EXECUTIVE SUMMARY

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
CONUS	Continental United States
cDAQ	Compact Data Acquisition System
EMI	Electromagnetic Induction
ESTCP	Environmental Security Technology Certification Program
GPS	Global Positioning System
IVS	Instrument Verification Strip
LISO	Large Industry Standard Object, Schedule 40, surrogate for a 105mm projectile
MPV	Man-Portable Vector, a man-portable G&G Sciences AGC system
MR	Munitions Response
MTA	Marine Towed Array
NRL	U.S. Naval Research Laboratory
QC	Quality control
RMS	Root Mean Square
SERDP	Strategic Environmental Research and Development Program
SNR	Signal to Noise Ratio
TEM	Transient Electromagnetic
TEMTADS	Transient Electromagnetic – Multi-sensor Towed Array Detection System
TOI	Target of Interest
UXO	Unexploded Ordnance
VIMS	Virginia Institute of Marine Science

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The project team 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 compact Data Acquisition (cDAQ) system to the project team's application.

1.0 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.

2.0 OBJECTIVES

The objective of this project is to demonstrate the UXO/clutter classification ability of an advanced EMI sensor system for underwater UXO sites. To achieve this objective, the project team 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 TOIs had been selected to explore the operational envelope of the new array.

3.0 TECHNOLOGY DESCRIPTION

3.1 TRIAXIAL RECEIVER CUBES

The design of the TEMTADS/3D EMI sensors is based on the advanced 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**.

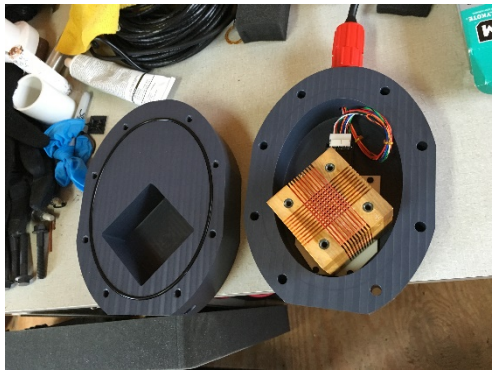

Figure E-1. Triaxial Receiver Cube Being Installed in Waterproof Housing

3.2 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 E-2**.

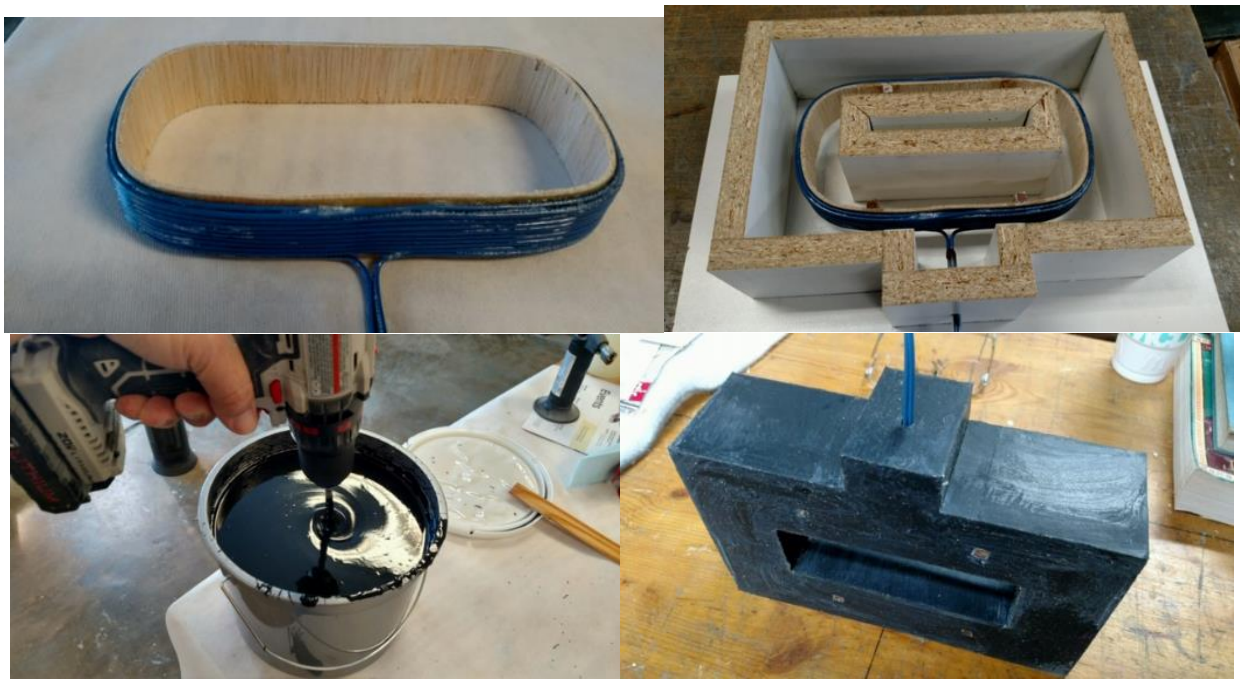

Figure E-2. **Fabrication Process Used for the Coils**

(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 American Wire Gauge (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; and Inner loops: 2.26 m x 0.97 m.

3.3 CDAQ DATA ACQUISITION SYSTEM

The EMI data acquisition system is based on the G&G Sciences' compact Data Acquisition (cDAQ) system. Originally designed for G&G Science's MPV, the system is capable of driving up to four transmitter loops of the TEMTADS/3D type and receiving from four 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 μs to 24.35 ms with proportional widths and are saved to disk.

The project team's unit was modified to support an additional four 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 a Global Positioning System (GPS) via the 1PPS signal.

The transmitters used in the TEMTADS family of Advanced Geophysical Classification (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.

3.4 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 TO or as clutter. The data are transferred to the analyst several times each day for near real-time analysis.

4.0 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 F**igure 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.

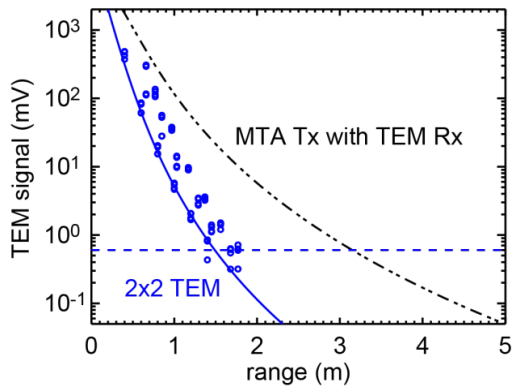

Figure E-1. Projected MTA Performance

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, the project team got 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 $5x10^6$ 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 m.

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 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 two to three times larger than those seen in air and on land during the project team's 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).

5.0 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 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.

5.1 COST MODEL

A four-week deployment to the opposite coast of the Continental United States (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 Instrument Verification Strip (IVS). 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, is used in the cost model.

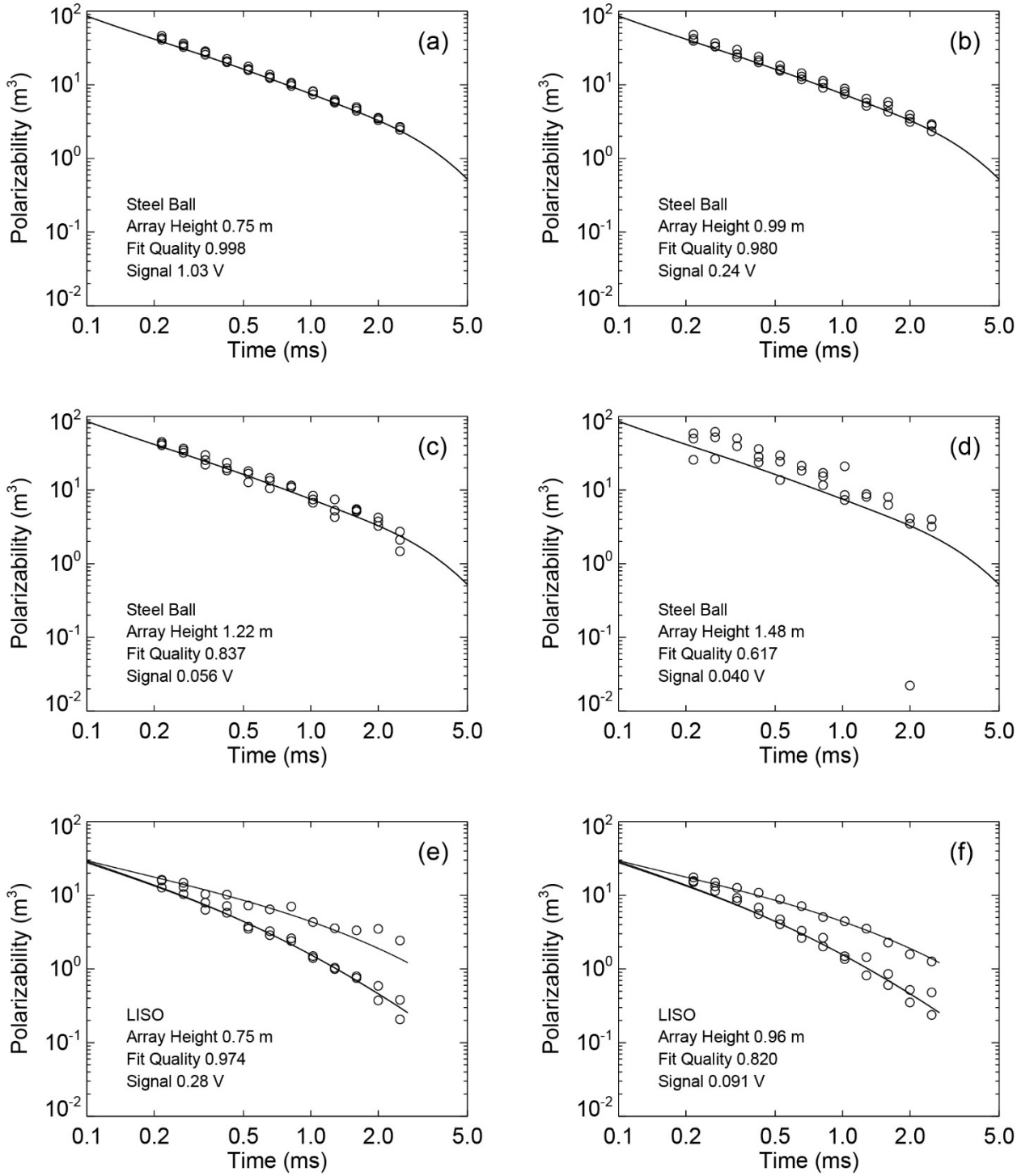

Figure E-1. Examples of Polarizabilities Determined by Inverting Array Data

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

5.2 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 quality control (QC) support can help moderate this effect.

5.3 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.

6.0 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 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-1. 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
Survey Costs	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