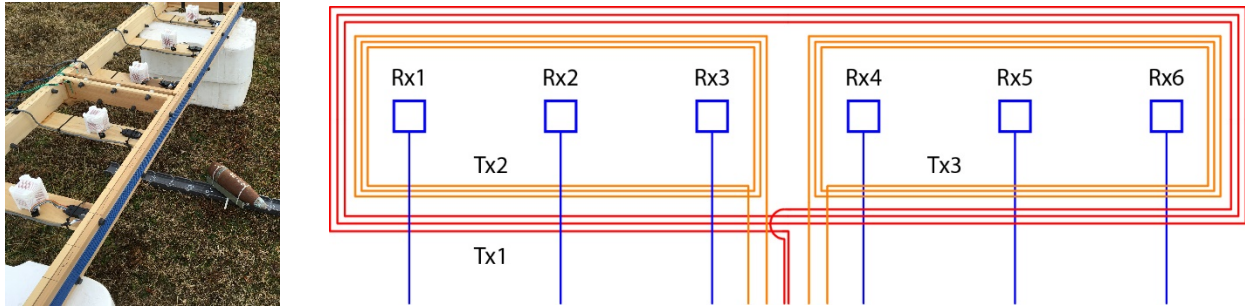


Figure 2-6. One-half Scale Model of the miniMTA EMI Array Used for Design Validation.

Data collected with the miniMTA were used to validate array performance models [6]. These were then combined with background response models validated in SERDP project MR-2409 and used to evaluate the performance of a full-scale array towed 1–1.5 m above the bottom.

Based on the results of the miniMTA analysis, the full-sized EMI array was constructed along with an updated electronics bottle. The modifications necessitated some modification to the MTA wing internal structure as well. The original and updated geophysical sensor configurations are shown schematically in the MTA wing in Figure 2-7. Transmitter loops are shown in green (main) and blue (inner). Total-field magnetometers are shown as blue circles and the triaxial receiver cube are shown as orange ovals.

Full-sized EMI transmitter loops were designed to fit in the MTA wing while maximizing the generated transmit current. Based on the lessons learned from SERDP Projects MR-2409 and MR-2500, and from ESTCP Project MR-201313, a buffer area of non-conducting epoxy as insulation was added around each transmitter coil. This buffer is necessary to limit noise generated from the interactions of the loops with a conductive media (*e.g.*, sea water). The fabrication process used for the coils is shown for a small-scale example in Figure 2-3.

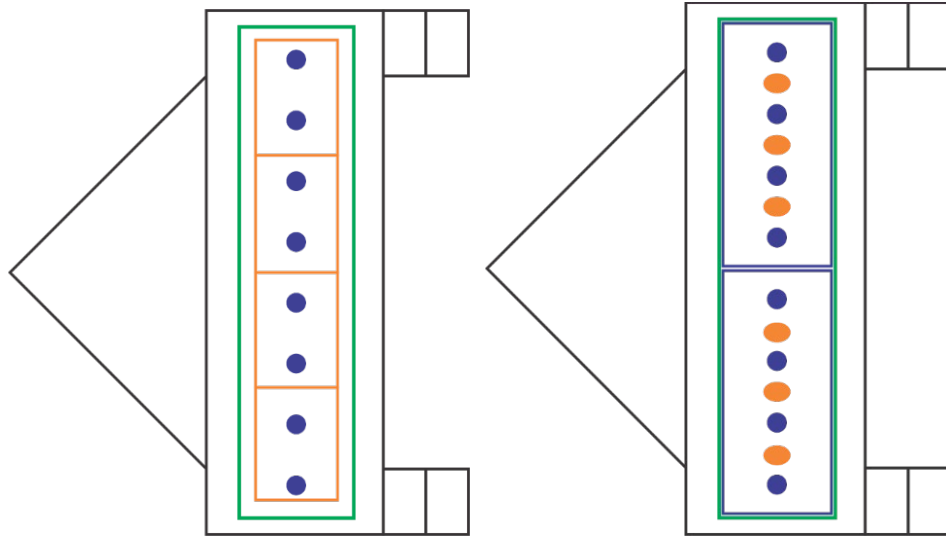


Figure 2-7. (Left) Original MTA Sensor Configuration, (Right) Updated MTA Sensor Configuration.

Each loop consists of 20 turns of 14 AWG copper wire. Individual turns were carefully wound, like was done with the mini-MTA, on structural forms. A sealant was then poured into the molds around the forms and wires. Final coil dimensions were: Main loop: 4.63 m x 1.07 m; Inner loops: 2.26 m x 0.97 m.

After installation of the transmitter coils and the triaxial receiver cubes, in waterproof housings, the full-sized array was tested first in air, on land at our facility in Welcome, MD in August, 2019. After characterization, the entire wing was sent to VIMS in Gloucester Point, VA for in-water testing with emplaced UXO surrogates in September, 2019.



Figure 2-8. (Left) MTA with EMI Array Installed, (Center) Sphere Rolling Test, (Right) Close-up of MTA Showing Magnetometers, Receiver Housings, and Transmitter Loops.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The MTA is an underwater, flying wing sensor array originally designed for the detection and mapping of underwater unexploded ordnance (UXO). The flight characteristics and deployment strategy of the MTA make it an ideal survey instrument for relatively flat-bottomed, open areas suspected of UXO population such as suspected munitions transfer areas. The electromagnetic induction sensor suite has been updated with advanced geophysical classification (AGC) type electronics and sensors and has been shown to be capable of classifying UXO and clutter targets in a marine environment.

While the existing tow cable for the MTA allows for operational depths of 60 ft., the hydrodynamics of the cable angle and autopilot command authority make using altitude mode difficult at these depth. The current implementation of the EMI array limits the operational depth of the array from 60 ft. to roughly 20 ft. The transmitter current moment in the current configuration limits the acceptable standoff distance for the EMI array to roughly 1 meter for the design goal TOI. Discussion is provided in this report on the next steps to resolve this issue.

3.0 PERFORMANCE OBJECTIVES

Performance objectives are given as a basis for the evaluation of the performance and costs of the demonstrated technologies. The objectives are summarized in Table 3-1 and then discussed in more detail in the following sections.

The success levels for this project's objectives were lowered relative to levels which would have otherwise been specified in accordance with the projected MTA performance shown in Figure 2-5. The levels specified here reflect the expected performance of the system as actually fielded on the York River in 2019. The predicted performance shown in Figure 2-5 was based on a 480 A-t transmitter and 0.6 mV RMS noise. As discussed in Section 5.4.2 we were limited to 114 A-t by the transmitter electronics and the fact that we only used 20 turns in the new transmitter loops. Furthermore, we found in SERDP project MR-2409 that the median RMS noise level (scaled to account for sampling differences) from ten stations along the York River measured during summer 2016 was 3.0 mV, compared with the 0.6 mV noise level (based on Camp Spencer data [5]) which is indicated by the dashed line in Figure 2-5. Together, these factors indicate that the expected SNR for these tests should have been roughly 35 times smaller than what was used for the MTA prediction in Figure 2-5. The stated success levels for the objectives that follow were correspondingly lowered.

3.1 OBJECTIVE: DETECTION OF ANOMALIES

This objective relates to the detection of metallic anomalies overflown by the MTA's wing.

3.1.1 Metric

All seed items were emplaced on the bottom surface and the MTA wing was flown over the items at increasing altitudes. Based on the array performance characteristics determined on land, the detection response of the area for a given seed item can be modeled. Any targets covered by the wing at the demonstrated altitudes should be detected.

3.1.2 Data Requirements

The data requirements are the locations and identifications of the test objects and an analysis of the flight path and altitude for each run.

3.1.3 Success Criteria

Success is defined as having detected all seed items that were actually overflown by the wing on a given pass, and were expected to be detectible based on predicted response and measured SNR. As stated above, this success criterion has been reduced from a more rigorous criterion based on physically-based detection levels and measurement standoff distances.

Table 3-1. Performance Objectives for this Demonstration

Performance Objective	Metric	Data Required	Success Criteria
Quantitative Performance Objectives			
Detection of Anomalies	Detection of emplaced seed items	Detection of anomalies as a function of reconstructed trajectory and altitude	All seed items detected when overflowed by array at or below expected altitude
Correct Classification	Number of seed items correctly identified	Classification results from Data Analyst	100% correct classification of seed items with peak signal > 0.1V
Positional Accuracy	Reproducibility of reconstructed seed item locations from pass to pass	Similar results as from previous magnetometer surveys with the MTA	Reproducibility within 20% of previously demonstrated 1 m
Qualitative Performance Objectives			
Implementation	Upgraded system was assembled, deployed, and data collected	Team and Data Analyst feedback	EMI data were collected in the marine environment
Robustness & Reliability	Number of significant technical issues	Field logs of significant technical issues	≤ 1 significant technical issue per day

3.2 OBJECTIVE: CORRECT CLASSIFICATION

This objective relates to the classification of metallic anomalies detected from the dynamic data collected by the MTA's EMI array.

3.2.1 Metric

A limited set of seed items were emplaced, each with a unique magnetic polarizability signature. The metric is therefore the correct classification of each detected seed item.

3.2.2 Data Requirements

The data requirements are the locations and identifications of the test objects and an analysis of the flight path and altitude for each run, the list of detected anomalies for each run, and the classification results.

3.2.3 Success Criteria

Success is defined as having correctly classified all seed items that were actually overflowed by the wing on a given pass, and were expected to be detectable based on predicted response and measured peak signal. Given the limited, and diverse set of objects to match against, no issues of classification for detected items is anticipated. As stated above, this success criterion has been reduced from a more rigorous criterion requiring all seed items to be correctly classified.

3.3 OBJECTIVE: POSITIONAL ACCURACY

This objective relates to the precision of the reconstructed position and fit results from analysis of the dynamic data collected by the MTA's EMI array.

3.3.1 Metric

The metric is comparing the demonstrated positional accuracy to that previously demonstrated by the original MTA.

3.3.2 Data Requirements

The data requirements are the reported locations of the test objects for each run.

3.3.3 Success Criteria

A limited amount of test data was collected over the course of two days with the GPS 1PPS synchronization not enabled. The metric is therefore that the positional accuracy is similar (within 20%) of that previously demonstrated by the original MTA.

3.4 OBJECTIVE: IMPLIMENTATION

This qualitative objective relates to the implementation of the upgrade to the MTA EMI array.

3.4.1 Metric

The upgrade of the MTA's EMI array was a complicated process that involved reactivating an underwater survey platform after several years of idle storage and the integration of an AGC-grade EMI array and electronics into the original wing. The metric is whether or not the wing was successfully upgraded to the point that dynamic survey EMI data could be collected in the water.

3.4.2 Data Requirements

The data requirements are team evaluations and any available survey results.

3.4.3 Success Criteria

Success is defined as having been successful in installing the upgraded EMI array and collecting dynamic survey data, underway, in the water.

3.5 OBJECTIVE: ROBUSTNESS AND RELIABILITY

This qualitative objective relates to the ongoing operation of the MTA after reactivation and upgrade.

3.5.1 Metric

One sure sign of the ruggedness of a system is how often it requires "persuasion" to keep operating normally. This metric relates to how many issues were encountered during the two test flights.

3.5.2 Data Requirements

The data requirements are team evaluations and records.

3.5.3 Success Criteria

Success is defined as having no more than one major incident requiring surveying be delayed or postponed each survey day.

4.0 SITE DESCRIPTION

The demonstration site originally selected for this project was in the Potomac River, off the shore of our home facility in Welcome, MD. The site was selected to overlap with the survey area from the MTA's magnetometer survey from 2007. With the redirection of the project, the testing site for the MTA near VIMS is presented.

4.1 SITE SELECTION

A research vessel from VIMS's inventory was selected for the in-water testing of the MTA and of the upgraded EMI array. For this reason and for rapid access to the VIMS support staff for testing and debugging the new electronics bottle, all testing was done in the waters off of Gloucester Point, VA and VIMS's boat basin. The two locations were items were seeded for the 2019 testing are shown in Figure 4-1.

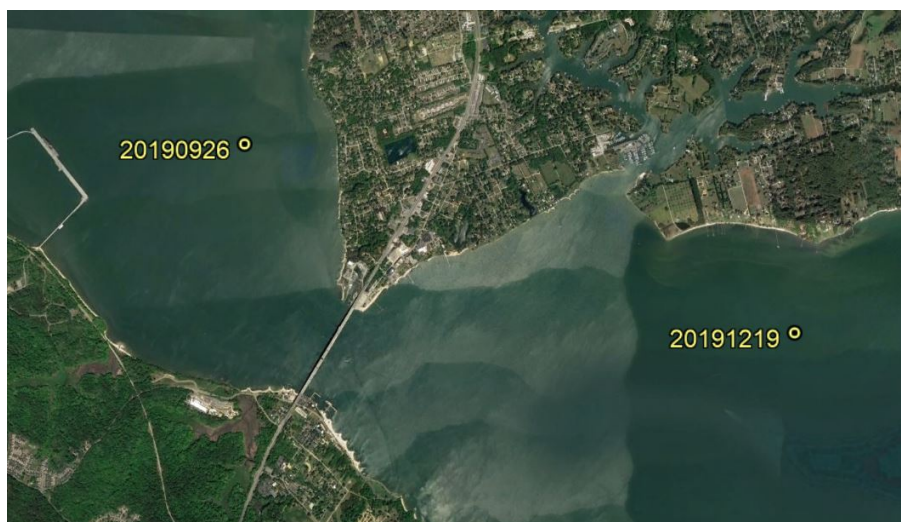


Figure 4-1. Map of the Test Sites on the York River, VA, near VIMS.

For the September 26, 2019 testing, data were collected over a test strip during the period of low tide from noon to 3:30 PM at the location indicated in Figure 4-1. The water depth was 6.7 m, and the water column was weakly stratified with an average conductivity of 3.45 S/m. For the December 19, 2019 testing, data were collected during high tide from about 2 PM to 4 PM. The water depth was 5 m, and the water column was weakly stratified with an average conductivity of 3.5 S/m. In both cases and for earlier test runs, the MTA was towed by the *R/V Tidewater*, with 25 m of cable scope and at a nominal speed of 1 m/s.

4.2 SITE HISTORY

The York River is formed at West Point, VA approximately 35 miles east of Richmond, VA by the confluence of the Mattaponi and Pamunkey rivers [7]. It drains into the Chesapeake Bay towards the southeast, entering the bay approximately 5 miles east of Yorktown, which sits along its southern shore. U.S. Highway 17 crosses the estuary from Yorktown to Gloucester Point on the George P. Coleman Memorial Bridge.

The peninsula formed by the York and the James rivers just to the south became the scene of the end campaign of the American Revolutionary War in October 1781. The British Army under Cornwallis at Yorktown found itself cornered by the Americans under George Washington on land and by the French fleet at sea. The ensuing American victory at the Battle of Yorktown forced the surrender of Cornwallis and the end of the war in the east. During the American Civil War, the same area became the theater of the Peninsular Campaign of 1862.

In the third millennium, York River State Park is located along the southern shore northwest of Yorktown in James City County. Also on the south shore are several large military reservations, including Camp Peary and the Naval Weapons Station Yorktown (and Cheatham Annex) of the U.S. Navy. Large areas of preserved wetlands and forest are considered ecologically important to migratory waterfowl. Site Topography and Geology

The York River is an estuary with typical tidal currents in the mid to upper estuary approaching 1 m/s [8]. The lower York near Gloucester Point is generally more stratified than the upper York near West Point because of the shallower depths and stronger currents found upstream. Salinity stratification fluctuates in the York River associated with tidal straining, the spring-neap cycle, and variations in freshwater discharge. Estuarine circulation in the York River, which averages ~5 to 7 cm/s, is often modulated by moderate winds. Waves are usually insignificant, although occasional severe storms have a major impact. The York River channel bed is predominantly mud, while the shoals tend to be sandier, and the mid- to upper York is marked by seasonally persistent regions of high turbidity. Fine sediment is trapped in high turbidity regions in response to tidal asymmetries and local variations in stratification and estuarine circulation.

4.3 MUNITIONS CONTAMINATION

The two test sites are on the eastern shore of the York River as it passes between Yorktown and Gloucester Point, VA. The area was part of battles conducted during the American Revolutionary and Civil Wars. The US Navy's Naval Weapons Station Yorktown is located across and upriver of the test sites. VIMS staff reports no previous identification of any munitions in the test areas and none was found during our testing.

5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The demonstration of the performance of the upgraded EMI array installed in the MTA was two-fold. First, land-based testing was conducted at our facility in Welcome, MD where the target – sensor distances and geometries can be well-known and controlled. The main testing was conducted in the relatively benign waters off the shores of VIMS’s boat basin on the York River, VA. UXO surrogates and exemplar clutter items (e.g. a vehicle wheel rim) were emplaced by VIMS staff in test strips and the MTA flown over them in turn.

5.2 SITE PREPARATION

The *R/V Tidewater* is based in the VIMS boat basin at Gloucester Point, VA and the MTA was transported to VIMS from Blossom Point in advance of all testing events. VIMS staff emplaced the seeds items in the days prior to each of the two tests in 2019.

For the September testing, the test strip had six targets attached to a line stretched between a pair of anchors a distance of 102 m apart. The targets were spaced at 10 m intervals in the middle of the line. There were two 12-in diameter hollow steel balls (wall thickness 1/8-in, which had been drilled through so they would sink), two 4-in diameter by 12-in long steel pipe sections (105mm projectile surrogates) and two 6-in diameter by 18-in long steel pipe sections (155mm projectile surrogates). The 105mm surrogates are the large industry standard objects (LISO) referred to in the Geophysical System Verification documentation [9]. We refer to the 155mm surrogates as extra large industry standard objects (XLISO). The EMI response of the sphere is comparable to the transverse response of the XLISO.



Figure 5-1. (Left) *R/V Tidewater*, (Right) UXO Surrogates Used.

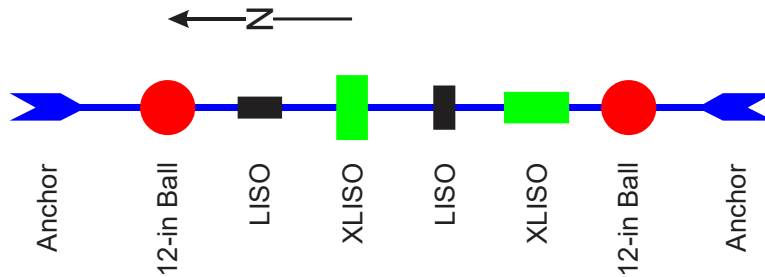


Figure 5-2. Schematic of York River Test Strip

For the December, 2019 testing, the test strip had six targets spaced at 10 m intervals along a line stretched between a pair of anchors. The targets are shown prior to deployment in Figure 5-3: from left to right the targets are a 12-inch diameter hollow steel float ball (with holes drilled for flooding), a section of chain attached to a board, a crab pot, a tire rim, an axle rod (shown also in the photo on the right) and a 6-inch diameter by 18-inch long pipe section (155mm projectile surrogate). At the far right is one of the Danforth anchors used to secure the test strip. The targets were selected from recovered items warehoused at VIMS as representative of potential clutter items which could be encountered during marine surveys.

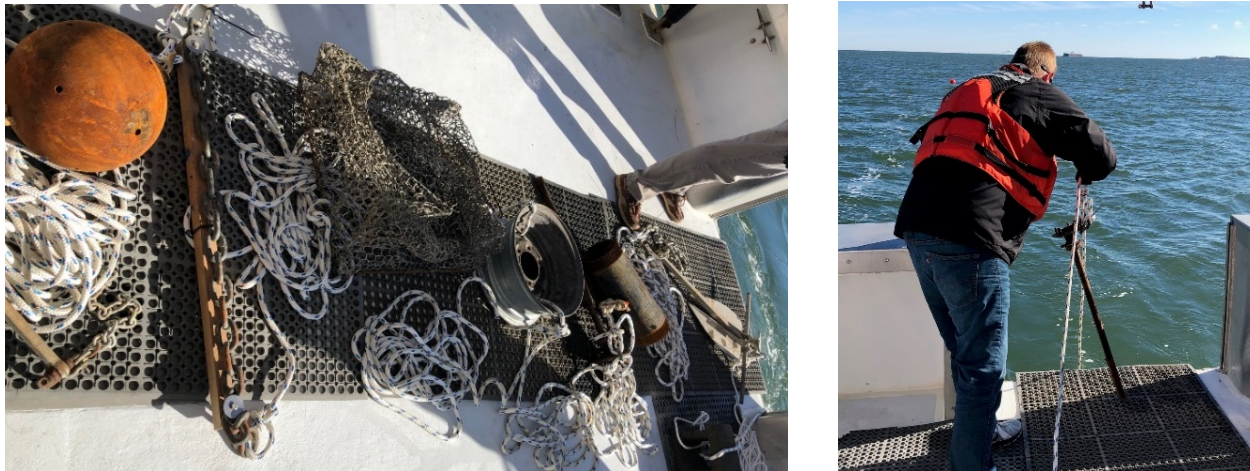


Figure 5-3. (Left) Targets Used for In-water Test, (Right) Deployment of Items in Progress.

5.3 SYSTEMS SPECIFICATION

The technological focus of this project is to replace the EMI sensor array originally fielded for the MTA, developed under SERDP and ESTCP funding, with one based on advanced EMI electronics and sensor designs.

The original MTA technology consists of an integrated suite of hardware and software for data acquisition, Figure 5-4 (left), and software tools specifically adapted for data preprocessing and analysis, particularly for magnetic anomaly data. A 30-foot long, triple-pontoon boat manufactured by Crest, Figure 5-4 (right), was chosen for the original tow vessel. This is the maximum width boat that can be transported over the road without special wide load permits.

A 175-horsepower outboard engine was chosen for propulsion. Most of the furniture was stripped from the deck and the deck railings removed on the forward half of the boat so that the sensor platform could be stored and transported on the deck. A marine winch was installed on the deck to lift and deploy the sensor platform. Marine hardware was installed to serve as tie-downs for the instrument racks and the generator. Mounting fixtures were designed and built for the tow point fixture, the GPS antennas, the depth sounder, and the imaging sonar.



Figure 5-4. (Left) The 30 ft Pontoon Boat Is Shown Towing the Sensor Platform During a Survey on Ostrich Bay. The Sensor Platform Is Submerged About 7 ft. Below the Surface. (right) The Tow Point Fixture is Located at the Rear of the Boat. The master GPS antenna is located on the mast above this point. The digital angular encoder measures the angle of the tow cable relative to the boat heading. The weak link cable is located between the shackles at the end of the tow arm.

The sensor platform is towed by a cable attached to a custom tow point fixture located at the center of the boat at the stern, Figure 5-4 (right), allowing for operational depths of up to 60 feet. The maximum operational design towing speed is 5 knots. Assuming the system is used to survey 4-meter wide lanes at 5 knots, the survey production rate is 3.7+ hectares/hour, or slightly less than 10 acres/hour. To maximize the SNR for this test series, we have intentionally slowed the towing speed to 2 knots, which would represent a survey production rate of 1.5 hectares/hour, or 3.7 acres/hour. Typical survey operations would presumably fall within these two bounds. See Section 5.5.2 for additional details on the effect of towing speed on EMI sample density.

The attitude and depth of the sensor platform is controlled by an autopilot operating from a computer on the tow vessel, Figure 5-5 (left). The inputs to the autopilot include a tactical-grade IMU mounted on the sensor platform (determining pitch, roll, and yaw of the platform), depth sensors and digital magnetic compasses on both the platform and on the tow vessel, and a dual antenna GPS system on the tow vessel. The autopilot, which controls the sensor platform, can be programmed to either maintain a fixed standoff distance from the bottom or to maintain a fixed depth below the water surface. This system provides a truly unique capability for underwater UXO search systems.



Figure 5-5. (Left) All Sensor Data Are Recorded by the Computers in These Data Racks Mounted Across from the Drive Console, near the Port Rail. (Right) The Tow Vessel Console Is Located on the Starboard Side. The Pilot Is Responsible for Maintaining the Survey Course and Avoiding Bottom Obstacles.

The number of sensor systems operating and the complexity of the data streams requires the fulltime attention of a field geophysicist to monitor the data flows. The survey plan and the real time survey course are displayed on the Pilot Guidance display shown immediately to the right of the steering wheel in Figure 5-5 (right). The digital readout from the forward depth sounder is shown to the left of the steering wheel.

The primary Data Acquisition (DAQ) computer operates a version of the Geometrics Maglog® software adapted for this application. Maglog has been the primary DAQ GUI for all magnetometer and EM61 MTADS platforms. The sensors from the marine platform, except the EM68, are recorded in this utility. Additionally, the GPS data and data from the depth sounder are recorded using this GUI.

A new GUI that we developed to allow us to control and monitor the sensor platform behavior, was developed in SERDP Project UX-1322 and is extensively described in the SERDP UX-1322 Final Report [10]. Three primary operational control algorithms were developed for the sensor platform GUI. The first allows us to operate the platform at an operator-specified depth below the surface. The second mode is designed to operate the sensor platform at a specified height above the bottom. The third mode is referred to as the Emergency Rise mode. This can either be called from the keyboard or automatically invoked by pressing the Emergency Rise Button on the electronics rack console panel. In this mode, the elevators are driven to their full up stops and held there until the platform ascends to 0.5 m below the surface. This mode is intended for use if we observe a bottom obstruction that is likely to cause an impact with the sensor platform.

The sensor platform is a 5 m wide fiberglass structure, which basically has an airplane wing cross-section. Figure 5-6 (left) shows the MTA wing floating in the water beside the pontoon boat. Figure 5-6 (right) shows another image with the hatch covers removed. In this image several of the sensor components are identified. The sensor platform accommodates 8 Cs vapor full field magnetometers on a 0.6 m spacing and an EM array consisting of a 1 X 4.5 m transmit coil and four 0.5 X 1 m receiver coils.



Figure 5-6. (Left) The Assembled Sensor Platform Is Shown, (Right) The Marine Sensor Platform Is Shown with the Hatch Covers Removed.

The system components are labeled.

In case of a severe impact of the platform with some bottom structure, a breakaway link is installed inline with the tow cable, which will part at 1,100 lb tension. The electrical connectors from the tow cable to the bulkhead connector at the rear of the boat are designed to part at 50 lb.; and these cables can be wet re-mated.

The MTA wing was transported to VIMS in November, 2017 for weight and balance measurements, a float test in the VIMS boat basin (Figure 5-7 (left)), and for availability to the VIMS staff for design and construction of the new electronics bottle for the new EMI electronics. A test pull of the wing, as originally designed, by a VIMS *R/V Tidewater* (Figure 5-7 (center, right)). Figure 5-8 shows the new EMI Sensor Interface Bottle (EMI-SIB) being assembled.



Figure 5-7. (Left) Marine Towed Array During a Float Test at VIMS, (Center) R/V Tidewater, and (Right) R/V Tidewater aft Lift.

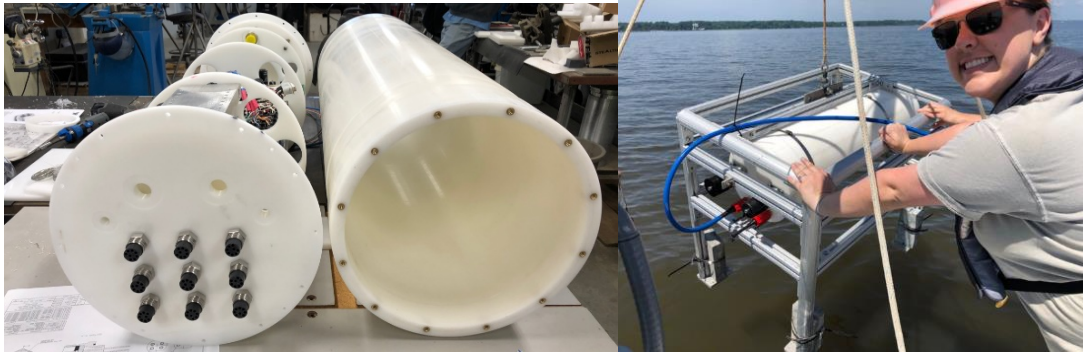


Figure 5-8. a) EMI-SIB from Rear End Cap. BURTON Bulkhead Connectors Being Manufactured by SEACON b) Pressure Test in the Field.

A following test flight successfully flew the wing, including diving the wing below the surface and maintaining flight in both depth mode and altitude mode. Test pictures shown in Figure 5-9.

Full-sized EMI transmitter loops were designed to fit in the MTA wing while maximizing the generated transmit current. Based on the lessons learned from SERDP Projects MR-2409 and MR-2500, and from ESTCP Project MR-201313, a buffer area of non-conducting epoxy as insulation was added around each transmitter coil. This buffer is necessary to limit noise generated from the interactions of the loops with a conductive media (*e.g.*, sea water). The fabrication process used for the coils is shown for a small-scale example in Figure 2-3.



Figure 5-9. MTA Wing Under Tow During Two Test Flights.

Each loop consists of 20 turns of 14 AWG copper wire. Individual turns were carefully wound, like was done previously with the mini-MTA, on structural forms. A sealant was then poured into the molds around the forms and wires. Final coil dimensions were: Main loop: 4.63 m x 1.07 m; Inner loops: 2.26 m x 0.97 m. After installation of the transmitter coils and the triaxial receiver cubes, in waterproof housings (shown in Figure 5-10), the full-sized array was tested first in air, on land at our facility in Welcome, MD in August, 2019, as shown in Figure 2-8. After characterization, the entire wing was sent to VIMS in Gloucester Point, VA for in-water testing with emplaced UXO surrogates in September, 2019.

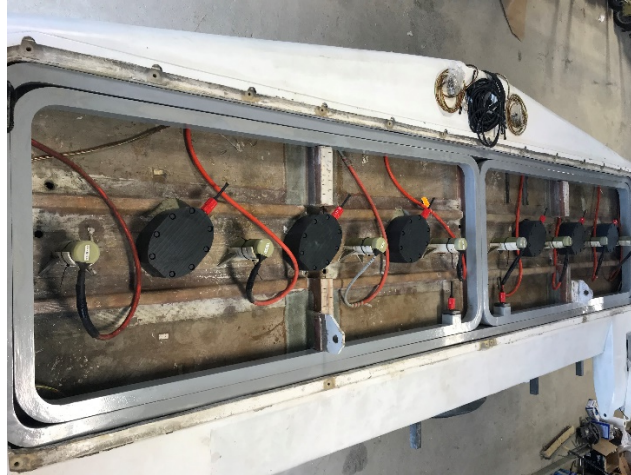


Figure 5-10. Interior of the Marine Towed Array.

Rounded gray rectangles are transmit loops, black ovals are pressure housing containing receiver cubes and green cylinders contain magnetometers.

Incorporated in the EMI-SIB, shown in Figure 5-8, is a cDAQ data acquisition system from G&G Sciences, shown in Figure 5-11. The data acquisition system is composed of a ruggedized computer (the black unit in the upper center portion of the image, a National Instruments cDAQ data acquisition chassis (middle image), a G&G Sciences UXO Data Acquisition System cDAQ1 transmitter / receiver unit (left image), and an additional cDAQ1 receiver-only module (bottom center).

Not shown is the Trimble Thunderbolt E unit used to provide inter-system synchronization with the GPS 1PPS signal via an L1 GPS antenna positioned on the vessel and fed to the EMI-SIB via a waterproof coaxial cable. At the time of the demonstration testing, the GPS synchronization was not enabled. The MagLog data acquisition computer is independently synchronized to the GPS 1PPS signal. The vendor-provided software package EM3D is used to control the cDAQ1 system via Microsoft Remote Desktop (RDP) from the MagLog computer on the vessel. Operation of EM3D is described elsewhere [11].

5.4 CALIBRATION ACTIVITIES

For the purposes of this document, calibration activities will refer to the land-based testing performed with the half-scale model (miniMTA) and the upgraded wing (MTA) at our Blossom Point, MD facility.

5.4.1 Mini-MTA – Half-Scale Model

In 2017, we tested a one-half scale model (0.5 m by 2.3 m) of the proposed array, demonstrating that it can accurately classify 57 mm projectiles at a range of 68 cm. The test data were used to validate models for the array performance. Simulations using the verified model show that an equivalent array scaled up to the original MTA specifications should reliably classify larger munitions items (*e.g.* 105 mm projectiles) at standoff ranges exceeding 2 m.

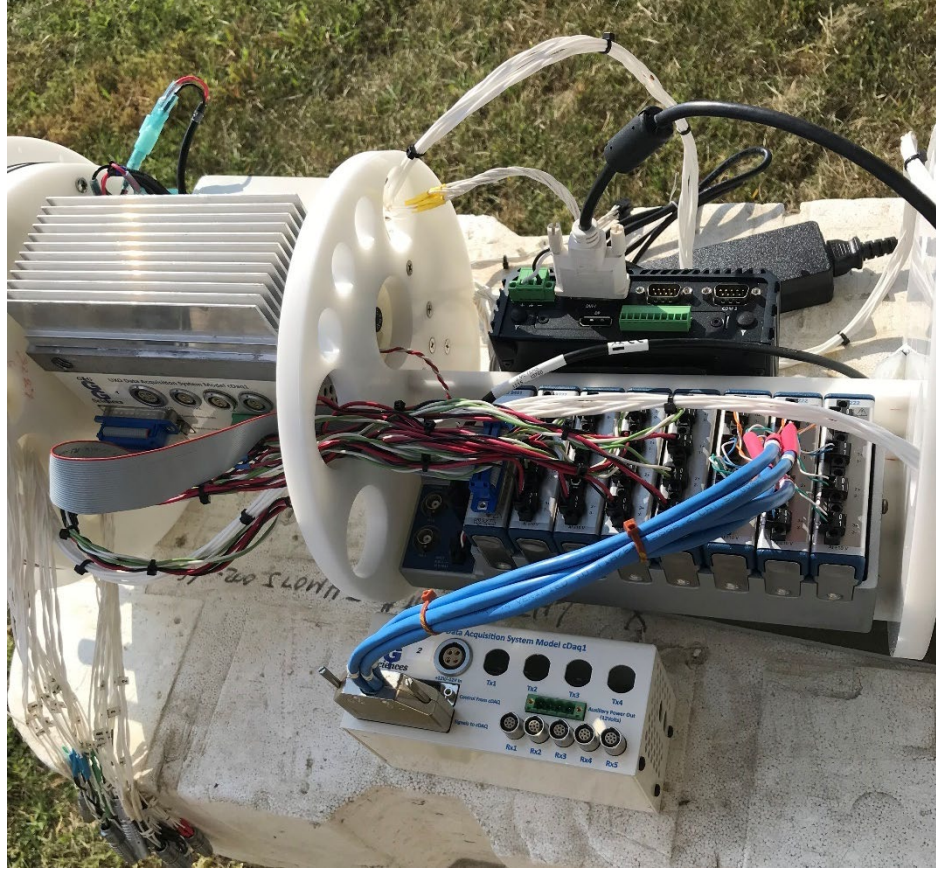


Figure 5-11. cDAQ Data Acquisition System

The array that we tested has a large (0.53 m by 2.34 m) outer transmit coil surrounding pair of smaller (0.5 m by 1.14 m) transmit coils. Each has 14 turns. The outer coil carries 3.5 A and the inner coils each carry 4.0 A. There are six 3-axis receive cubes spaced along the width of the array. The “miniMTA” array is shown in Figure 5-12.

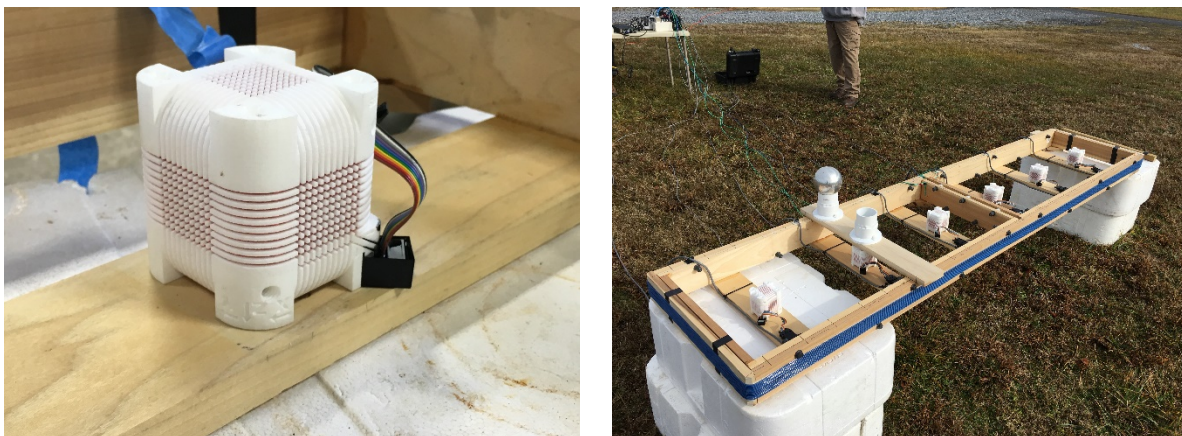


Figure 5-12. 3D Printed Receive Cube (Left) and Array Calibration Using Standard 4 in Diameter Aluminum Ball (Right).

By itself, the outer coil can accurately locate targets as they pass underneath. It does not, however, have adequate cross-track target illumination over its central half to properly constrain data inversions for estimating target polarizabilities used for classification. It performs better for targets out more towards the edges. The full array performs well over its entire width, as does the pair of inner coils by itself (*i.e.* without the outer coil). Figure 5-13 shows the primary field components for each of the transmit coils across the array along a line 20 cm from the array centerline and 50 cm below the array. The cross-array (Y) field component goes through zero at the center of Tx1. The target polarizabilities will not be properly constrained with inversions that rely on data collected when the target passes through this area. Combining data using Tx2 and Tx3 should eliminate this problem by providing cross-track illumination over the entire width of the array. Significantly, the strengths of the primary field components for each of the transmit coils are comparable to each other at this range. This is because we are still in the near field of the coils.

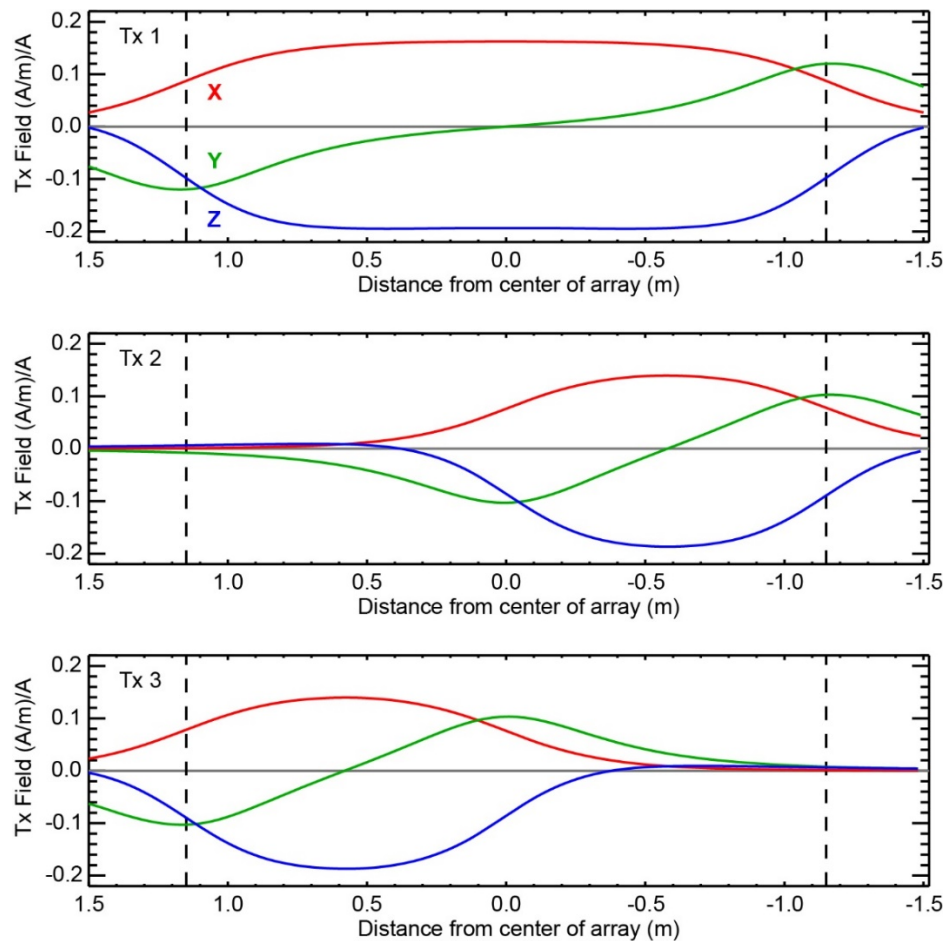


Figure 5-13. Primary Field Components Across the Array Along a Line 20 cm from the Array Centerline and 50 cm Below the Array.

The validated signal and noise models have been combined with background response models validated in SERDP project MR-2409. Calculations using these models with background variability consistent with the MR-2409 data (appropriately scaled up the MTA array) lead us to conclude that the proposed full-size MTA array will be able to reliably classify large (105 mm and larger) munitions at ranges exceeding 2 m in marine environments.

Figure 5-14 compares test results for the classification performance of the half-scale MTA array with the results of simulations which combine signals calculated from the 57mm library polarizabilities using the standard dipole model [12] with an empirical noise model. Results for the full three Tx coil array are shown in the plot on the left and those using only the inner pair of Tx coils are shown in the plot on the right. Gray dots correspond to individual calculations and serve to show the expected variability. The curves show the median through a series of 1000 runs each at 10 cm intervals across the left half of the array and continued over the right half assuming symmetry. Dashed lines show the edges of the array. The blue diamonds represent collected data. For the most part the model calculations are in good agreement with the test data. Both show that for each Tx configuration classification performance is best across the center half of the array and drops smoothly and monotonically towards the edges. In both cases there is sufficient cross-track target excitation to successfully constrain the inversion over the entire width of the array. Classification performance with the two Tx coil array is not quite as good as with the full array. Simulations with enhanced noise levels suggest that about 60% of the difference can be accounted for by the fact that we use 50% more data with the three-Tx inversions than with the two-Tx inversions in this static test.

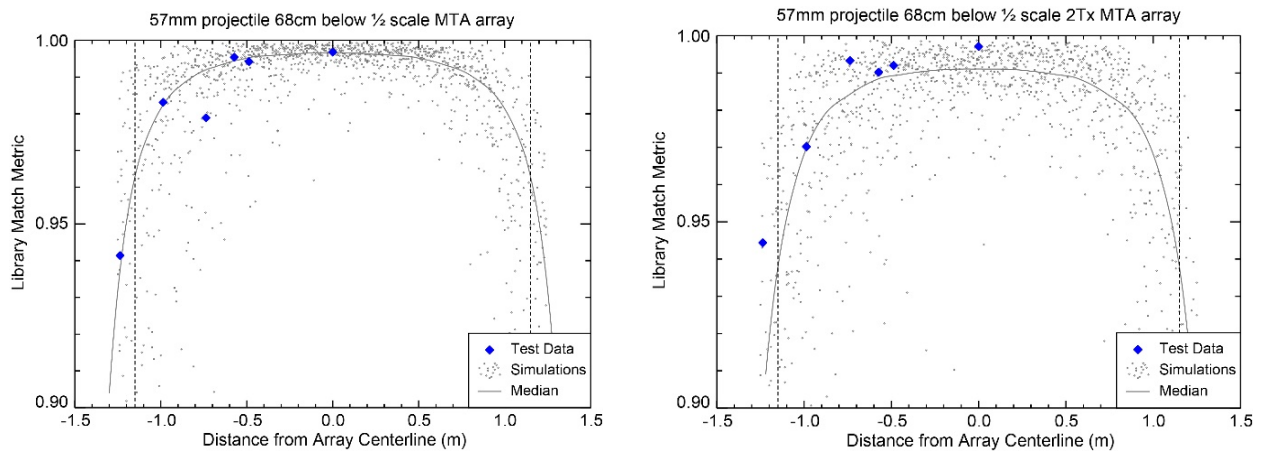


Figure 5-14. Test Data for Classification Performance of the Half-scale MTA Array Compared with Model Simulation Results.

Full array (three transmit coils) on the left, two inner transmit coils on the right.

Figure 5-15 shows model simulation results for expected performance of the full-size MTA array with 480 A-turns transmit current. Gray dots show individual simulation results and the solid curve shows the median through a series of 1001 runs each at 20 cm depth intervals. The dashed curve shows the expected performance using only the inner pair of transmit coils. The simulations combine target signals calculated from library polarizabilities for a 105 mm projectile (105mmP ATC#006_HE-M1) with noise from the empirical noise model. The signal plus noise data are inverted and the calculated polarizabilities compared with the library polarizabilities using the UX-Analyze classification algorithm. We used the average tow speed (1.72 m/s) from the Lake Erie MTA demonstration [13] with random cross-track target locations distributed uniformly over the width of the array and random target orientations distributed uniformly over the range $\pm 90^\circ$ yaw and $\pm 10^\circ$ pitch. The transmit coils have 24 turns each and carry the nominal 20 A MTA current (*i.e.*, 480 A-turns). At a range of 2 m the median library match value is 0.983.

We ran simulations for several variants of the array. Using only the two inner transmit coils the performance is slightly reduced to 0.976. In this case (survey mode) the data rate for a complete (2 Tx) cycle is 15 Hz compared to 10 Hz for the baseline 3 Tx cycle, so we don't take the hit seen with the static test data. Increasing the receiver density to twelve cubes spread evenly across the full array has little effect on performance (0.985 vs. 0.983 at 2 m with the three Tx coils). At ranges of interest (the array typically flies > 1 m above the bottom) the spacing with six cubes (0.77 m) provides adequate resolution. By way of comparison the standard 2x2 TEMTADS array rides a nominal 20 cm above the ground and has a receiver cube spacing of 40 cm. Increasing the transmit moments can significantly improve performance. With 1000 A-turns in each of the Tx coils the median library match value at 2 m is increased from 0.983 to 0.997.

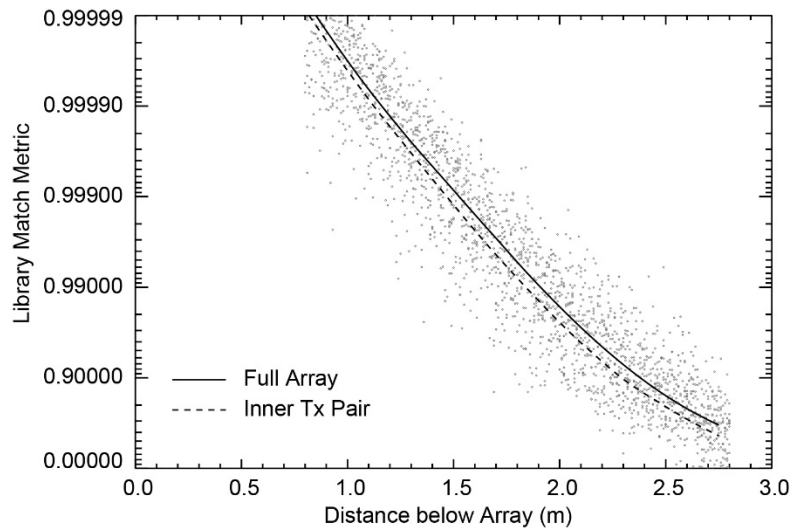


Figure 5-15. Simulation Results for Expected Performance of Full-size MTA Array with 480 A-turns Transmit Current.

The target is a 105 mm projectile. Gray dots show individual simulation results and the solid curve shows the median. The dashed curve shows the expected performance using only the inner pair of transmit coils.

The next phase of the project was to construct a full-size array that can be tested in salt water in a series of carefully controlled experiments, combined with additional modeling and simulations. The detailed results of our testing and analysis of the effects of array configuration on classification performance are available in our interim report from 2017 [6].

5.4.2 Upgraded MTA

After installation of the transmitter coils and the triaxial receiver cubes, in waterproof housings, the full-sized array was tested in air, on land at our facility in Welcome, MD in August, 2019. The basic characteristics of the MTA array response were characterized following the evaluation methods used previously for the miniMTA. Dynamic data collection was simulated in two ways. First, by observing the response from each of the receivers in one half of the array as a 12-in diameter steel ball was rolled along a fiberglass rail placed across the array as shown in Figure 2-8 (center). The rail was placed above the receiver cubes and transmitter loops, and forward of the receiver cubes so that a response would be observed in all three axes of the receiver cubes.

The observed responses for all of the data channels are shown in Figure 5-16 and Figure 5-17. Responses for receiver cubes Rx1 – Rx6 are shown by the red, orange, yellow, green, blue and violet curves, respectively. In Figure 5-16, the sphere passes over Tx3 and Rx1, Rx2, Rx3. In Figure 5-17, the sphere passes over Tx2 and Rx4, Rx5, Rx6. The plots are arranged as follows. The left-hand column of plots shows responses in the X-direction, the center column of plots shows responses in the Y-direction and the right-hand column of plots shows responses in the Z-direction. The top row shows responses to Tx1 (the large outer coil), the middle row shows responses to Tx2 (the smaller coil enclosing cubes 4-6) and the bottom row shows responses to Tx3 (the smaller coil enclosing cubes 1-3). The ball is roughly 60 cm above the array and offset 25 cm from the array centerline. With Tx1, there is a strong response in each receiver axis as the ball passes each cube. With Tx2 and Tx3 there is a correspondingly strong response in each of the cubes enclosed within their respective coils. With the six receive cubes like this, either the outer transmit coil (by itself) or the inner Tx pair can serve to detect and locate targets. At issue is their classification performance. For comparison, the results of similar testing from the miniMTA are shown in Figure 5-18.

Secondly, classification performance was evaluated by placing a target in a series of fixed positions along the X-direction (perpendicular to the array) under the array, collecting several hundred data points at each position, inverting the data using the standard dipole response model [12], and then comparing the principal axis polarizabilities from the inversion with corresponding polarizabilities from the standard munitions library assembled in ESTCP project MR-201424 using the UX-Analyze library matching procedure [14].

The target (item 105mmP ATC#006_HE-M1 in the ESTCP MR-201424 library) was placed on the ground, lying flat and parallel to the array. The target run consisted of sixteen measurements of the response at 30 cm intervals as the target was moved in from 4.98 m behind the array to 18 cm behind the array centerline, trailing behind Rx4. The rail was oriented perpendicular to the array in the X-direction. In this case the center of the array was nominally 66 cm above the center of the target. Data were collected using dynamic mode with the standard 2.77 ms decay and 20% gate widths. Each measurement represents an average of about 300 points. The results are shown in Figure 5-19.

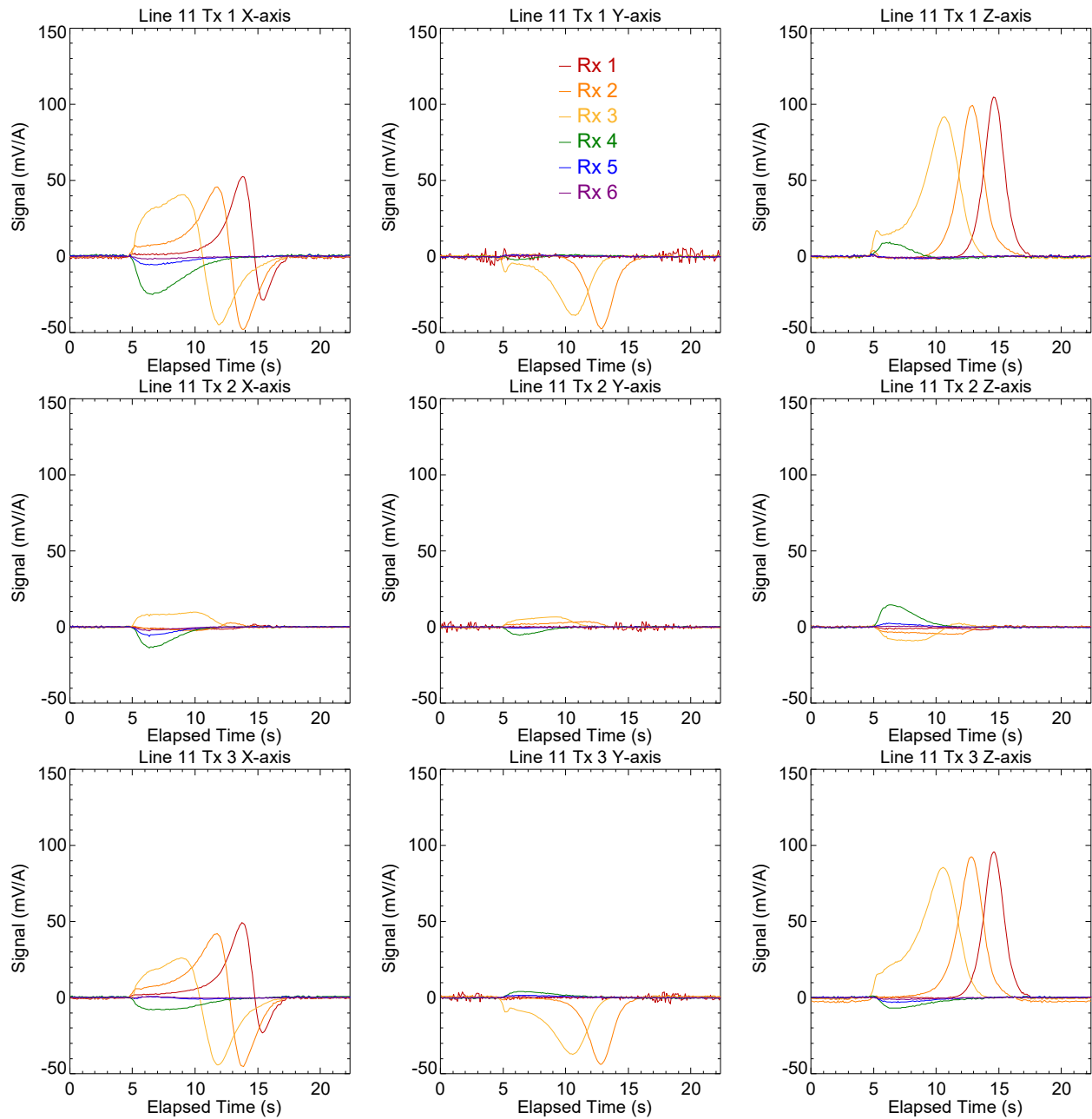


Figure 5-16. Measured Response as a 12-in Diameter Steel Ball Is Rolled Along a Rail Above the MTA Array.

Responses for receiver cubes 1-6 are shown in red, orange, yellow, green, blue and violet. The ball is roughly 60 cm above the array and offset 25 cm from the array centerline.

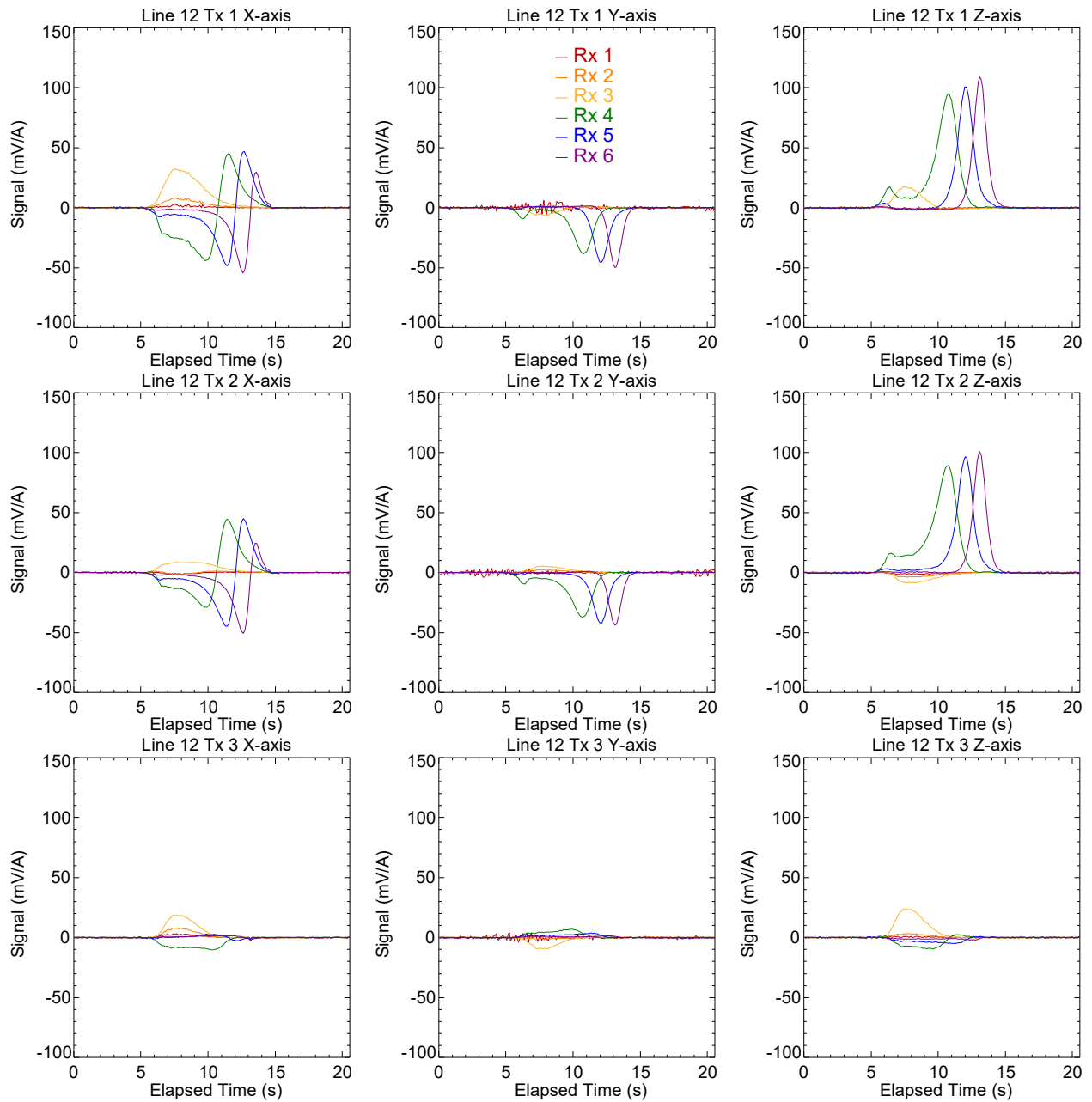


Figure 5-17. Measured Response as a 12-in Diameter Steel Ball is Rolled Along a Rail Above the MTA Array.

Responses for receiver cubes 1-6 are shown in red, orange, yellow, green, blue and violet. The ball is roughly 60 cm above the array and offset 25 cm from the array centerline.

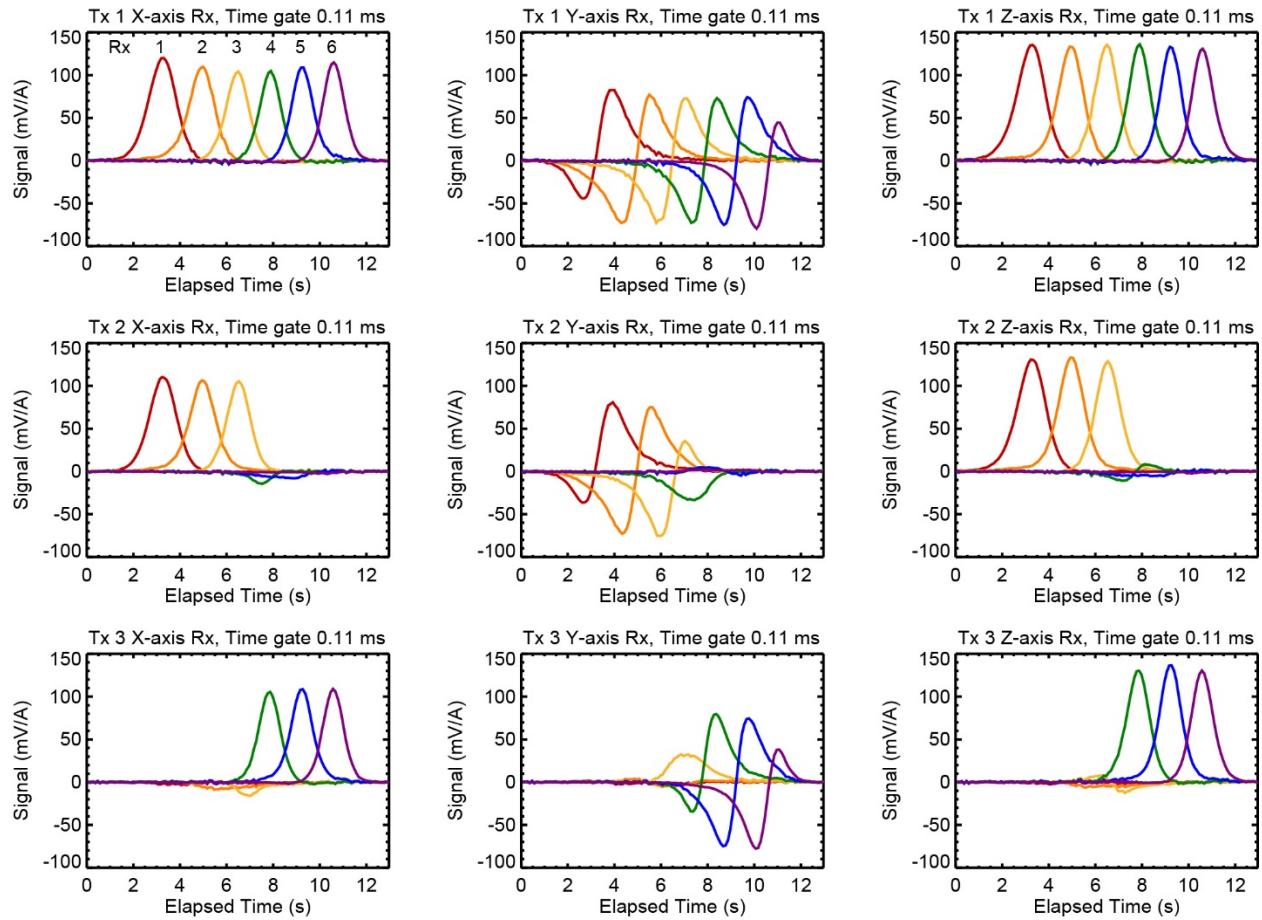


Figure 5-18. Measured Response as a 15 cm Diameter Aluminum Ball Is Rolled Along a Rail Across the miniMTA Array.

Responses for receiver cubes 1-6 are shown in red, orange, yellow, green, blue and violet. The ball is roughly 20 cm above the array and offset 20 cm from the array centerline.

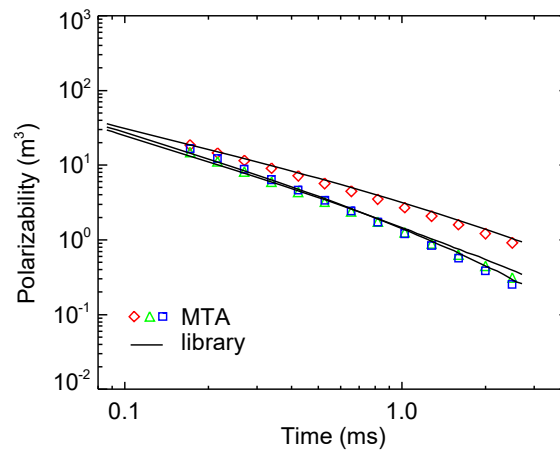


Figure 5-19. Inversion Results for a 105mm Projectile, Data Collection Simulating a Dynamic Collection Pass under the MTA.

The black lines represent the corresponding library polarizabilities.

Based on these results, it was determined that all elements of the array were functional, but that the transmit currents that could be achieved with the existing configuration did not meet the design goals of the planned upgrade. In consultation with the transmitter manufacturer, it was determined that the original modification plan for the standard cDAQ EMI transmitter from nominally 6 to nominally 20 A was not feasible with the new, larger EMI coils.

The transmitter was modified to operate on ± 24 VDC supplies, up from the standard ± 15 VDC supplies. Increasing the supply voltages to the transmitter directly increases the transmitter output current, as shown in Figure 5-20 (a). However, without serious risk to the transmitter itself, the manufacturer recommended not increasing the supply voltage beyond ± 24 VDC. At this supply voltage, the transmit current achievable are main (outer) loop to 5.7 A, and to 8.3 A in the inner loops. As a window of opportunity was available in September, 2019 for in-water testing, the team determined that comparing the in-water performance of the EMI array to the land-based performance was more valuable than the potential of damaging the transmitter electronics by pushing the supply voltage further.

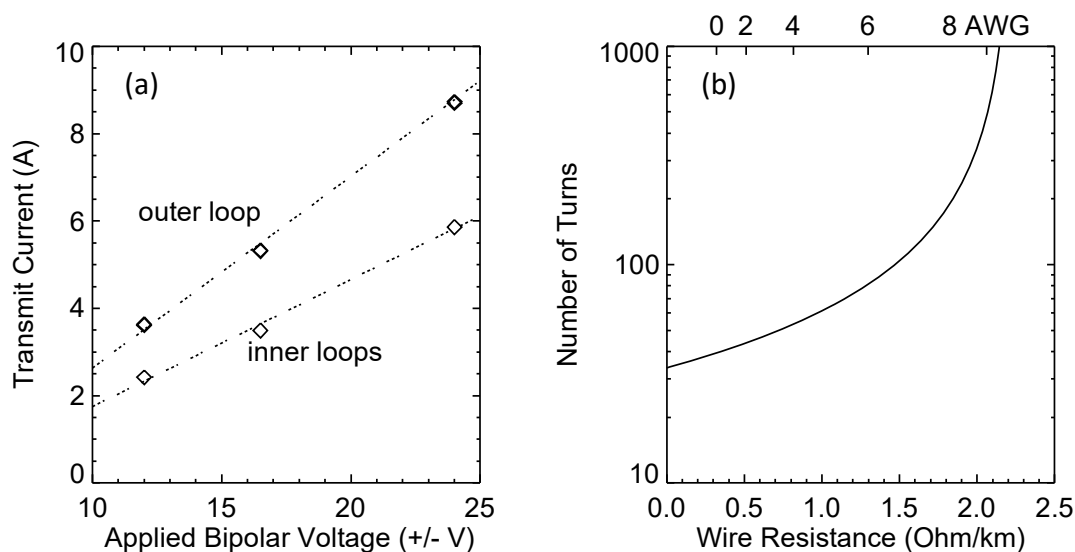


Figure 5-20. (a) Transmit Current vs. Applied Bipolar Voltage for MTA EMI Array (See Text for Discussion of Voltage Nomenclature). (b) Number of Turns and Wire Resistance Need to Achieve 800 A·Turns of Transmit Current in the Main (Outer) Loop.

5.5 DATA COLLECTION

5.5.1 Scale of the Demonstration

The demonstration portion of this project was comprised of two single-day sorties, one on September 26, 2019 and one on December 19, 2019. Prior to each sortie, a test strip of metallic items were seeded onto the river bottom. For each sortie, the captain of the vessel navigated as closely as feasible over the centerline track of the test strip. Multiple passes were made in both directions on each sortie at several altitudes to maximize the data collection opportunity.

5.5.2 Sample Density

Emplaced target separation was 10m. Cross-track separation between the receiver cubes in the array is fixed at roughly 60cm between left and right pairs and 120cm between sides^a. With a nominal rate of forward advance of 1 m/s for the vessel and array) and an overall operating frequency^b for the array of 10 Hz, a downtrack sample spacing of 10 cm was achieved. This survey speed and corresponding downtrack sample spacing was chosen to maximize the SNR of the EMI data collected. As was discussed in Section 5.4.2, the results of our land-based testing indicate that downtrack sample spacing of 25cm, and a corresponding survey speed of 2.5 m/s, would still allow for the collection of sufficient quality EMI data to support classification.

5.5.3 Quality Checks

Preventative maintenance inspections were conducted at least once a day by all team members, focusing particularly on the sensors and cabling. Any deficiencies were addressed according to the severity of the deficiency. Parts, tools, and materials for many maintenance scenarios were available in the system spares inventory which was on site.

Numerous visual indicators are provided in MagLog and EM3D to alert the geophysicist operator to the status of the various subsystems. Due to the short duration of the demonstration and the difficulties of making useful QC measurements already being underway, typical quality checks of target response and background noise levels are discussed as part of the data collection in the next section.

5.5.4 Data Summary

5.5.4.1 *September 26, 2019 Testing*

On September 26, 2019, the test strip had six targets attached to a line stretched between a pair of anchors a distance of 102 m apart. The targets were spaced at 10 m intervals in the middle of the line. There were two 12-in diameter hollow steel balls (wall thickness 1/8-in, which had been drilled through so they would sink), two 4-in diameter by 12-in long steel pipe sections (105mm projectile surrogates) and two 6-in diameter by 18-in long steel pipe sections (155mm projectile surrogates). Fifteen passes along the test strip were run with the array at nominal altitudes above the bottom ranging from 0.75 m to 1.5 m. Layback calculations for reconstructing the array trajectory which were part the original data acquisition system were not available for this test. Signals were registered for 33 of the 80 possible target encounters. For 28 of these the target passed under the array and the remaining 5 targets passed nearby, off to the side of the array.

^a 61.3, 60.3, 121.6, 61.3, and 60.9 cm, from cube 1 to cube 6, respectively.

^b For 60 Hz rejection, the system collects 3 shots, or stacks, for each transmit cycle of a decay time of 2.78 ms, or 33 ms total, per transmitter. There are three transmitters, so the operational frequency is $1/(3*33 \text{ ms})$, or 10 Hz.

The *R/V* Captain maneuvered the vessel along the target string for each pass using the onboard GPS navigation and the known coordinates of the anchors at either end of the string, attempting to compensate for cross-track winds and currents. It was apparent from the data, that on many of the passes the array track passed to one side or the other of some or all of the targets as the Captain honed his approach to running survey lines. The low number of successful target encounters was largely due to the fact that, because of miscommunication with the VIMS crew, buoys had been tethered at either end on the target line and the Captain had to maneuver around them. They had understood that the plan was to cross perpendicular to the target line over each target individually.

5.5.4.2 *December 19, 2019 Testing*

On December 19, 2019, the test strip had six targets spaced at 10 m intervals along a line stretched between a pair of anchors. The targets are shown prior to deployment in Figure 2: from left to right the targets are a 12-inch diameter hollow steel float ball (with holes drilled for flooding), a section of chain attached to a board, a crab pot, a tire rim, an axle rod (shown also in the photo on the right) and a 6-inch diameter by 18-inch long pipe section (155mm projectile surrogate). At the far right is one of the Danforth anchors used to secure the test strip. The targets were selected from recovered items warehoused at VIMS as representative of potential clutter items which could be encountered during marine surveys. During data collection the captain steered the *R/V* parallel to the line between the two anchor points using his on-board navigation display while attempting to compensate for currents in order to keep the array along the line. Nine passes along the test strip were run with the array at nominal heights above the bottom ranging from 0.75 m to 1.25 m. Following the target data runs, we collected noise data with the array at mid depth.

The buoys marking the test strip were offset for this deployment. Additionally, array trajectories were reconstructed using the vessel GPS track, vessel compass heading, and tow cable angle at the tow point at the stern of the vessel. The reconstruction includes layback distance corrections and tow point angle offset corrections which minimized the spread in same-target positions. The array was too far off to the side of the target line on the first two passes. Signals were registered on 30 of the remaining possible 42 crossings. We also observed signals on some crossings over one or the other of the anchors. For the eight missed targets the reconstructed track was seen to drift off to one or the other side of the target string and the array did not pass over the target. Exceptions were seen in a few of the higher altitude passes over the piece of chain, which had the weakest signal of all of the seed items.

5.6 VALIDATION

Validation of the performance of this technology comes primarily from comparison of the classification results of the data analysis to the ground truth. The identification of the seed items is known to the project team in advance from deployment and verified during recovery. Precise location information was not recorded during emplacement and was therefore not a major focus of the demonstration results.

6.0 DATA ANALYSIS AND PRODUCTS

6.1 PREPROCESSING

Array location as a function of time was calculated using the vessel GPS location, heading, tow cable angle and cable length. Time offset between sensor data and array location was determined by comparing known target locations with time of peak signals in the sensor data. The sensor data and array position data (including array height above the bottom) were then merged. The array data were median filtered using a filter width of 4 m to remove background variability due to sensor height above bottom variations.

6.2 TARGET SELECTION FOR DETECTION

Target detection was based on signal levels standing above background noise in the median filtered data in any of the Z-axis data channels at 0.216 ms decay.

6.3 PARAMETER ESTIMATION

The raw signature data from AGC sensors reflect details of the sensor/target geometry as well as inherent EMI response characteristics of the targets themselves. In order to separate out the intrinsic target response properties from sensor/target geometry effects, we invert the signature data to estimate principal axis magnetic polarizabilities for the targets. The data are inverted using the standard induced dipole response model wherein the effect of eddy currents set up in the target by the primary field is represented by a set of three orthogonal magnetic dipoles at the target location [12]. The measured signal is a linear function of the induced dipole moment $\mathbf{m}$, which can be expressed in terms of a time dependent polarizability tensor $\mathbf{B}$ as

$$\mathbf{m} = \mathbf{U}\mathbf{B}\mathbf{U}^T \cdot \mathbf{H}_0$$

where $\mathbf{U}$ is the transformation matrix between the physical coordinate directions and the principal axes of the target and $\mathbf{H}_0$ is the primary field strength at the target. The eigenvalues $\beta_i(t)$ of the polarizability tensor are the principal axis polarizabilities.

Given a set of measurements of the target response with varying geometries or "look angles" at the target, the data can be inverted to determine the local (X,Y,Z) location of the target, the orientation of its principal axes (ϕ, θ, ψ), and the principal axis polarizabilities ($\beta_1, \beta_2, \beta_3$). The basic idea is to search out the set of nine parameters (X,Y,Z, $\phi, \theta, \psi, \beta_1, \beta_2, \beta_3$) that minimizes the difference between the measured responses and those calculated using the dipole response model.

Inversion is accomplished by a two-stage method. In the first stage, the target's (X,Y,Z) dipole location is solved for non-linearly. At each iteration within this inversion, the nine element polarizability tensor ($\mathbf{B}$) is solved linearly. We require that this tensor be symmetric; therefore, only six elements are unique. Initial guesses for X and Y are determined by a signal-weighted mean. The routine normally loops over a number of initial guesses in Z, keeping the result giving the best fit as measured by the chi-squared value. The non-linear inversion is done simultaneously over all time gates, such that the dipole (X,Y,Z) location applies to all decay times. At each time gate, the eigenvalues and angles are extracted from the polarizability tensor.

In the second stage, six parameters are used: the three spatial parameters (X,Y,Z) and three angles representing the yaw, pitch, and roll of the target (Euler angles ϕ, θ, ψ). Here the eigenvalues of the polarizability tensor are solved for linearly within the 6-parameter non-linear inversion. In this second stage both the target location and its orientation are required to remain constant over all time gates. The value of the best fit X,Y,Z from the first stage, and the median value of the first-stage angles are used as an initial guess for this stage. Additional loops over depth and angles are included to better ensure finding the global minimum.

Figure 6-1 shows an example of the principal axis polarizabilities determined from TEMTADS 5x5 array data. The target, a mortar fragment, is a slightly bent plate about 0.5 cm thick, 25 cm long, and 15 cm wide. The red curve is the polarizability when the primary field is normal to the surface of the plate, while the green and blue curves correspond to cases where the primary field is aligned along each of the edges.

Not every target exhibited a strong enough TEM response to support extraction of target polarizabilities. All of the data were run through the inversion routines, and the results manually screened to identify those targets that could not be reliably parameterized. Several criteria were used: signal strength relative to background, dipole fit error (difference between data and model fit to data), and the visual appearance of the polarizability curves.

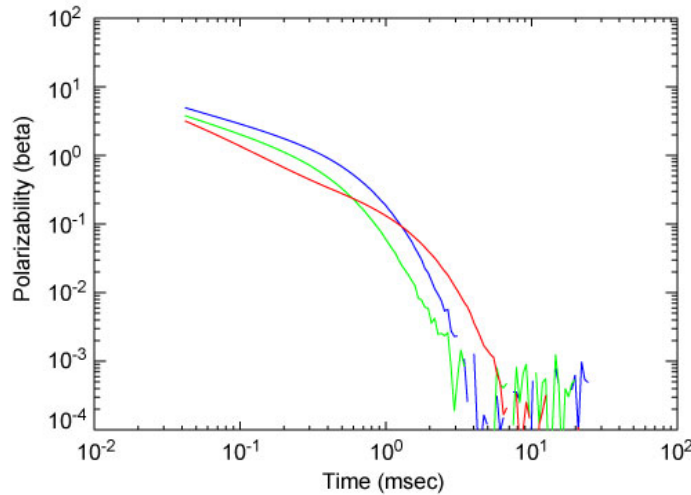


Figure 6-1. Principal Axis Polarizabilities for a 0.5 cm Thick by 25 cm Long by 15 cm Wide Mortar Fragment.

6.4 CLASSIFIER AND TRAINING

Target classification is based on a library matching procedure wherein we compare the quality of both an unconstrained dipole inversion of the TEM array data and the ratio, ρ . ρ is defined as the ratio of the quality of an unconstrained dipole fit of the TEM data to the quality of a dipole fit constrained by principal axis polarizabilities drawn from the signature library. Fit quality is the squared correlation coefficient between the model fit and the data. If ρ is equal to one, then the library item is as good a match to the data as possible. If the value of ρ is small, then the library item is a poor match. For the unconstrained inversion, we utilize an algorithm which compares our derived polarizabilities with a library of known target signatures.

The match is based on three criteria: the amplitude of the primary polarizability, and the ratio of the second and third polarizabilities to the first. We have computed match metrics, each of which runs from 0 (terrible match) to 1 (perfect match).

Our experience with these sensors has been that principle polarizabilities determined from in-air measurements are indistinguishable from those determined from measurements taken over emplaced targets. We have an extensive collection of inert military munitions collected from many sources which were measured at our home facility using the TEMTADS family of sensors mounted on a test stand. We have also assembled a fairly extensive polarizability database for clutter items recovered from several different sites. This was used as training data for establishing UXO/clutter discrimination boundaries on the coherence ratio ρ and on the direct comparison metric.

6.5 DATA PRODUCTS

The basic data products were plots of (median filtered) signal as a function of time for each survey line over the target string and dipole model fits to the data over each detected target. Figure 6-2 is an example of signals vs. time for survey line 10 on September 26, 2019. Examples of the results of dipole inversion are shown in sections 7.6 and 7.7.

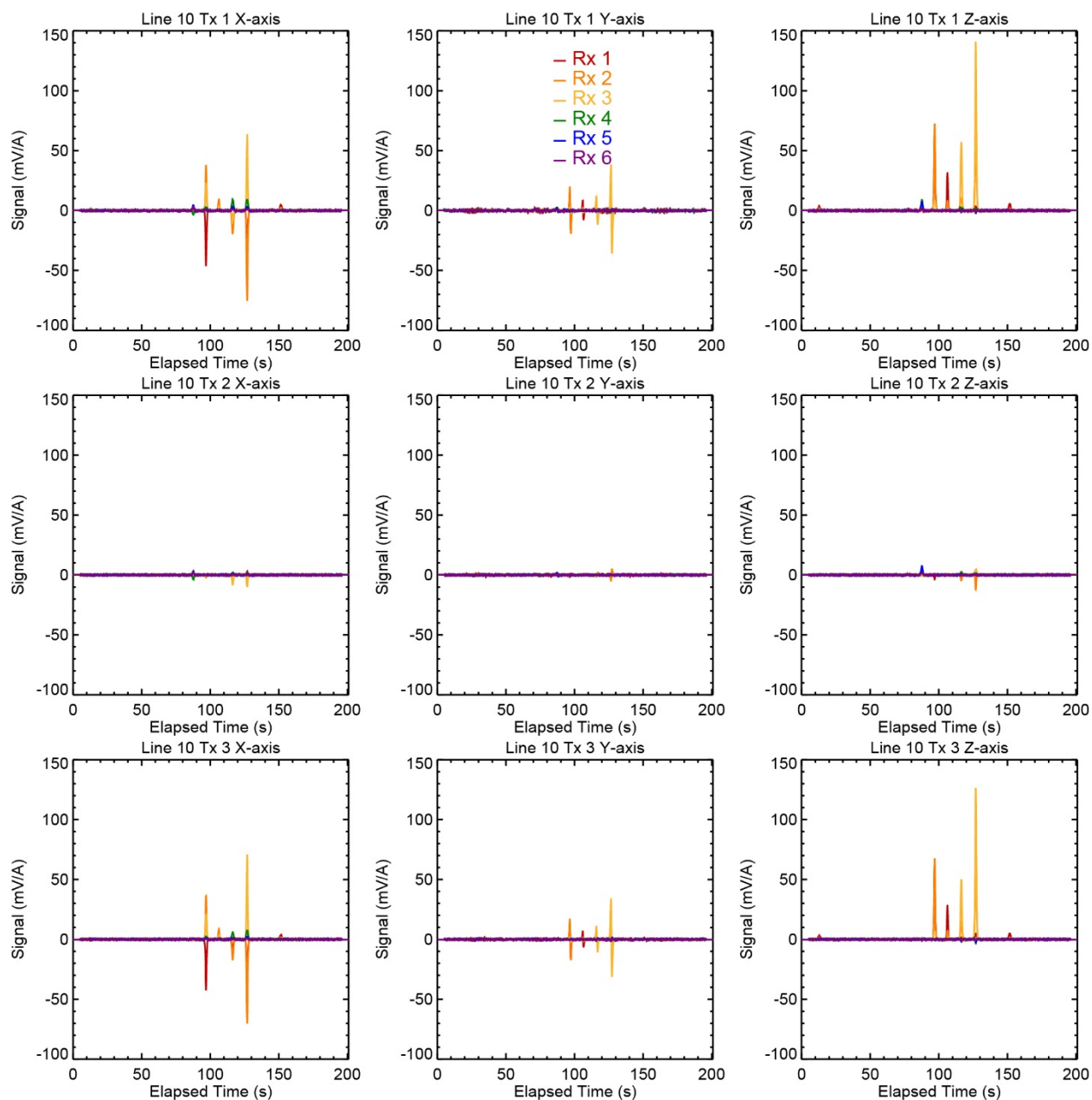


Figure 6-2. Median Filtered Signals for Survey Line 10 on September 26, 2019.

7.0 PERFORMANCE ASSESSMENT

The performance objectives for the MTA test flights are summarized in Table 3-1 and are repeated here as Table 7-1. The results for each criterion are subsequently discussed in the following sections. As discussed in Section 3.0, the success levels for this project's objectives were lowered relative to levels which would have otherwise been specified in accordance with the projected MTA performance shown in Figure 2-5.

Table 7-1. Performance Results for this Demonstration

Performance Objective	Metric	Data Required	Success Criteria	Success? (Yes/No)
Quantitative Performance Objectives				
Detection of Anomalies	Detection of emplaced seed items	Detection of anomalies as a function of reconstructed trajectory and altitude	All seed items detected when overflowed by array at or below expected altitude	Yes
Correct Classification	Number of seed items correctly identified	Classification results from Data Analyst	100% correct classification of seed items with peak signal > 0.1V	Yes
Positional Accuracy	Reproducibility of reconstructed seed item locations from pass to pass	Similar results as from previous magnetometer surveys with the MTA	Reproducibility within 20% of previously demonstrated 1 m	Yes
Qualitative Performance Objective				
Implementation	Upgraded system was assembled, deployed, and data collected	Team and Data Analyst feedback	EMI data were collected in the marine environment	Yes
Robustness & Reliability	Number of significant technical issues	Field logs of significant technical issues	≤ 1 significant technical issue per day	Yes

7.1 OBJECTIVE: DETECTION OF ANOMALIES

This objective relates to the detection of metallic anomalies overflowed by the MTA's wing.

7.1.1 Metric

All seed items were emplaced on the bottom surface and the MTA wing was flown over the items at increasing altitudes. Based on the array performance characteristics determined on land, the detection response of the area for a given seed item can be modeled. Any targets covered by the wing at the demonstrated altitudes should be detected.

7.1.2 Data Requirements

The data requirements are the locations and identifications of the test objects and an analysis of the flight path and altitude for each run.

7.1.3 Success Criteria

Success is defined as having detected all seed items that were actually overflowed by the wing on a given pass, and were expected to be detectible based on predicted response and measured SNR. As stated above, this success criterion has been reduced from a more rigorous criterion based on physically-based detection levels and measurement standoff distances.

7.1.4 Results

This objective was successfully demonstrated. All targets were detected when overflowed by the MTA wing at an altitude predicted to observe the target given the modeled response and flight-specific SNR.

7.2 OBJECTIVE: CORRECT CLASSIFICATION

This objective relates to the classification of metallic anomalies detected from the dynamic data collected by the MTA's EMI array.

7.2.1 Metric

A limited set of seed items were emplaced, each with a unique magnetic polarizability signature. The metric is therefore the correct classification of each detected seed item.

7.2.2 Data Requirements

The data requirements are the locations and identifications of the test objects and an analysis of the flight path and altitude for each run, the list of detected anomalies for each run, and the classification results.

7.2.3 Success Criteria

Success is defined as having correctly classified all seed items that were actually overflowed by the wing on a given pass, and were expected to be detectible based on predicted response and measured peak signal. Given the limited, and diverse set of objects to match against, no issues of classification for detected items is anticipated. As stated above, this success criterion has been reduced from a more rigorous criterion requiring all seed items to be correctly classified.

7.2.4 Results

This objective was successfully demonstrated. All items overflowed at survey altitudes which corresponded to peak signals large enough to support classification were classified.

As is discussed further in Sections 7.6 and 7.7, the transmit current and therefore the transmit moment of the EMI array, as implemented, did not meet the design goals of the original modeling and therefore the effective distance below the array for correct classification of the target item, a 105mm projectile is only 1.25m, not the 2.4m design goal. With the 0.75 to 1m standoff from the bottom required to fly the MTA wing, this effectively requires the MTA to fly directly above the 105mm projectile to confidently classify it.

7.3 OBJECTIVE: POSITIONAL ACCURACY

This objective relates to the precision of the reconstructed position and fit results from analysis of the dynamic data collected by the MTA's EMI array.

7.3.1 Metric

The metric is comparing the demonstrated positional accuracy to that previously demonstrated by the original MTA.

7.3.2 Data Requirements

The data requirements are the reported locations of the test objects for each run.

7.3.3 Success Criteria

A limited amount of test data was collected over the course of two days with the GPS 1PPS synchronization not enabled. The metric is therefore that the positional accuracy is similar (within 20%) of that previously demonstrated by the original MTA.

7.3.4 Results

This objective was successfully demonstrated. The positional accuracy demonstrated, with the MTA as deployed, ranges from 0.25m to 1.25m, depending on what range of base course deviations are included in the calculation, as discussed in Section 7.7.

7.4 OBJECTIVE: IMPLIMENTATION

This qualitative objective relates to the implementation of the upgrade to the MTA EMI array.

7.4.1 Metric

The upgrade of the MTA's EMI array was a complicated process that involved reactivating an underwater survey platform after several years of idle storage and the integration of an AGC-grade EMI array and electronics into the original wing. The metric is whether or not the wing was successfully upgraded to the point that dynamic survey EMI data could be collected in the water.

7.4.2 Data Requirements

The data requirements are team evaluations and any available survey results.

7.4.3 Success Criteria

Success is defined as having been successful in installing the upgraded EMI array and collecting dynamic survey data, underway, in the water.

7.4.4 Results

This objective was successfully demonstrated. The new EMI-SIB was successfully installed in the wing and did not substantively effect the weight and balance of the wing. Most subsystems checked out as ok. One wing actuator and the tow angle optical encoder needed to be replaced. Several cables and connectors required maintenance / replacement. Once completed, the wing did fly as previously and EMI array data could be collected.

7.5 OBJECTIVE: ROBUSTNESS AND RELIABILITY

This qualitative objective relates to the ongoing operation of the MTA after reactivation and upgrade.

7.5.1 Metric

One sure sign of the ruggedness of a system is how often it requires “persuasion” to keep operating normally. This metric relates to how many issues were encountered during the two test flights.

7.5.2 Data Requirements

The data requirements are team evaluations and records.

7.5.3 Success Criteria

Success is defined as having no more than one major incident requiring surveying be delayed or postponed each survey day.

7.5.4 Results

This objective was successfully demonstrated. For the September 26, 2019 flight, a significant event occurred when the cooling water line for the transmitter broke loose on the deck, spraying water on the MTA electronics rack and shorting out all ship power. Power was successfully restored and the MTA reinitialized successfully. For the December 19, 2019 flight, the captain tried a new survey pattern which effectively brought the wing to a stop during the turn arounds at the end of each line. This had the unintended consequence of destabilizing the wing’s autopilot program resulting in the degradation of altitude control. Several near-mishaps with the wing were experienced but passed with no ill effects. The survey pattern was modified and the issue was resolved.

7.6 SEPTEMBER 26, 2019 DATA SUMMARY

Figure 7-1 (a) is a scatter plot of signal strength vs. array height above the bottom for the 28 targets which passed under the array. The plotted signal strength is the maximum Z-axis response at 0.216 ms from the main transmitter loop on any of the cubes. Signal strength depends on where the target passes under the array, being strongest when the target passes directly under one of the cubes towards the center of the array, and at the closer ranges is weaker when the target passes under the array between two cubes. The dashed lines are response curve calculations intended to bound the measurements and show that the array performed as expected. The lower curve is the signal expected for a 105mm projectile lying flat on the bottom which passes under the array between two of the receiver cubes. The upper is for a 155mm projectile passing under one of the cubes.

Expected signal vs. range was calculated using the standard dipole response model [12] with library polarizabilities [15] for 105mm M1 and 155mm M107 projectiles.

The data were inverted to determine target location, orientation and polarizability using the standard dipole response model [12]. We used a four-meter stretch of data surrounding the target. The background response was subtracted using the average response of adjacent four-meter stretches. Figure 7-1 (b) shows inversion fit quality vs. signal strength for the targets. Fit quality is the correlation coefficient between the data and the model fit to the data. The dashed curve shows the expected behavior of this metric as a function of signal strength:

$$Fit\ Quality = S/\sqrt{S^2 + N^2}$$

where S is the signal and N is the noise. The curve is a universal function of signal to noise ratio (SNR). The peak signal is a proxy for the array SNR in this case. The agreement between the model curves and the data in Figure 7-1 shows that the array is performing as expected.

With this array, we get good estimates of the target polarizability with fit qualities of about 0.75 and higher. Figure 7-2 shows examples. Figure 7-2 (a)-(d) are for the hollow steel ball at nominal array heights of 0.75 m, 1.0 m, 1.25 m and 1.5 m above the bottom. The symbols show the polarizability determined by inverting the array data and the curves are the expected polarizability calculated from formulae derived by Hjelt [16], using a conductivity of 5×10^6 S/m and a relative permeability of 100. Our calculation accounts for the short pulse run-on and the 0.039 ms time lag in our electronics. The inversion fit quality is 0.998, 0.980, 0.837 and 0.617 for (a) through (d), respectively, with corresponding signal strengths of 1.03 V, 0.24 V, 0.056 V and 0.040 V. Deviations between the data-derived and actual (calculated) polarizabilities are less than 15% for the first three (with fit quality greater than 0.8), but 88% for the final one which has a fit quality less than 0.7. Figure 7-2 (e) and (f) show results for the LISO. Here the curves are library polarizabilities. The nominal array heights are 0.75 m and 1.0 m above the bottom, respectively. Fit quality and signal strength are as noted on the plots. The target passed under the starboard edge of the array in Figure 7-2 (e) and near the center in Figure 7-2 (f). Deviations of the data-based polarizabilities from the library polarizabilities are 17% and 15% in these cases.

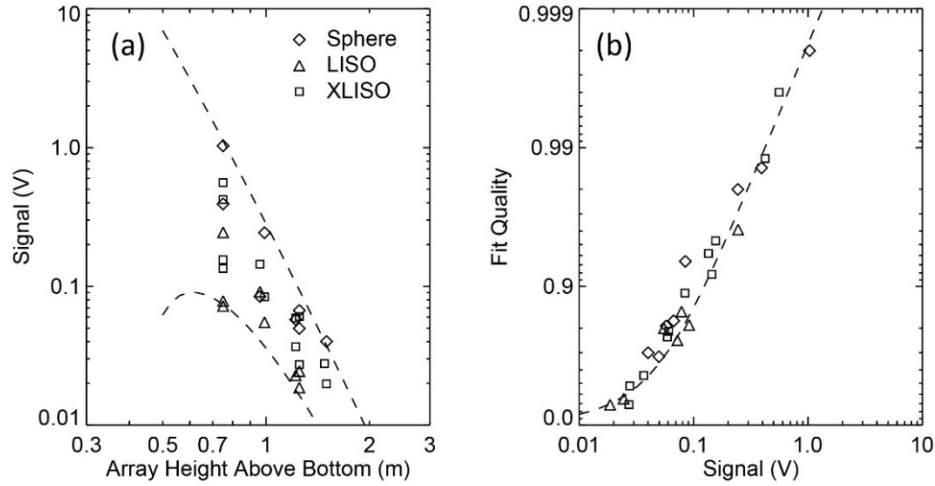


Figure 7-1. (a) Signal Strength vs. Array Height Above Bottom. Dashed Lines Show Calculated Range of Signal Strength for 105mm and 155mm Projectile Targets. (b) Inversion Fit Quality vs. Signal Strength.

Dashed line shows expected behavior.

The root mean square (RMS) noise level during the test was 2.3 mV at the 0.216 ms time gate. This is comparable to noise levels observed at other stations along the York River in the summer of 2016 using a standard TEMTADS transmit coil – receive cube pair [17] encased in a Delrin pressure housing and a second receive cube (offset horizontally by 35 cm) in a pressure housing like those shown in Figure 5-10. The data were collected during a study of background EMI response in marine environments conducted as part of SERDP project MR-2409 [18]. The MTA EMI array design study used a noise model based on in-air data collected with a one-half scale model at the Blossom Point test site and an assumed transmit current of 20 A [6]. The corresponding RMS noise level for these data was 0.69 mV. As presently configured the main loop of the array has 20 turns and carries a current of 5.7 A (114 A·t). Based on the performance models used to produce the curves in Figure 7-1, with noise levels in the 2-2½ mV range we would need about 800 A·t to classify 105mm projectiles at a range of 1.5 m.

New transmit coils could accommodate 800 A·t with the current +/-24 V system. Measurements of the transmit current in the MTA EMI loops at different applied voltages are plotted in Figure 7-3 (a). The dashed lines show the current – voltage relationship

$$\text{Transmit Current} = \frac{\text{Applied Voltage} - \delta V}{R_0 + n\rho L}.$$

$\delta V = 4$ V is a voltage drop across the diode switches, $n = 20$ is the number of turns in the transmit loops, $L = 6.25$ m and 11.28 m are the circumferences of the inner and outer loops, R_0 is the residual resistance in the circuit and ρ is the resistance per unit length of the wire in the loops. The data are fit with $R_0 = 0.84 \Omega$ and $\rho = 11.5 \Omega/\text{km}$. Figure 7-3 (b) shows the number of turns vs. wire resistance required to achieve 800 A·t with an applied voltage of 24 V. The AWG scale corresponding the wire resistance values is shown at the top. 6 AWG seems to be the best choice based on the cross-sectional area occupied by the windings. 81 turns are needed for 800 A·t.

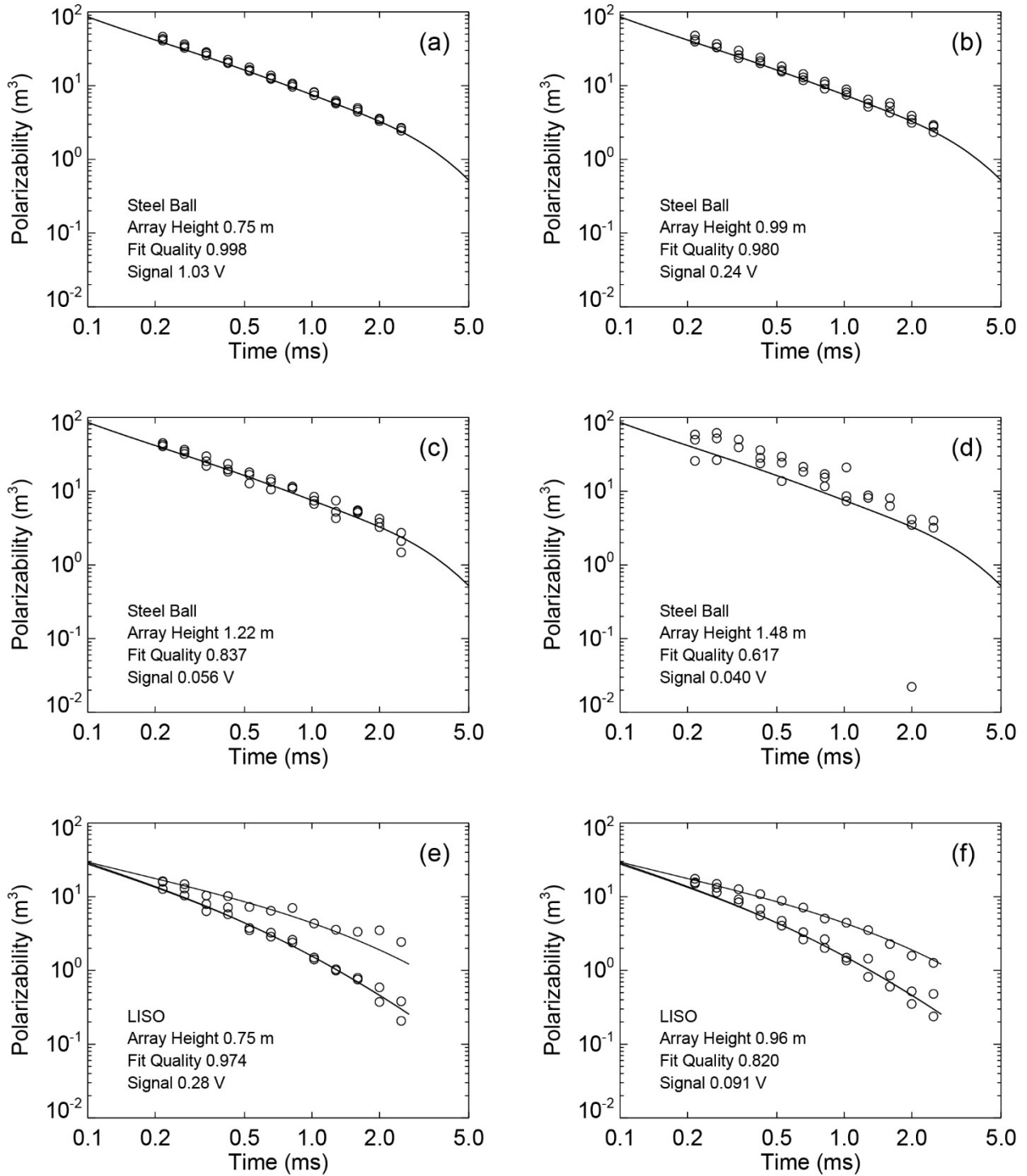


Figure 7-2. Examples of Polarizabilities Determined by Inverting Array Data.

Symbols are measured polarizability, curves are calculated (sphere) or library polarizability (LISO).

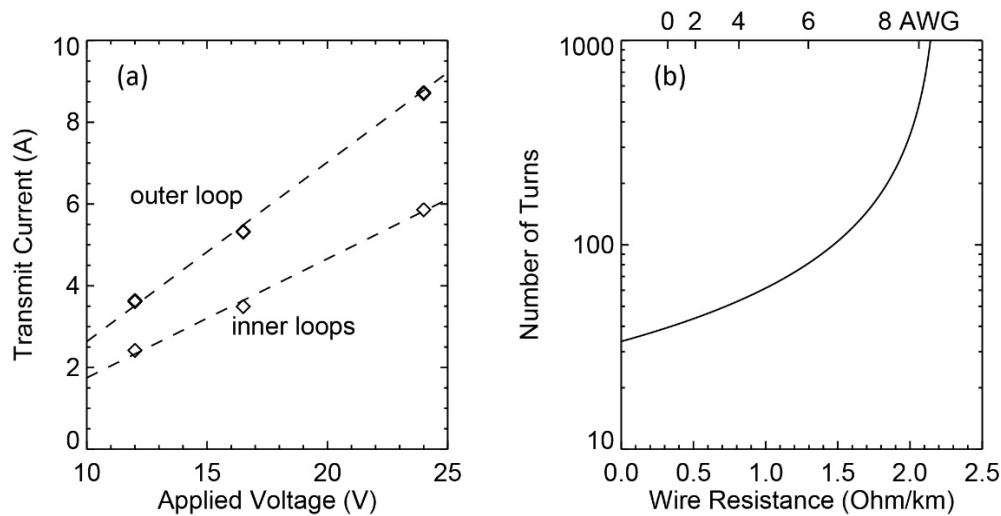


Figure 7-3. (a) Transmit Current vs. Applied Voltage for MTA EMI Array. (b) Number of Turns and Wire Resistance Need to Achieve 800 A·t of Transmit Current in the Main (Outer) Loop.

The available space for the coils is 7 cm high, and the windings are embedded in potting material which extends 2 cm out from the wires in all directions. Heavy-build 6 AWG film-insulated magnet wire (Superior Essex, Inc.) has a diameter of 0.42 cm. 85 turns of this wire could be wound in a bundle 3.8 cm high by 3.7 cm wide.

7.7 DECEMBER 19, 2019 DATA SUMMARY

Target Feature Extraction

The data were inverted to determine target location relative to the array, orientation and polarizability using the standard dipole response model [12]. We inverted a 4 or 5 m stretch of data surrounding the target. The background response was subtracted using the average response of adjacent stretches of the same length. Figure 7-4 shows the polarizabilities from data collected over the various clutter items (float ball, crab pot, tire rim, axle rod and Danforth anchor) and the 155mm munitions surrogate. Signals from the piece of chain were too weak ($\leq 0.058V$, corresponding fit quality ≤ 0.700) to extract reliable polarizabilities.

Target Locations

Figure 7-5 shows the locations of the stronger targets (12-inch diameter float ball, crab pot, tire rim and 6-inch diameter pipe section) determined by inversion of the array data on five or six different passes over the targets. Two of the estimated locations for the pipe section overlay in this plot. Reconstruction of the array trajectory is based on vessel Global Positioning System (GPS) track, vessel compass heading, tow cable angle at the tow point at the stern of the vessel and the cross-track target location from the inversion. It includes layback distance corrections and tow point angle offset corrections which minimize the spread in same-target positions. Array pitch and roll were constant to within a few degrees except when the array was changing depth and did not figure into the reconstruction. Array yaw was not recording during the exercise but could contribute tens of cm to the target location uncertainty for targets passing under the edges of the array.

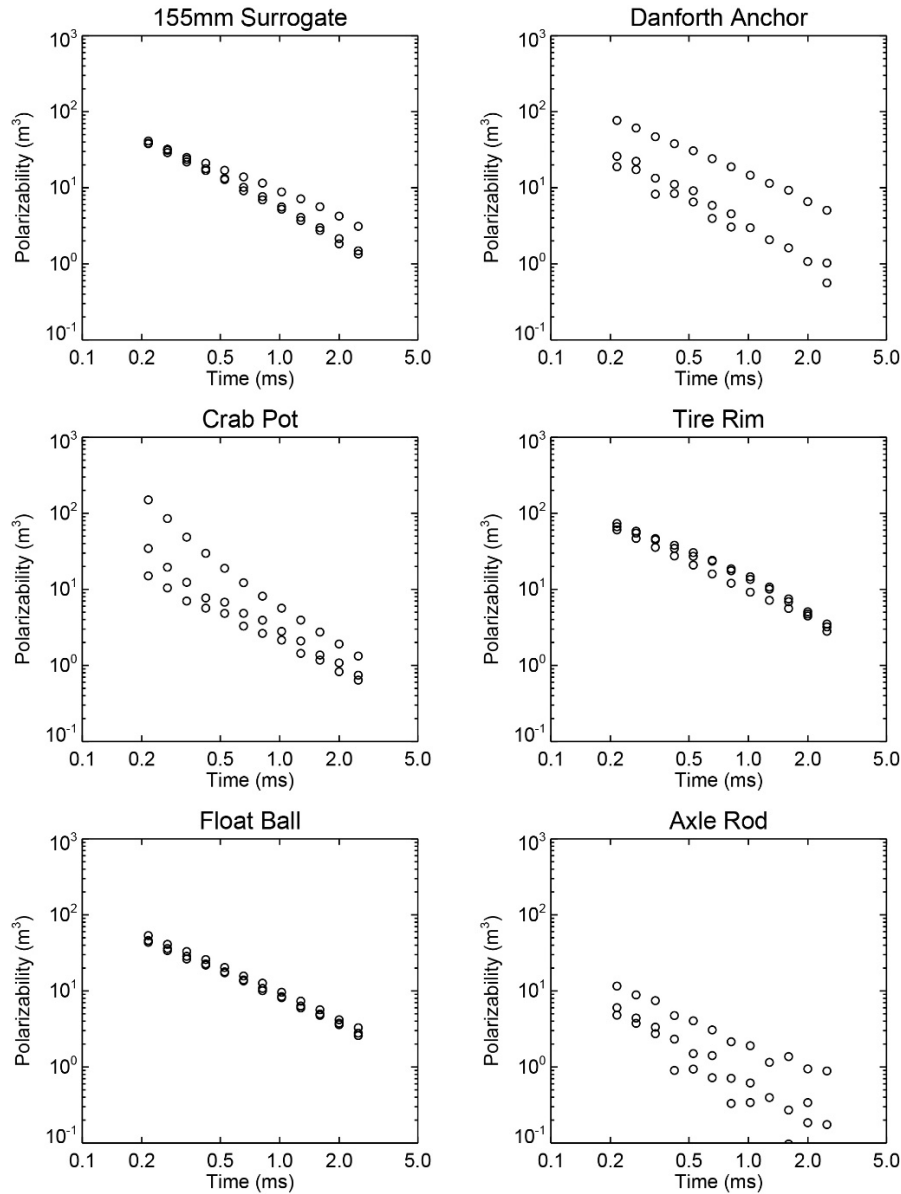


Figure 7-4. Polarizabilities for Clutter Items and Munitions Surrogates.

With the exception of the array attitude information this reproduces the reconstruction of the array position relative to the tow vessel used for the MTA magnetometer array. This is a static representation of the tow geometry, strictly valid only when the forces on the tow cable and body are constant. As noted in the MTA magnetometer array demonstrations the target location accuracy is best if the array is travelling straight and level during the pass over the target, with imprecise position corrections resulting when there are significant variations in the tow parameters during the lead-in to the target crossing [13,19]. It takes time for the motion of the cable and tow body to settle out into their stable tow configuration. Course variability is less important for target feature extraction so long as the array passes over the target because only short stretches of data (4 or 5 m) are used in the inversion.

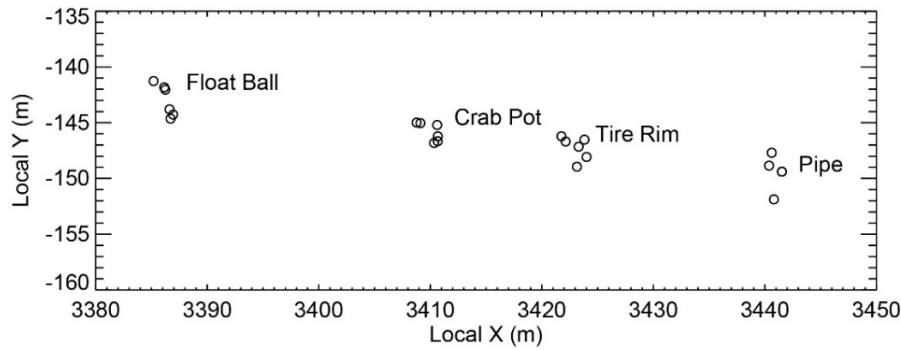


Figure 7-5. Target Locations Reconstructed from Array Crossing Data.

Actual target locations were not surveyed in. We can get an idea of the location accuracy by considering the distances between estimates of the locations of the same target from different passes. For a cluster of circularly normal distributed points (estimated target locations) about a fixed point (actual target location) the average distance between different points is $\sqrt{2}$ times the average distance between any single point and the centroid (actual target location) [20]. Hence $1/\sqrt{2}$ times the average distance between different estimates of the target location approximates the target location error with the array.

Figure 7-6 is a scatter plot of the variations in vessel course over ground and array height above the bottom during the time interval from when the vessel passed over the target to when the array passed over the target (24-25 s) for the target encounters shown in Figure 7-5. Restricting attention to the more-or-less straight and level encounters (course over ground variation less than 7° and height variation less than 0.3 m), we estimate that the position uncertainty with the EMI array is 0.25 m based on the average distance between estimated target locations. The spread in position estimates increases as we allow more course variation: including passes with course over ground variation up to 10° increases the estimate of position uncertainty to 0.50 m. Were we to include all of the passes in Figure 7-6 the target location uncertainty would be 1.25 m.

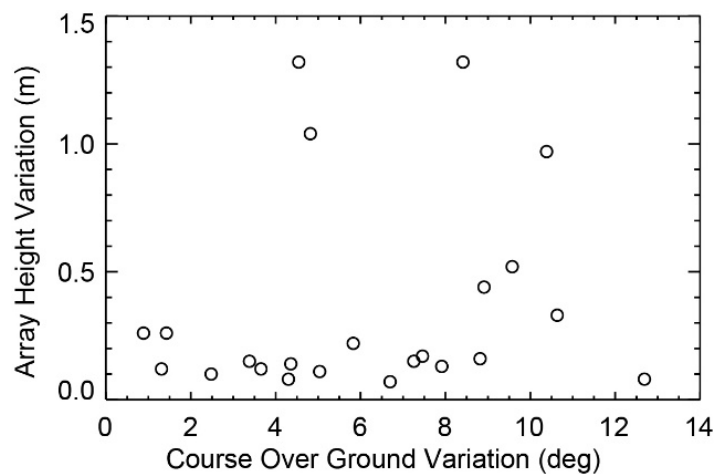


Figure 7-6. Course Over Ground and Array Height Variations During Target Crossings.

The target location uncertainty with the EMI array is consistent with what was reported for target location uncertainties in the magnetometer array demonstrations. Estimates of position accuracy based on calibration lane or instrument verification strip (IVS) collections with the MTA magnetometer array varied from 0.26 m and 0.28 m in shallow (1.3-1.7 m) water at Blossom Point [21] and Duck [4] to 0.61 m and 1.3 m in deeper water (>7 m) at Puget Sound [22] and Lake Erie [13]. It seems that some of the position error at the deeper demonstration sites reflected problems with the techniques used for the emplacement and initial position measurements of the targets. This is consistent with the analysis of the IVS data from the more recent San Diego Harbor data collections [23] (IVS water depth 1.5-3.0 m). In the Vieques demonstration [19] it was also believed that the reported positions of the targets had a larger position uncertainty than positions derived from fitting of the targets from the surveys. In that demonstration, in order to get a more accurate estimate of target location accuracy with the array a calibration line consisting of eleven targets at a depth of ≈ 5 m was surveyed five times on different days. Based on the average distance between fit locations from different surveys of the same target, the position uncertainty was 0.67 m.

Noise Levels

Following the target data runs we collected noise data with the array at mid depth. The upper plot in Figure 7-7 shows the Z-axis receiver noise for the various transmitter/receiver combinations at applied transmitter voltages of 0 V, ± 12 V and ± 24 V. In each group results for transmitter 1 (large loop) are in the middle, transmitter 2 (port) to the left and transmitter 3 (starboard) to the right. Noise level is calculated as the standard deviation of the shot-to-shot signal difference divided by $\sqrt{2}$ for the data channel during the run. There is no significant variation with voltage, although different cubes have different noise levels (lower plot). The mean Z-axis noise level was 2.19 mV. With the exception of the Y-axis on receiver 4 the other axes are similar, with average noise levels of 1.98 mV for the X-axis and 1.87 mV for the Y-axis (excluding receiver cube 4). The pattern of ups and downs for the different receiver cubes is different for the different axes, with no systematic pattern. For cube 4 the average Y-axis noise was 3.44 mV.

These noise levels are lower than the noise level during the first in-water test. In that case there were no dedicated noise runs and the reported level (2.3 mV) was simply the smallest root mean square (RMS) variability over a 10 m window observed on any of the Z-axis data channels for transmitter 1 (large coil). For our data, the corresponding minimum Z-axis noise level for transmitter 1 at 24 V was 1.65 mV.

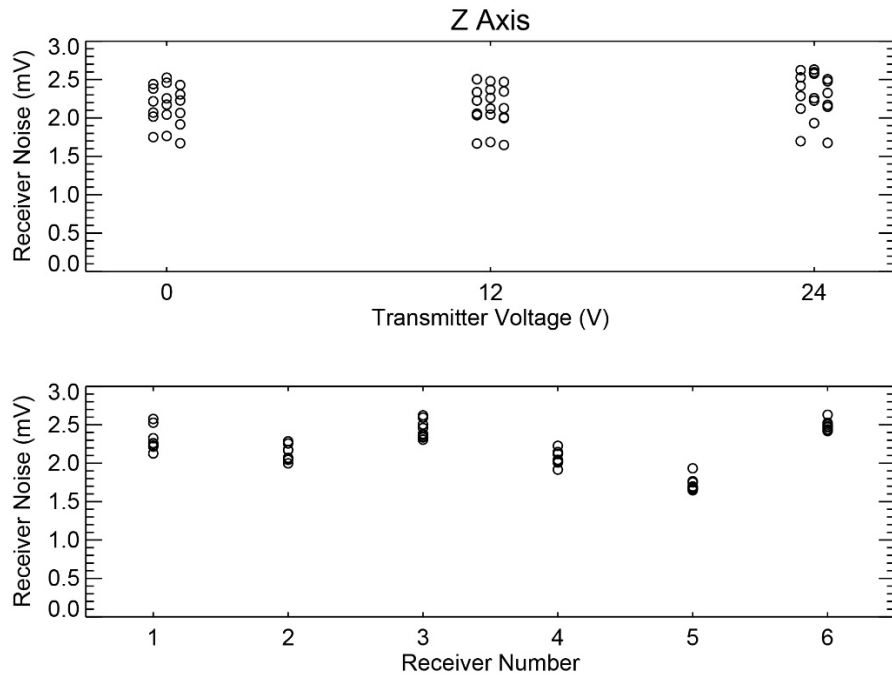


Figure 7-7. Z-axis Receiver Noise Levels for the Various Transmitters and Receiver Cubes at Different Transmitter Voltages.

8.0 COST ASSESSMENT

For the purposes of assessing the costs of implementing this technology, a cost model was developed, which is presented in the next Section. The cost drivers and cost benefits are discussed in the following Sections.

The four-week deployment would survey approximately 415 hectares, or 1025 acres at a total cost of \$212k. At the expected survey rate or 20.7 hectares/day, the survey costs would be roughly \$310/hectare and data analysis costs would be roughly \$65/hectare.

8.1 COST MODEL

A four-week deployment to the opposite coast of CONUS is used as the basis for this model. A team of three (two-person survey team and one-person data analysis team). The rental of a vessel of opportunity for towing the MTA is included along with the use of a local dive team for emplacement of an IVS strip. The model is shown in Table 8-1. As a production rate has not been demonstrated for this array at a significant scale, the average of the coverage rates given in Section 5.3, 20.7 ha/day, used in the cost model.

8.2 COST DRIVERS

Two factors were expected to be strong drivers of cost for this technology as demonstrated. The first is the number of hectares which can be surveyed per day. Higher productivity in data collection equates to more area (and therefore anomalies) investigated for a given period of time in the field. The time required for analyzing individual anomalies can be significantly higher than for other, more traditional methods and could become a cost driver due to the time involvement. The thoughtful use of available automation techniques for data processing and analysis with operator QC support can help moderate this effect.

8.3 COST BENEFIT

The main benefit to using a UXO classification process is cost-related. The ability to reduce the number of non-hazardous items that have to be reacquired and remediated as presumptively-hazardous items directly reduces the cost of a remediation effort. The additional information for anomaly classification provided by these sensor systems provides additional information for the purposes of anomaly classification. If there is buy-in from the stakeholders to use these techniques, this information can be used to reduce costs.

Table 8-1. MTA Tracked Costs

Cost Element	Data Tracked	Cost
Data Collection Costs		
Pre/Post Survey Activities	Component costs and integration costs Spares and repairs (/week)	\$3,250
	Cost to pack the array and equipment, mobilize to the site, and return - Personnel required to (re)pack (Re)packing hours - Personnel to (de)mobilize (De)mobilization hours - MTA transportation (one way)	\$42,800
		1
		40
		3
		8
		\$10,000
	Cost to emplace IVS - Personnel required - Hours required - Boat hours required	\$2,200
		4
		4
		4
	Cost for initial IVS - Personnel required - Hours required - Boat hours required	\$1,525
		3
Survey Costs		2
		2
	Cost per survey day	\$6,425 / day
	Cost per hectare	\$310 / ha
	Production Rate (ha/day)	20.7 ha/day
	- Boat Rental (hour/day) - Survey personnel required - Daily IVS (hour/day) - Survey hours (/day) - Break-down and setup (hours/day) - Team per diem (/day)	10
Processing Costs		2
		1
		8
		1
		2
Preprocessing	Time required to perform standard data clean up and to merge all data streams.	4 hr/day
Parameter Estimation	Time required to extract parameters for all anomalies in data set.	2 hr/day
Dig List Preparation	Time to assemble ranked dig list	2 hr/day

9.0 IMPLEMENTATION ISSUES

The MTA's EMI array was successfully upgraded to incorporate a more modern, AGC-grade EMI data acquisition system, transmitter loops, and tri-axial receiver cubes. All existing MTA systems were successfully reactivated or replaced after years of storage. Notionally, there are no new implementation issues for the MTA. The MTA was and remains ideally suited for deployment in relatively flat-bottoms, open areas such as bays where munitions transfers occurred ship to ship.

Due to limitations of the specific transmitter / transmitter loop implementation, the maximum transmit moment which can be generated by the EMI array is significantly small than was included in the original design. Additionally, measurements of environmental noise during the two test flights indicate that the original estimates of noise levels were optimistic. Therefore, transmit moments on the order of $1000 \text{ A}\cdot\text{t}$ would be needed to reach the design goal of correctly classifying a 105mm projectile at a survey altitude of 1.4m.

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