EEGS Fast TIMES

Volume 27, 1, November 2024

UXO Geophysics

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https://www.eegs.org/sageep-2025

President's Message

Dr. Janet E. Simms, President
US Army Corps of Engineers

janet.e.simms@erdc.usace.army.mil

Welcome to the return of FastTimes (FT) to its former downloadable PDF format and homebase on the EEGS website. Our FT editor, Mehrez Elwaseif, has been diligently working to make the transition. I have always enjoyed reading FastTimes because the articles present topics that might not be suitable for a peer-reviewed journal and they provide additional details that are interesting but often omitted from a journal publication. I hope you enjoy this issue and feel free to provide Mehrez with suggestions for future issue topics.

The EEGS BOD recently had its virtual Fall Meeting. This meeting is typically longer than the monthly meetings but shorter than the annual in-person meeting held during SAGEEP. The primary topics discussed were SAGEEP2025 and the new GAINS course. SAGEEP2025 will be April 13-17 in Denver, CO at the Hilton Denver City Center. This symposium is in conjunction with the 3rd Munitions Response Meeting, similar to SAGEEP2023. Jeff Leberfinger, VP SAGEEP, John Jackson, SAGEEP General Chair, and other SAGEEP/Munitions Response Meeting committee members are busy putting together an interesting and exciting program of guest speakers, technical sessions, short courses, and special events. The call for abstracts should be released soon so start thinking about your SAGEEP presentation!

An exciting EEGS event this year is the Geophysical Applications in Near Surface (GAINS) course produced by our Education Committee, led by Sarah Morton Rupert. Gains is a 14-week virtual training course designed for those looking for an introduction or refresher on practical applications in engineering and environmental geophysics. And best of all, it is free to EEGS members! Access to the course requires registration, which is done through the EEGS website (https://www.eegs.org/gains-course-information). The first session was October 9, but don't worry about missing a session because each session is recorded and available to view at your leisure. I encourage everyone to register for GAINS and enjoy listening to different subject matter experts on a variety of topics.

Let's get Geophysical!!!

Editorial

FastTIMES Editor-in-Chief
Mehrez Elwaseif, PhD, PGp
Jacobs

editorfasttimesnewsmagazine@gmail.com

Jeff Leberfinger, PGp, PG
Pika International

jleberfinger@pikainc.com

Steve Saville, PG
Jacobs

Steve.saville@jacobs.com

On behalf of the FastTIMES editorial team, I am excited to welcome you to Vol 27.1, dedicated to the pivotal field of unexploded ordnance (UXO) geophysics. This edition showcases four remarkable articles from esteemed experts in the UXO community. In this issue, we present some cutting-edge research and developments that underscore the immense value of UXO geophysics. These articles not only highlight technological advancements in detecting and classifying UXO in land and marine environments, but also emphasize the profound importance of the efforts to help creating safer environments for countless individuals in over 60 countries affected by explosive remnants of war (ERW). This issue builds on our commitment to providing high-quality FastTIMES content that highlights the significant advancements across our environmental and engineering geophysics practice.

I would like to extend my heartfelt thanks to our guest editors, Steve Saville and Jeff Leberfinger, whose expertise and dedication have been instrumental in bringing together the valuable contributions in this issue. Jeff's contributions as the Associate Editor for the UXO Community Geophysics column added a well-rounded view of the news and advancements shaping the UXO community. A special acknowledgment is due to Doug Crice (Geostuff) and Jackie Jacoby (EEGS administration) for their tireless efforts in communicating with our advertisers whose support is fundamental to the financial viability of FastTIMES.

I hope you find this issue both informative and inspiring. Enjoy your reading, and please take the time to explore the websites of our advertisers. Thank you for your ongoing support, and I look forward to your continued support and active participation in shaping the future of FastTIMES. As we move forward, I encourage all of you to engage with the articles and share your insights. FastTIMES is more than just a publication; together we can make it a platform for collaboration and innovation!

Sincerely,

Mehrez Elwaseif
Editor-in-Chief, FastTIMES

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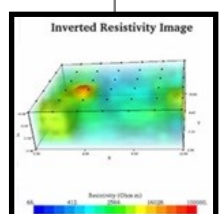

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UXO Community Geophysics News

Jeff Leberfinger, PGp, PG
jleberfinger@pikainc.com

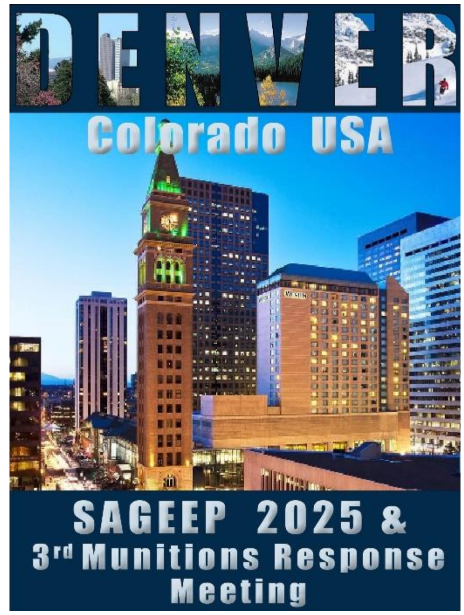
NAOC
NATIONAL ASSOCIATION OF ORDNANCE CONTRACTORS

Welcome to the UXO Geophysics Community News column. In this column you will be introduced to the new Technology Committee Chair for NAOC as I step down after serving as the chair for over 10 years and read information on AGC sensor updates, MMRP geophysics case histories, and other news.

New NAOC Technology Committee Chairman – Craig Murray

Craig Murray recently transitioned from deputy chair to chair of the NAOC Technology Committee after the long-serving chair, Jeffrey Leberfinger, stepped down. Mr. Murray grew up in Massachusetts and graduated from Cornell University with a Bachelor's Degree in Physics (1995) and a Masters of Engineering in Geological Sciences (1996). Since then he has worked as a geophysicist in the MMRP industry, first with Geophex, Ltd. and for the last 23 years with Parsons. He has primarily worked with electromagnetic induction sensors to detect and classify MEC on Formerly Used Defense Sites and has served as Parsons DAGCAP Technical Manager since 2017. Mr. Murray has been licensed as a Professional Geophysicist in California since 2003. He lives in Denver Colorado with his wife, youngest daughter, and faithful, old flat-coat retriever.

SAGEEP 2025 and 3rd Munitions Response Meeting



Planning is ongoing for the **3rd Munitions Response Meeting (MRM)** which will be held in April 13-17, 2025 in Denver, Colorado. NAOC will continue our partnership with the Environmental and Engineering Geophysical Society (EEGS) to offer the meeting in conjunction with the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP). John Jackson (USACE CX) will be the General Chair with Craig Murray (Parsons) the MRM Technical Chairman. Harry Wagner (Weston) will be supporting as the Short Course Chairman. The meeting will be build on the success of the previous MRM meetings with perspectives on Munitions Response from all angles, including USACE, NAOC, the Environmental Data Quality Workgroup (EDQW), SERDP/ESTCP, and other government and industry representatives.

Reducing Minimum Separation Distance (MSD) using Advanced Geophysical Classification (AGC) for MILCON

USA Environmental, Inc.

A proposed Military Construction (MILCON) site at Anderson Air Force Base, Guam, carries historical significance as part of the battlefield during the 1944 Guam invasion by US forces to retake the island from the Japanese. Today, the site is part of an active installation that supports a diverse community of over 5,000 individuals, including active-duty service members, families, civilians, and retirees.

Figure 1: Marines pursue the Japanese through the ruins of a Guam Town, July-August 1944. Buildings like these were ideal hiding places for snipers, and were thoroughly searched.

As a DAGCAP Accredited GCO, USA Environmental AGC-surveyed the 5-acre site using WRT's APEX One-Pass Sensor. With 3rd Party QA (CEHNC) approval of the AGC results, USAE implemented the ranked dig list results in accordance with an ESS Amendment which was endorsed by NOSSA and approved by DDESB.

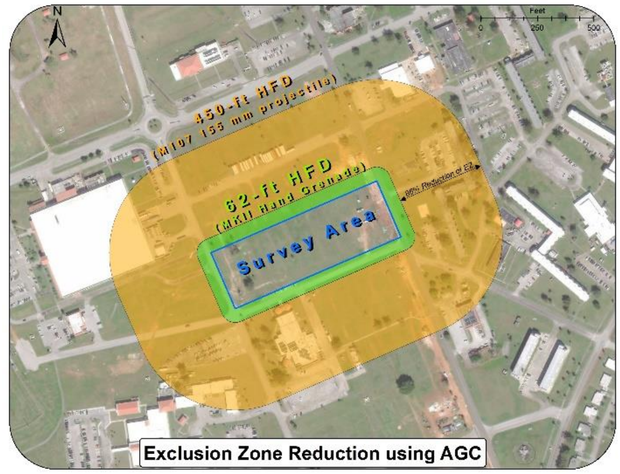


Figure 2: **Image overlay illustrating primary and contingency Exclusion Zones.**

In summary, AGC in support of MILCON pre-construction activities provides construction contractors with accurate TOI (MEC/MPPEH) quantities and the ability to use the classification results to adjust MSDs based on the TOI being intrusively investigated. AGC was successfully implemented IAW the DoD Policy and reduced the Primary MSD arc from 450 ft to 62 ft, and incorporated five additional Contingency MSD arcs correlating to the approved AGC TOI list. Reduction of the MSD will reduce costs associated with future evacuations during intrusive activities, reduce overall cost, and make the construction schedule more attainable.
504 International Parkway Ste 2000 | Plano, TX 75093
Phone: 800-550-1071 | Fax: 650-529-1436

Case History – Temsense AGC Mapping at Camp Robinson, AR

TETRA TECH

Tetra Tech is serving as the Geophysical Classification Organization (GCO) for a Remedial Design (RD) at the former Camp Robinson near Little Rock, Arkansas using the TemsenseTM Advanced Geophysical Classification (AGC), electromagnetic induction (EMI) sensor.

The purpose of the Temsense survey is to collect data to support one pass classification of sources throughout the 2,130-acre Munitions Response Site (MRS) to meet the project objectives. The MRS is

comprised of private lands used for residential, agricultural, and recreational purposes.
Data were collected in spring and summer 2023, with ambient temperatures frequently surpassing

Figure 3: Temsense data collection with Stencil SLAM positioning

100 degrees Fahrenheit and relative humidity of 70-80%. Ground surface conditions varied from flat open grassy fields to rocky, wooded hills with slopes >20% (See attached photos)

The Temsense demonstrated an ability to collect high-quality data in difficult conditions without lost time due hardware breakdown or failure.
Discrete targets were picked in grids with extreme densities (e.g., 3,500-8,000 anomalies per acre [ApA]). Of the 113 grids surveyed, 27% exhibit anomaly densities >3,500 ApA. The information obtained from this effort, including the highest-density grids, contributes to answering the RD study questions regarding site-specific limits of AGC technology.

Case History – Successfully Navigating Unexpected Difficulties and Determining Data Usability Limitations for a Challenging Remedial Investigation

Jacobs

Jacobs is performing a Remedial Investigation (RI) using advanced geophysical classification (AGC) at a project site comprised of five former Field Bombing Targets (FBTs) identified as historical ranges. All five of the FBTs were closed in 2010 but were reopened as a single MRS following discovery of AN MK-5 practice bombs. All current lines of evidence for this site indicate that the practice bombs are “nonexplosive.” Two FBTs are the focus of the RI, the horizontal extents of which were delineated from aerial photographs. FBT 1 is 3.5 acres and is located within a frequently used physical exercise course at the facilities' training school that also contains roads and a building. FBT 2 is 1.0 acre and is located where a gym, which has been demolished, once existed. The land encompassing FBT 2 has been reworked since bombing operations ceased, including regrading to allow for positive drainage.

The RI fieldwork resulted in many challenges, including: (1) extremely high anomaly densities (7,000 sources/acre); (2) unknown or estimated horizontal boundaries; (3) quality control (QC) seed failures at the maximum depth of detection; (4) classification of the AN Mk 5 practice bomb, which has different polarizabilities from potential surrogates and is not in the current Department of Defense (DoD) target of interest (TOI) library; and (5) an unexpected TOI, 40-millimeter (mm) hand grenades, identified during classification. These challenges were successfully addressed in a variety of ways. For the high anomaly densities and QC seed issue careful analysis of the data led to the establishment of data usability limitations in terms of AGC effectiveness and adjustment of the maximum reliable depth of detection/classification at the site. Acquisition of AN Mk 5 polarizabilities through test stand measurements allowed this item to be placed in the site-specific library and direct comparison made to this munition item during classification (Figure 1). An interim intrusive investigation of select TOI, including practice bombs with a high decision statistic and the 40-mm grenades identified through a cluster analysis,

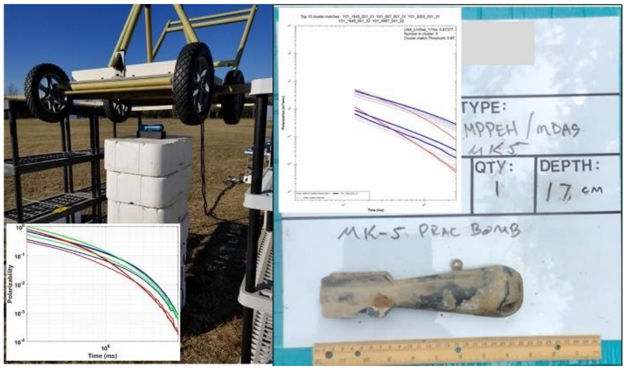


Figure 4: Acquisition of AN Mk 5 polarizabilities through test stand measurements allowed this item to be placed in the site-specific library

led to confirmation of the conceptual site model, that is this site had been used solely as an FBT and that grenades were not present. The results from the interim intrusive investigation also indicated that the current horizontal site boundary needs to be expanded and additional data collected to establish the lateral extents of contamination (Figure 2). This approach to a complex site has allowed the development of a plan which includes collection of additional data that will successfully achieve the objectives of the RI, including horizontal extent of contamination and a refinement of the vertical boundary, and provide the information needed to guide decisions regarding the site.

White River Technologies – APEX Dynamic AGC Sensor Updates

white river technologies

White River Technologies, Inc. continues to grow its fleet of APEX dynamic AGC systems with a focus on addressing the wide variety of site challenges. From lighter weight, person-portable systems designed for operation in wooded areas or steep slopes, to wider array systems capable of high production rates in open environments, the APEX provides a modular and scalable building block to develop the optimal AGC solution for any site. Using the same base unit accredited by DAGCAP in 2020, WRT has developed several options for dynamic AGC deployments. These configurations include:

- A lightweight litter mode for two-person, hand-carry operation in difficult terrain.
- A hybrid cart/litter mode for conditions where wheeled operation in difficult conditions may require an occasional two-person assist.
- A scalable array configuration where 1, 2, 3,…N systems may be linked together to build a larger vehicle-towed system.

Figure 5: The APEX hybrid cart/litter system configuration is designed for operations in difficult conditions.

Figure 6: Modular and scalable, the APEX units can be linked to build wider towed arrays for operation in relatively flat, open sites. The scalable architecture allows for building arrays of N units. Several projects are planned in 2024 for towed arrays comprising as many as 3 to 4 units per towed system, enabling high production rates.

As part of the APEX lease package, WRT offers 24/7 offsite technical support to provide assistance for projects both CONUS and OCONUS. WRT also provides on-site support for staff training and project kickoff. The APEX units can be integrated easily with a variety of positioning systems including GNSS, SLAM, and RTS. APEX data processing is currently supported in WRT's EMCLASS and Seequent's UX-Analyze.

GapEOD & BlacTusk Expand AGC Sensor Rental Fleet

Following the successful validation of the 3-transmitter UltraTEM Portable Classifier, GapEOD & BTG have focused efforts towards expanding the rental fleet of portable systems throughout 2023. The UltraTEM systems have achieved high project utilization throughout the year. The 2-transmitter variant of the UltraTEM Portable Classifier (Figure attached) has recently been validated for one-pass and screening surveys. When configured as a carried-array the 2-Transmitter variant is 18 lb lighter than the 3-transmitter system, enhancing system mobility while still delivering comparable performance even in complex multi object scenarios. Notably, reduction in the number of transmitters does not result in a reduced system swath width, allowing clients to maintain high production rates even in challenging terrain. The 2-transmitter system can also be deployed at a faster survey speed for surveys where only ISS rather than one pass classification is required which allows for higher production rates when the project objective is to determine source densities.

In the upcoming year, there will be a shift in focus towards completing validation of the UltraTEM XC Classifier. This system is specifically designed as a narrow swath, single-person portable system, intended for efficient one-pass classification. The UltraTEM-XC system will be optimised to work seamlessly with the new UltraTEM-V receiver and transmitter electronics. BTField will also be validated to allow users to self process one pass classification data in the new year.

Figure 7: The data collection with the new 2Tx Portable Classifier

Author Bio

PIKA International, Inc
Stafford,
Texas 77477, USA
jleblerginger@pikainc.com

Jeffrey Leberfinger is a senior geophysicist with PIKA International, Inc. and Exploration Instruments, LLC. He is a licensed Professional Geophysicist (CA) and Geologist (PA) with over 35 years' experience performing geophysical surveys across the US for Munitions Response/UXO, environmental, geotechnical, water resource, mineral exploration, and archaeological projects. Jeffrey is currently serving on the EEGS Board of Directors as the Vice President, SAGEEP 2025. He is also a former Board of Director of the National Association of Ordnance Contractors (NAOC) and is transitioning out of his position as the NAOC Technology Committee Chairman. Jeffrey has also served as President and served on the Board of Directors for the Pennsylvania Council of Professional Geologists (PCPG).

United States Army Corps of Engineers (USACE) Perspectives on the Current State of MMRP Practices

Corresponding Author:

Steve Stacy, MMRP Geophysicist

USACE Environmental and Munitions Center of Expertise (EM CX)

Email: stephen.m.stacy@usace.army.mil

Authors:

Elise Goggin, MMRP Geophysicist, USACE-EMCX
John M. Jackson, MMRP Geophysicist, USACE-EMCX
James Salisbury, MMRP Environmental Scientist, USACE-EMCX
Andrew Schwartz, MMRP Geophysicist, USACE-EMCX

Introduction

As a result of decades of live-fire testing and training, the Department of Defense (DoD) has a Military Munitions Response Program (MMRP) liability estimated to be over 11 billion dollars. Significant improvements in guidance, technology, and quality have been achieved over the last decade that have significantly improved project execution.

In this paper, the USACE EMCX provides their perspective on the current state of the industry to include discussions of guidance document updates, a focus on quality, one-pass advanced geophysical classification (AGC), remedial investigation characterization, and what they see in the future of MMRP.

Guidance Documents Update

It has been a good year for new guidance document issuances in the MMRP! The Office of the Secretary of Defense (OSD) and the U.S. EPA jointly signed the *Munitions Response Quality Assurance Project Plan (MR-QAPP) Toolkit Module 2 for Remedial Action*; the OSD published the *Military Munitions Response Program Risk Management Methodology (RMM)*, and the U.S. Army Corps of Engineers published *Engineer Manual 200-1-12 Conceptual Site Models (CSM)*. The *MR-QAPP Toolkit Module 2: Remedial Action* was developed to, "assist project teams in planning for the characterization and remediation of munitions and explosives of concern (MEC) using geophysical methods at [DoD] installations and formerly used defense sites (FUDS). [The MR-QAPP] employs the systematic planning process (SPP) to illustrate scientifically sound approaches to characterizing and remediating MEC at MRS in accordance with the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) as amended." (OSD and USEPA, 2023)

The RMM was developed to be a tool to help project delivery teams fulfill the CERCLA requirement to complete a MEC risk assessment as part of the remedial investigation phase of CERCLA projects. RMM provides, "…a consistent process for understanding and evaluating risk at munitions response sites …[It] is a qualitative risk evaluation tool that project teams can use to facilitate discussions about cleanup and build consensus for risk management decisions at Munitions Response Sites (MRSs). The RMM itself does not determine the level of risk at an MRS; it is only a tool to guide project team discussion about the level of risk." (OSD, 2023)

The USACE *Engineer Manual* 200-1-12 was updated to "[provide] procedural guidance to develop [CSMs] for sites where [MEC], chemical warfare materiel (CWM), munitions constituents (MC), and/or hazardous, toxic, and radioactive waste (HTRW) are known or suspected to be present." (USACE, 2023)

A new Army technical memorandum was released in 2022 titled "Minimum Separation Distance Reduction with Advanced Geophysical Classification" that allows AGC source size estimations to be utilized in reducing explosive safety distances, as appropriate. The technical memorandum also allows for reduced evacuation during explosives operations while maintaining all appropriate safety arcs.

Two guidance documents are planned for publication in 2024: an update to the USACE *Engineer Manual (EM) 200-1-15, Technical Guidance for Military Munitions Response Actions*, and the USACE *Engineer Pamphlet (EP) 200-1-20, Establishing & Maintaining [Land Use Controls] for Environmental Actions* [working title only]. The EM 200-1-15 will provide comprehensive updates to the planning, execution, and quality management of MEC response actions, and the revisions and updates will align this guidance document with the publications listed above. The EP 200-1-20 will similarly revise and update that guidance document to reflect DoD and USACE policies now in effect and to align its content with current best practices in planning and implementing land use controls on munitions response sites.

Focus on Quality

In the past fifteen years, the munitions response process has substantially changed to focus on collecting high quality data to support defendable decision-making processes and to better ensure the safety of the public. As a result, the definition of 'high quality' continues to evolve as USACE integrates new technologies and incorporates lessons learned into its workflows. The inevitable lag between developing new quality requirements and their implementation is unavoidable; however, frequent and open communication with stakeholders and industry has been an invaluable component in the USACE strategy to maintain a consistent and high quality of work products. This strategy includes quarterly calls with the National Association of Ordnance Contractors (NAOC), where USACE and NAOC professionals share in recent developments, exchange project and program information, and where industry's concerns can be voiced. USACE also offers training opportunities for State Regulators and creates opportunities for stakeholders to comment on draft guidance. Internal communication and dissemination of information within USACE also continues to improve. Monthly lessons learned calls typically draw an audience of over 100 participants, and munitions response training courses are provided to all Munitions Response Design Centers each year. In addition to training, the USACE is developing Performance Work Statement (PWS) templates for use in its Requests for Proposals, standard operating procedures for quality assurance, and other tools to help project teams succeed. While the industry continues to evolve, maintaining these open lines of communication will help USACE ensure the quality of its work and continue to deliver excellence in its programs and to the safety of the public.

One-Pass Classification

Geophysical classification is a broad term that has historically been used in various ways; however, AGC refers to a specific subset of multi-axis, multi-coil electromagnetic induction (EMI) sensors and methodologies used for munitions response that have been validated by the DoD Advanced Geophysical Classification Accreditation Program (DAGCAP). More generally, AGC refers to the process that measures the intrinsic properties of buried metallic objects to generate principal-axis polarizability decay curves which, in turn, allow for the classification of the buried metallic objects as targets of interest (TOIs) or non-target of interests (non-TOIs). The polarizability curves reflect the size, symmetry, material composition, and wall thickness of the buried metallic objects.

Until 2019, the general AGC approach was to detect an anomaly in an initial dynamic survey, then return to the anomaly to take a second EMI measurement for 30-70 seconds with an AGC sensor stationary over the anomaly. That approach to using AGC typically reduced the number of anomalies requiring expensive excavation by UXO specialists by between 85 and 93%, so the cost benefit of taking the second EMI measurement over all detected anomalies was significant. But over the past few years hardware vendors and researchers have developed a dynamic one-pass classification approach where the detection and classification phase is done in one data collection event greatly improving the cost benefits of using AGC. The first hardware to do so was successfully validated under DAGCAP in 2019 with other equipment manufacturers to offer their versions to follow. One-pass AGC approaches also bring higher quality data to the anomaly detection phase, which improves the fidelity of individual anomaly interpretations and further reduces overall project costs.

Focus on HUA and LUA Delineation during Remedial Investigations

The MR-QAPP Toolkit Module 1 was published in December 2018 and revised in April 2020. It lays out a phased process that starts with identifying High Density (HD) and Low Density (LD) areas that could respectively be High Use Areas (HUAs) and Low Use Areas (LUAs) that could contain MEC. This approach builds on the use of Visual Sample Plan (VSP) to 1) design a geophysical transect survey to traverse and detect high concentrations of metal associated with munitions use or munitions disposal, and 2) to perform geostatistical analysis of anomaly density to identify HD areas potentially associated with munitions use.

In the last few years USACE has identified a need for better training in VSP and in how HD areas and HUAs are delineated. An HD area is defined as an area within an MRS where the anomaly density is above a critical density, where the critical (anomaly) density is a VSP input parameter defined in the MR-QAPP Toolkit Module 1 as, "the upper bound of acceptable anomaly density, i.e., the estimated, site-specific upper bound of anomaly density considered to be attributable to background (non-munitions-related) sources. It is the project-specific, user-defined value for anomaly density (inclusive of background) used to delineate [HD] areas from [LD] areas" (OSD and USEPA, 2020). A problem the EM CX has identified is that project teams often set the critical density at a very large number (e.g., hundreds or thousands of anomalies/acre above background). The impacts of too high of a critical density are twofold: it can lead to poorly defined HUA boundaries, and worse, the project team can fail to detect HUAs. A consequence to both is that it can result in significant errors in assessing explosives risks to the public. There are multiple potential causes for these issues: insufficient VSP and/or MR-QAPP training; a lengthy time between VSP training and project execution; incomplete, or rushed, analysis of preliminary characterization transect data in VSP; a lack of communication between all project delivery team members; or contracting methods that impede simple expansions to needed field work.

The EM CX recommends preliminary characterization data analysis in VSP be discussed during Systematic Planning Process (SPP) meeting 5. This discussion should focus on how anomaly density estimates are translated into HD and LD areas and on all the inputs that are used to generate those anomaly density estimates. These include, but are not limited to, the window diameter; variogram model and inputs used to fit to the data; how background anomaly density is defined; how the critical anomaly density is defined; and the minimum size of an HD area.

Often the only personnel involved in discussions of the VSP analysis are the contractor and government geophysicists, but the EM CX recommends the discussion include project managers, technical managers, UXO technicians, and risk assessors, because HUAs and LUAs may have different levels of risk and may ultimately have different selected remedial alternatives. Incorrect delineation of HUA and LUA boundaries may lead to inaccurate risk assessment determinations and incorrect assumptions, to include cost estimations, forming the basis of an MRS's selected remedy. Including these additional team members and having a detailed and thorough discussion of each of the inputs and outputs fosters collaboration and buy-in to the risk attributed to each portion of an MRS, as well as the remedy selected to protect the public from that risk.

The EM CX has presented, both internally and to the NAOC, on the Remedial Investigation (RI) MEC characterization guidance contained in the EM 200-1-15, and on the methods for identifying HD areas using VSP. USACE will continue to monitor trends in the application of VSP to identify HD areas and in defining HUAs and will present those findings to the user community.

Moving Forward

The EM CX continues to be forward looking, to incorporate lessons learned from across industry into its workflows, and to identify and resolve issues that may affect the munitions response program. At the top of the current issues list are the HUA/LUA delineation discussed above; identifying more robust procedures to delineate and remediate saturated response areas (i.e., areas with anomaly densities too high to reliably detect or classify individual sources); and implementing better methods to estimate source sizes from AGC data.

On the research side, the Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) have moved further past the land side and into the underwater side of munitions detection and classification. The last several years, SERDP and ESTCP have released statements of need for underwater research proposals as they attempt to address DoD's underwater munitions environmental liabilities. Detection, classification, and location (DCL) are the primary research needs from a geophysical perspective (both EMI and acoustics); however, SERDP and ESTCP are also addressing underwater munitions burial and mobility, containment and recovery, and UXO penetration depth modeling.

The Office of the Secretary of Defense has formed an underwater workgroup with plans to implement some of the research on live site demonstrations. As part of that effort, DoD will be engaging with stakeholders through the Interstate Technology and Regulatory Council (ITRC) and the ESTCP Advisory Group. The focus in those two groups is twofold: the appropriate implementation and transfer of emerging research technology, and the development of appropriate MR-QAPP processes, measurement performance criteria, and measurement quality objectives for underwater munitions response actions. Alongside the implementation, the discussion of how DAGCAP will fit underwater munitions response will need to be addressed.

Conclusion

As new technology and guidance evolve, USACE will continue to work with industry and the regulatory community to communicate, update, and seek feedback from all stakeholders, and will continue to foster understanding and collaboration throughout the munitions response industry. The DoD guidance resources published in 2023 (and those planned for 2024), the increased collaboration between Government and industry, and the prevalence of DAGCAP and the quality management systems it requires, all combined, signal the beginning of a new chapter in the MMRP. Munitions response actions will begin to rely heavily on informed processes and evidence-based decisions. And those decisions will be founded on information all project team members can agree is the right data for their project-specific needs.

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Author Bios

Steve Stacy is a Senior Geophysicist with the United States Army Corps of Engineers (USACE) Environmental and Munitions Center of Expertise (EM CX). At the EM CX, Mr. Stacy develops geophysical guidance, leads training, and works with industry partners to cooperatively help the Munitions Response community continuously improve. Prior to joining the EM CX, Mr. Stacy had over 20 years of environmental consulting experience, with 17 years' experience planning, executing, and reporting munitions response (MR) geophysical investigations and removal actions using Digital Geophysical Mapping (DGM), Advanced Geophysical Classification (AGC), and analog methods on Formerly Used Defense Sites, active military installations, and other projects.

He has developed and trained staff in the implementation of data collection, processing, interpretation, and quality control procedures. He is an expert using the Geosoft Oasis montaj software package, including the UX-Analyze Advanced and UX-Detect modules to process, select targets, interpret, QC, and classify geophysical data. He is also an expert using Visual Sample Plan (VSP) to develop statistical approaches to characterize the nature and extent of MEC and to evaluate the results of MEC investigations. He is also an expert with ESRI ArcGIS software for geospatial data analysis and display. Mr. Stacy is also experienced in numerous geophysical methods and positioning systems, including electromagnetic, magnetic, GPR, seismic reflection/wide-angle refraction, induced polarization/resistivity, and various borehole logging techniques.

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Electromagnetic Induction Sensing of Underwater Munitions: Detection and Classification with the UltraTEM system

Lin-Ping Song, Stephen D. Billings, Leonard R. Pasion, and David Sinex
Black Tusk Geophysics, Vancouver, BC, V6J 4S5, Canada

Abstract

In the complex marine environment, the detection and characterization of metallic items using electromagnetic induction (EMI) sensing face some unique physical and operational challenges. These challenges include the effects of conductive seawater, surveying altitude, navigational accuracy, coverage area, and a low signal-to-noise ratio. In this paper, we first provide a brief overview of the UltraTEM system and the processing methods we developed to address these challenges. These methods encompass modeling and characterizing conductive backgrounds, enhancing detection capabilities, and performing robust inversions even with sensor positional uncertainty. We assessed these methods using the UltraTEM marine data acquired at the designated Sequim Bay Demonstration site. We then shift our focus to the detection and classification performance of the blind test data at both low and high altitudes, highlighting insights gained from successful and unsuccessful examples in this demonstration. Our analysis and results show that marine EMI sensing has considerable potential to be deployed as a practical and effective advanced geophysical classification (AGC) tool.

Introduction

Increased human recreational and industrial activities in the offshore environment have led to more potential interactions with discarded military munitions (DMM) and Unexploded Ordnances (UXO). Over the years, a variety of sensing techniques including sonar, laser, optical, electromagnetic induction, and magnetometry have been developed to help remediate shallow water sites contaminated by munitions. Of particular is marine EMI sensing, which is adopted from the terrestrial case (Pasion and Oldenburg, 2001; Bell et al, 2001), that aims to identify and classify if detected munitions belong to UXO or clutter based on the polarizabilities (the physical property) of a target extracted from measurements. With this discriminative, diagnostic information of polarizabilities, marine EMI sensing has emerged as a promising technique for underwater munitions detection and characterization (Shubitidze, 2011; Schultz et al, 2011; Bell et al, 2016; Billings and Song, 2016).

Marine EMI sensing has some distinct physical and operational challenges. For a survey deployed in a dynamic underwater environment, strong, variable background EMI responses can be ubiquitously observed due to the conductive seawater (the conductivity around 4-6 S/m) and variations of sensor altitude and attitude. As a result, such seawater responses would inevitably obscure and distort the responses of a target of interest. With the presence of conductive seawater and limited accessibility in environmentally sensitive areas, EMI measurements taken at large standoff distances to the seafloor are likely to contain signals that are too weak to be detectable. Moreover, accurate sensor positioning of a marine EMI survey is more difficult than for the terrestrial case. Relative positional errors between adjacent survey lines can lead to an erroneous inversion and subsequent misinterpretation.

With the recent development and demonstration of underwater EMI systems, e.g., UltraTEM (Billings, et al, 2023), acquired marine EMI data are available for evaluating our developments to address technical difficulties. In the following paper, we first provide a synopsis of methods that use 1) an integral equation technique for characterizing and removing background responses; 2) a synthetic aperture scheme for enhancing target detectability; and 3) data inversion methods that are robust to sensor positioning errors. Next, the results of processing UltraTEM data collected at the Sequim Bay test-site are presented to demonstrate the effectiveness of the combination of the marine UltraTEM system and the processing methods. Finally, the conclusions follow. Below, we start with a description of the sensor system.

UltraTEM system

The UltraTEM system (for a thorough description, see Billings et al., 2023), a multi-component multi-sensor system that uses time-domain electromagnetic induction (TEM) to detect and characterize buried metal, can be deployed for both terrestrial and marine applications. The plot on the left of Figure 1 shows the sensor geometry in which the four transmitter loops and twelve tri-axial receiver cubes are mounted to the platform. For each transmitter excitation, UltraTEM records the response at all receivers. Thus, it has spatial–temporal data of 144 × N_t for a survey point, where N_t is the number of logarithmically spaced time gate measurements of transient signals. To minimize the effect of 60 Hz powerline frequency used in the United States, the system is designed to have the excitation current waveform in a transmitting loop regulated in either fast (90 Hz base-frequency) or slow (30 Hz base-frequency) modes. In the fast-transmitter mode, the transient signals may be measured ranging from 0.124ms to 2.42ms with N_t= 27; in the slow-transmitter mode, 0.124ms to 7.7ms with N_t= 37. With the three 1.8m x 1.8m transmitter loops, and one 3.6m x 0.9m overlapping transmitter loop, as well as distributed receiver cubes, the system approximately samples an effective footprint area of 4 square meters.

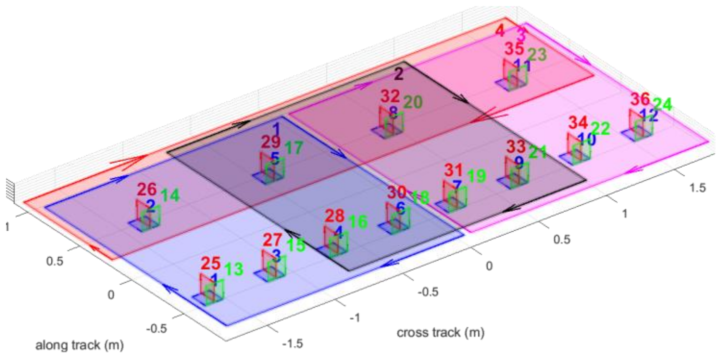

Figure 1. Left: sensor geometry of the UltraTEM: four horizontally arranged transmitters and twelve triaxial receiver cubes. Right: View of the UltraTEM and Ugly Duckling vessel from a camera mounted at the stern of the tow-fish. This photograph was taken at Lake Washington.

The sensor system is installed in a submersible tow-fish that is towed by a surface vessel. Through ESTCP MR19-5073, the UltraTEM marine towed system has been built for detection and classification of buried ordnance and designed as a vessel-towed single-pass marine dynamic classification system. The system combines RTK GNSS, ultrashort base line (USBL) acoustic positioning, and subsea inertial navigation system (INS) to provide the most precise marine positioning available. Data from the tow-fish are remotely monitored and logged via fiber optic telemetry through the tow cable using computers aboard the deployment vessel. The plot on the right of Figure 1 shows a deployment of the system at Lake Washington.

For the specific task of UXO detection and classification, the UltraTEM system has been enhanced by integrating Gap Explosive Ordnance Detection's (GapEOD) and Black Tusk Geophysics' (BTG) existing multi-component multi-sensor UltraTEM package and associated software into Tetra Tech's (Tt) towed electromagnetic array (TEMA) platform. The evaluation and analysis of the system performance were reported in Billings et al, 2023. Next, we will briefly describe the methods that were developed to address the challenges aforementioned in the marine environment.

Methods

Integral equation modeling and characterizing EMI responses

In the absence of noise, the measured EMI transient responses at an instant *t* in seawater may be described as the sum of the conductive background fields and the scattered fields due to the presence of a buried metallic target upon excitation. The transient responses can be modelled by the integral equation (IE) method in layered media (Song et al, 2016; Billings and Song, 2020).

When surveying in a dynamic marine environment, the sensor pitch and roll as well as altitude above sea-bottom will vary. The variations of these sensor parameters change the transmitter and receiver couplings with layered interfaces and therefore influence the EMI response measured by the sensor. Our modeling and experiments show that the characteristics of EMI responses correlate well with the variations of survey parameters. The z-component of background responses is more influenced by the variation of sensor altitude, the y-component by the variation of sensor pitch, and the x-component by the sensor roll.

As an illustration, Figure 2 shows a comparison of modelled results (Tx4-Rx1Z) with data acquired at the blind-grid area of Sequim Bay. The three-layered structure is used to model the conductive background responses. The seawater depth and conductivity are set as 23m and 3.6 S/m, respectively. A homogenous half-space seabed is assumed with a conductivity of 1 S/m.

The plot on the left shows the platform altitudes (Figure 2a) and depths (Figure 2b) during the survey. Figure 2c shows the observed (in blue) and modeled (in red) background profile at *t* = 0.19ms. One sees that the field amplitude decreases as the system descends deeper (Figure 2a).

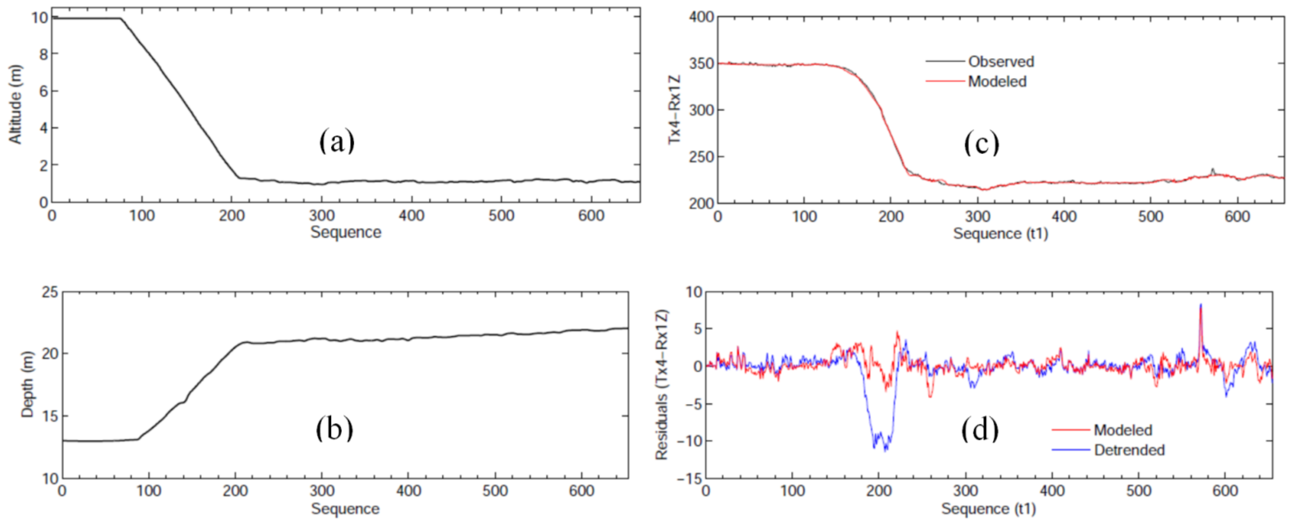

Figure 2. Left: Observed and modelled responses of Tx4-Rx1Z. right: Background subtracted responses with the modelling and de-trending methods.

The conductive background responses correlate well with the sensor heights. A de-trend filter may be applied to remove the background fields. Figure 2d shows that the de-trend filter works well for smooth changes in altitude and attitude but produces a relatively large filtering artifact around the rapid changes in the observed responses. In contrast, the modeled responses well predict the observed data, including those rapid changes. Overall, the high-amplitude background can be effectively removed using the model or a de-trending filter, and an anomaly response (the spikes) can be extracted for a subsequent processing.

Enhancement of target detection: TEM synthetic aperture method

In a standard analysis, target detection is performed on a data image created by combining z-component data of all transmitters. An anomaly 'blob' on the data map, which has an amplitude exceeding a threshold, is identified and picked as a target. However effective target detection can become difficult due to weak strength of signals at large standoffs. To improve detection and sharpen anomalies in gridded images or along profiles, we explore a superposition approach, called synthetic aperture (SA) method (Knaak et al, 2015), that attempts to boost target signals by stacking the responses from multiple transmitters or receivers.

Assume an EMI survey that fires a transmitter at $\mathbf{r}_l$ ($l = 1, 2, \cdots, L$), to interrogate the subsurface. There are the receivers at $\mathbf{r}_i$ ($i = 1, 2, \ldots, N$) to record the responses. Denote d_{il} as the response measured at the *i*-th receiver associated with the *l*-th source excitation. The idea of a SA method is to sum the responses measured by the same receiver from the excitation of all sources (ibid). The SA data at the *i*-th receiver associated with the synthetic source can written be as $d_{i,\mathrm{SA}} = \sum_{l=1}^{L} w_l d_{il} = \mathbf{d}_i^T \mathbf{w}$, where $\mathbf{w} = [w_1\ w_2 \cdots w_L]^\mathrm{T}$ is the vector of the synthetic aperture weights and the *i*-th common receiver gather given as $\mathbf{d}_i = [d_{i1}\ d_{i2} \cdots d_{iL}]^\mathrm{T}$.

Similarly, the concept of the SA can be used to construct a SA receiver for common transmitter gathers. This shows that the reciprocity principle applies where the synthetic receiving aperture is formed by exchanging transmitting and receiving roles. In the synthetic receiving aperture, the original transmitter acts like a "receiver" and the synthetic receiver acts as a "transmitter." The above SA process may be used sequentially to form a set of composite SA data. The SA weights are determined by maximizing the SA energy function.

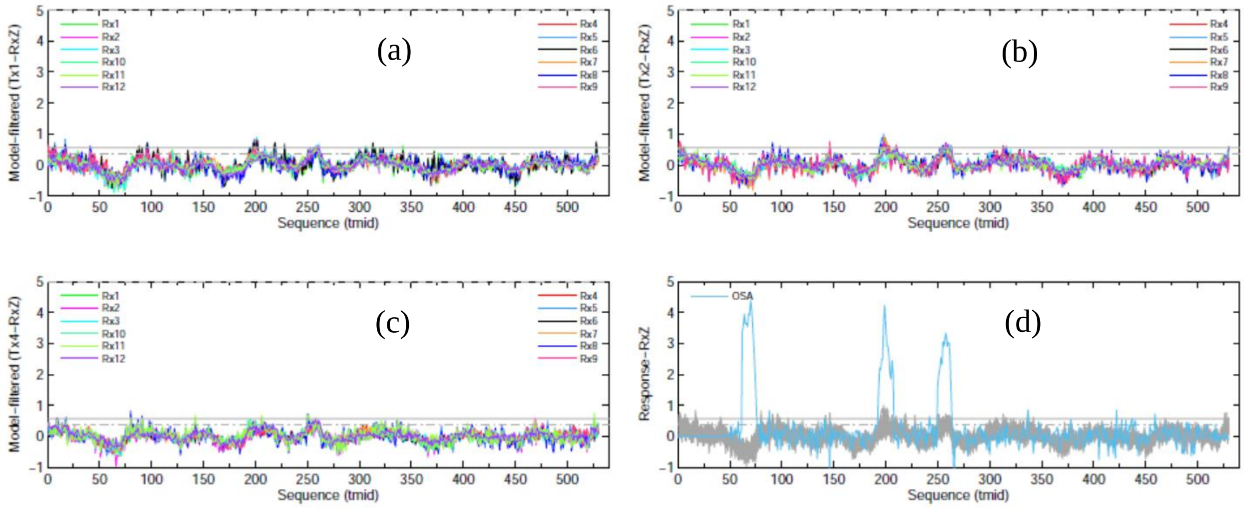

Figure 3. Example of SA detection for UltraTEM Blind-Grid data, Sequim Bay. (a)-(c) The twelve filtered vertical responses for Tx1, Tx2, Tx4. (d) SA response (plotted in cyan).

The SA method is a promising approach to boost potential target signals and thus help detection (Song and Billings, 2023). Figure 3 presents a case of applying the SA method to the UltraTEM blind-grid data collected at high altitude (about 1.5m). The regular responses of the twelve receivers' *z*-coils for transmitter Tx1, Tx2, and Tx4 are shown in Figure 3a-c. Visually inspecting along the profiles, it is unclear to identify a sequence where target signals are likely present. Next, the SA method was applied to all the responses, and the generated optimal SA (OSA in cyan) responses are shown in Figure 3d. For comparison, all the responses in 3a-c are re-imposed (in gray) in Figure 3d. Along the OSA profile with a threshold of 3 mV/A, three peak anomalies were picked as the potential targets. The first pick along the profile was ignored because its location is outside of the test area. The other two were processed and analyzed. The target around sequence 200 was correctly classified as target of interest (TOI) and was confirmed to be an 81mm projectile (U224). The other target was correctly classified as a non-TOI.

Inversion by mitigating sensor positional uncertainty

Within the time range of interest, the underwater measurements can be well approximated as the superposition of the conductive background responses and target signals. Upon removing background responses from raw underwater measurements and detecting potential targets, the dipole model is readily applied for downstream processing of inversion and classification (Shubitidze, 2011; Billings and Song, 2020). Suppose that η metallic targets are present in the sensor field of view, the measurements at time instant t are given as $\mathbf{d}(t, \mathbf{s}) = \mathrm{A}(\boldsymbol{\alpha}, \mathbf{s})\boldsymbol{\beta}(t)$. Set $\boldsymbol{\alpha} = (\mathbf{r},\ \boldsymbol{\theta})$ as the locations and orientations of η targets. The sensitivity matrix of $\mathrm{A}(\boldsymbol{\alpha}, \boldsymbol{s})$ relates the measurements to principal polarizations $\boldsymbol{\beta}(t)$. In the standard inversion method (Song et al, 2011), the locations, orientations, and principal transient polarizations, i.e.,$\left(\mathbf{r}, \boldsymbol{\theta}, \boldsymbol{\beta}(t_j)\right)$, are determined by minimizing an objective function that measures misfit between the observed data and the predicted ones. Sensing locations, correctively denoted as $\boldsymbol{s}$, are assumed to be precisely known and not the part of the model parameters.

In a hydrodynamic environment, the actual survey track or stand-off distance from the seafloor may significantly deviate from the measured nominal one. Inaccurate relative sensor positioning between multiple survey lines can lead to an erroneous inversion of data and a poor interpretation of results. We have developed inversion methods that attempt to implicitly and explicitly account for errors in sensor positioning, respectively (Pasion and Song, 2021; Song, Sinex and Billings, 2023).

The independent model location inversion (IMLI) method assumes that the *n*th sensing location $\mathbf{s}_n$ "view" the targets as if they were at $\boldsymbol{\alpha}_n = (\mathbf{r}_n,\ \boldsymbol{\theta}_n)$, not necessarily at the true locations $\mathbf{r}$ and orientations $\boldsymbol{\theta}$. Then the standard inversion method can be modified by introducing the *N* sets of current extrinsic source parameters $\boldsymbol{\alpha}_n, n = 1, \cdots, N$ and replacing the sensitivity matrix with $\mathrm{A}(\boldsymbol{\alpha}_n, n = 1, \cdots, N, \mathbf{s})$. In the joint estimation of target and survey parameters (JETSP) method, it imagines that the targets "see" through those sensing deployments and "demand" some adjustments $\Delta\boldsymbol{s}_n$ of the recorded nominal position values $\boldsymbol{s}_n$ so that the adjusted sensing locations $\hat{\mathbf{s}}_n = \mathbf{s}_n + \Delta\mathbf{s}_n$ can harmonize with the actual geometrical presence $\boldsymbol{\alpha} = (\mathbf{r},\ \boldsymbol{\theta})$ of targets. By treating the sensing location perturbations $\Delta\boldsymbol{s}_n$ as additional unknowns to source parameters, the standard inversion method is modified with the sensitivity matrix $\mathbf{A}(\boldsymbol{\alpha},\ \mathbf{s}, \Delta\mathbf{s})$.

We present an example of recovering two 81mm mortars (U222 and U223, PNNL-ID) from the marine blind data collected in 2022. The top panel of Figure 4 shows the observed data and three sets of the predicted data by the three methods (standard inversion, IMLI, and JETSP). The standard inversion has difficulty modelling the observed responses and yields a significant anomaly pattern in a residual map (not shown here). On the other hand, both the IMLI and JETSP fit the observed data fairly well. Perhaps the most striking difference between the standard method and the other two methods is seen on the recovered polarizabilities. As shown in the bottom panel of Figure 4, from left to right, the first set of polarizabilities recovered by the standard method may predict a target of interest with unequal minor polarizabilities. The second set of recovered polarizabilities likely predicts non-UXO, with the matching misfit of 0.864 against the 81mm reference item. On the other hand, the IMLI and the JETSP predict that the two sources have almost identical recovered polarizabilities, which match well with the 81mm reference polarizabilities. Matching misfits are 0.137 (IMLI-1), 0.222 (JETSP-1), 0.234 (IMLI-2), and 0.057 (JETSP-2).

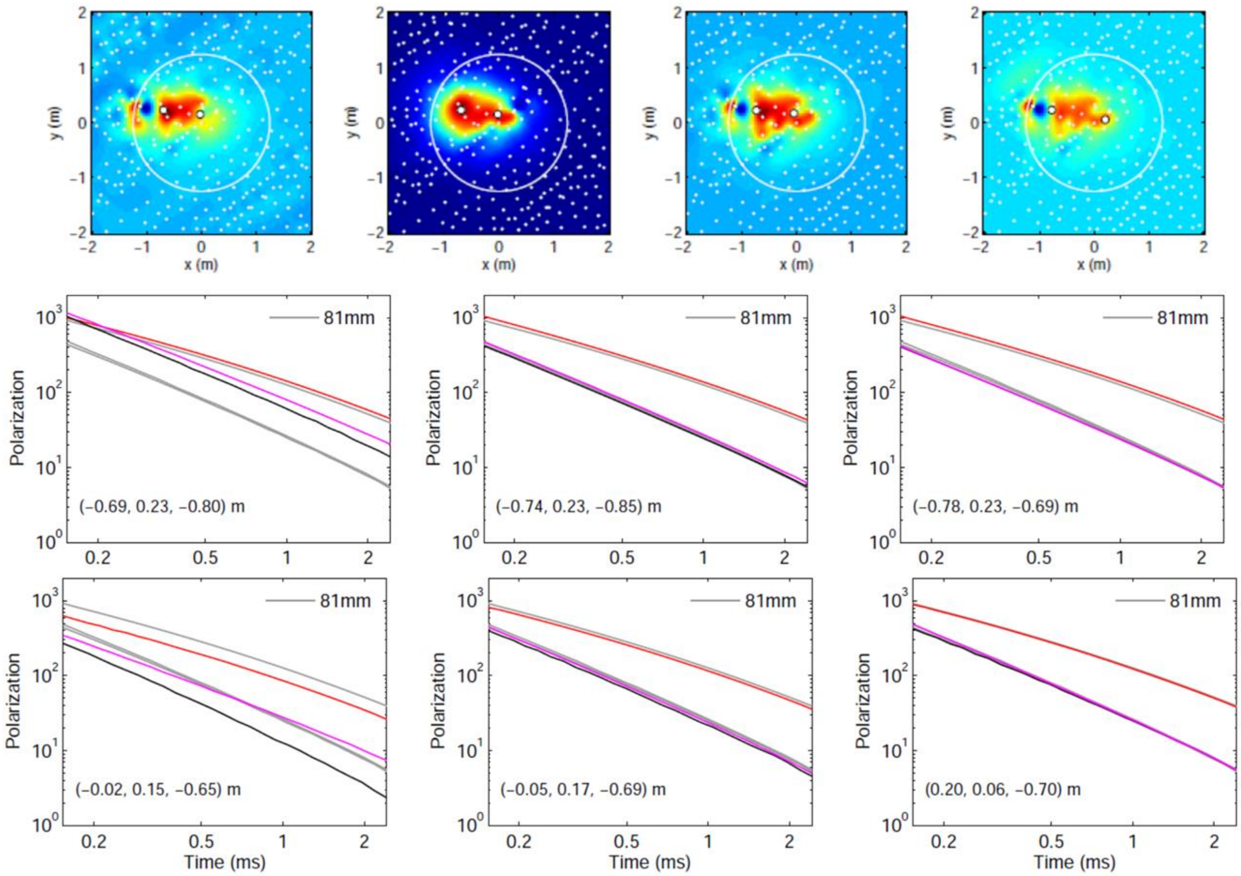

Figure 4. Example of inversions. Top: The four gridded data images show the observed and three sets of the predicted data by the standard inversion, IMLI and JETSP methods. Bottom: Recovered polarizabilities by standard inversion (left); IMLI (middle); JETSP (right). Note that the inverted source location is shown on the bottom left of each polarizability plot.

Demonstration at Sequim Bay Test Site

Site preparation and data acquisition

The UltraTEM has performed three shakedown tests. Billings et al., 2023 provided a detailed description of these tests, including experimental design, site preparation, item seeding, and the system deployment, etc. Briefly, the first two tests were conducted in Ostrich Bay and Sequim Bay, Washington in October 2021. The two tests were concerned about: 1) examining the capability of the TEMA system to deploy the UltraTEM system with acceptable stability, altitude control, and line following, and 2) evaluating performance metrics that were about location accuracy, noise and reproducibility of polarization tensor parameters. At the Sequim Bay shakedown test in 2021, UltraTEM data were collected over 0.54 Hectares, or 60% of the full Blind-Grid area. BTG processed the UltraTEM data and turned over a ranked dig-list to the ESTCP Program Office, with all 17 TOIs correctly detected and classified.

The third shakedown test was conducted in September 2022 at Sequim Bay. Two areas at Sequim Bay were undertaken by PNNL for assessing the performance of the UltraTEM system (**Error! Reference source not found.**a). A calibration area was designed with known targets (40mm to 155mm) emplaced at known positions. The calibration data were used to examine the performance metrics, and to test the processing workflows and establish site-specific polarizability libraries. A 0.79-Hectare circular blind-test area was set up with several MEC simulants and clutter items emplaced at positions blind to the demonstration team.

Calibration and blind-grid data were collected at 90 Hz and 30 Hz transmitter base-frequencies. Figures 5 (b)-(d) show the three different blind-grid surveys at lowest elevation and 90 Hz and 60 Hz transmitter mode (mode 4F and 4D) and high altitude (about 1.5m) and 90 Hz mode (4F), respectively. With 4.0m line spacing, the three blind-grid data correspond to 100%, 98.6%, and 92.9% coverage of the designed circular area.

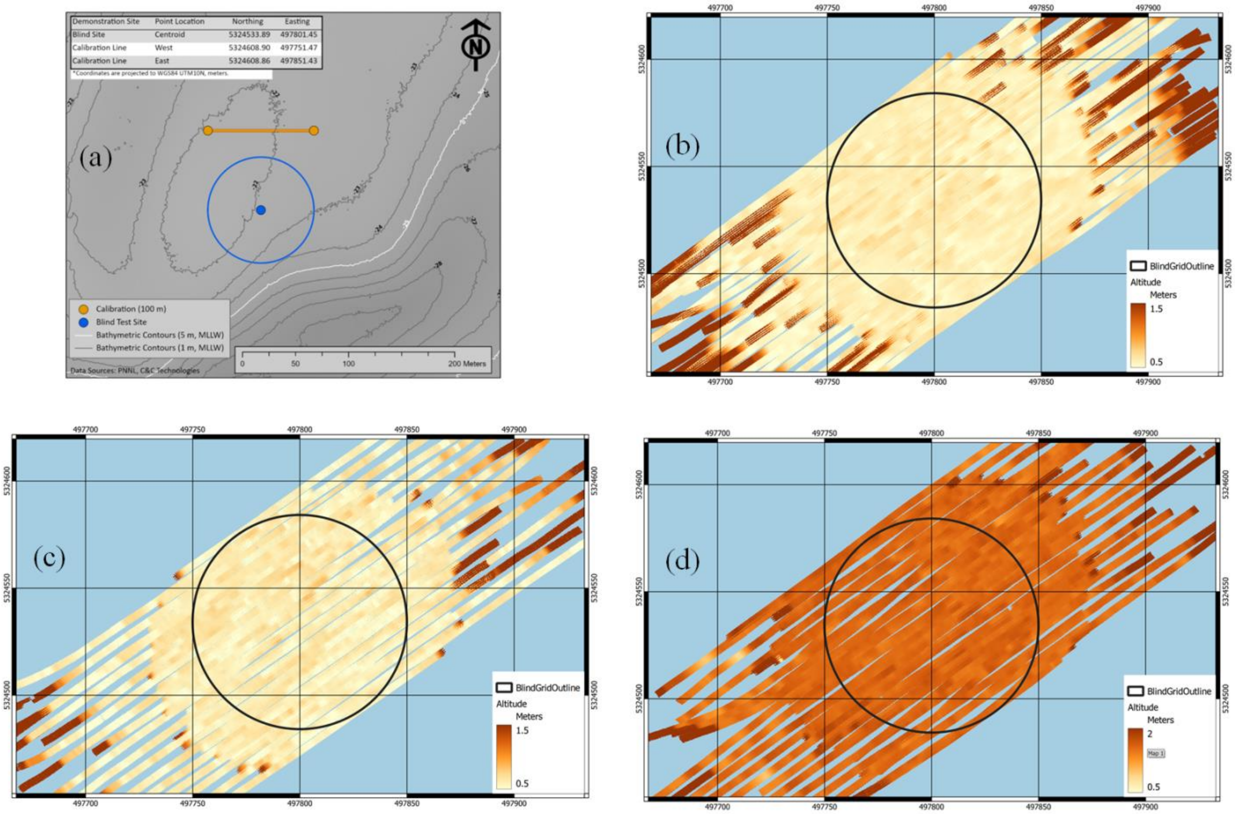

Figure 5. Data acquisition at Sequim Bay. (a) A calibration line and a blind circular test area. Survey altitudes over the blind grid area: (b) at the fast- transmitter mode and low altitude; (c) the slow-transmitter mode and low altitude; (d) the fast-transmitter mode and high altitude. Note that the color-maps have different scales. The circular black outline is the official Blind Grid area, and the solid lines are the survey tracks.

Classification

To determine if the system has the ability to detect targets of interest (TOI) to the required detection depth, we tested and applied methods to all the calibration and blind-grid data. Classification is performed by matching estimated polarizabilities to a library of polarizabilities and then ranking a target based on the matching misfit. Three ranked dig-lists were submitted to Institute for Defense Analyses (IDA) for the blind-grid tests using two datasets collected at low altitude (0.5-0.75m above the sea-bottom) with the fast and slow base-frequency (4F and 4D) and one data set at high altitude (>1.5m above the sea-bottom) with the fast base-frequency (4F). Counts of objects included in blind-grid scoring contain: TOI (35): 105mm HEAT (4); 105mm M60 (4); 81mm M889A1 (**8**); 81mm M821 finned (9); ISO Pipe (2); 60mm grenade (7); 40mm shell (**1**); Clutter (20). Results and the ESTCP Program Office's scoring are discussed in the next sections.

Performance at high altitude

On the left, Figure 6 shows a map of the UltraTEM data collected with the fast base-frequency (4F) and at high altitude (>1.5m). On the map, the 55 objects are annotated, and their locations are marked as crosses. Dig-decisions are marked as red circles. Within the 3.5m detection radius used by IDA, all TOIs larger than an 81mm mortar cartridge are detected, but four are incorrectly classified as clutter. At this altitude, we would not expect to have majority of items that have good matches to the library. The top-right panel of Figure 6 illustrates the case in which only a few in the top-ranked 81mm digs have the library matches (the highlighted values in each subplot) < 0.5, a threshold often used to generate a dig list, given sufficient SNR data. To reduce the likelihood of missing potential TOI, a much larger match threshold of 1.5 was used in this case. The use of large thresholds generally results in more false positives. The three items listed as #5, #6, and #8 in Figure 6 were incorrectly classified as TOI.

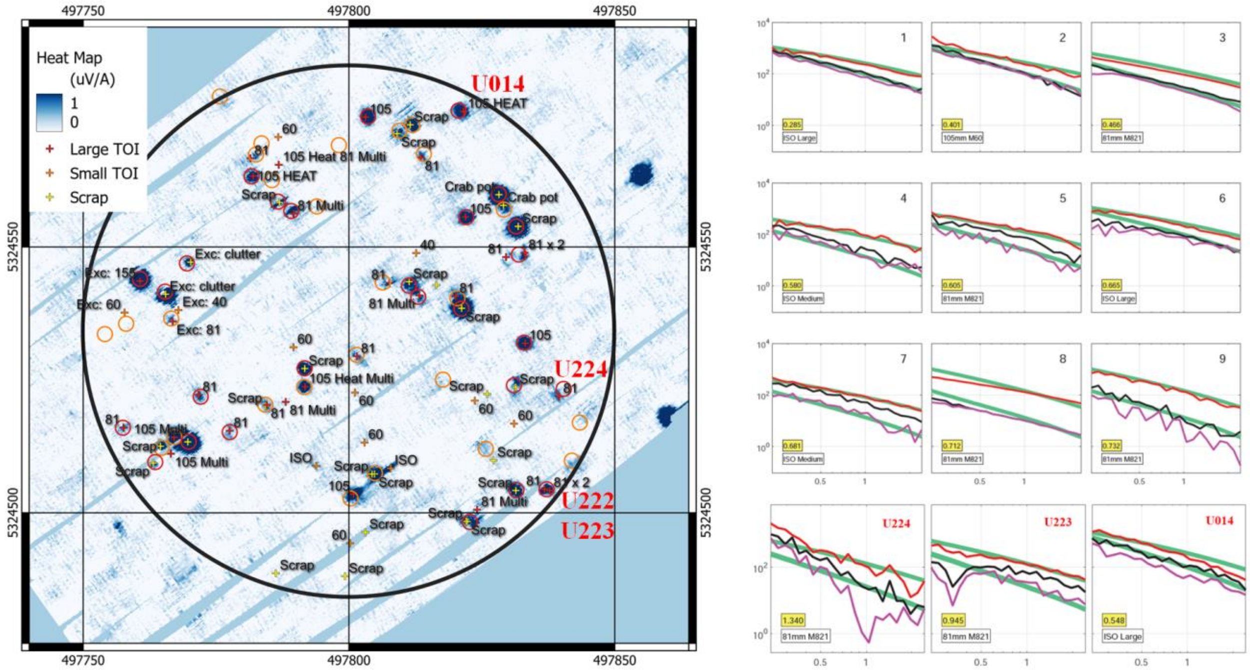

Figure 6. High altitude blind-grid test with fast-transmitter mode (4F). Left: heat-map of the mid time-channel and target list. The items marked with "Exc" were dragged out of the survey area and were not used for scoring. Red circles correspond to dig-decisions and orange circles to no-digs. Top-right: nine recovered polarizabilities of early digs. Bottom: recovered polarizabilities of three TOIs of U224, U223, and U014.

It is interesting to look at the three individual classification cases related to targets U224, U222/U223, and U014, which also are annotated near their locations in the heat map. Recall we discussed the use of the SA method to boost signals for detection. The SA example with high altitude data is shown in Figure 3. Using the SA response, we picked the two targets. One of the targets correctly classified as TOI is U224 (81mm) despite its noisy recovered polarizabilities shown in the bottom row of Figure 6. In our section on inversion, we discussed the case in which two objects U222 (81mm) and U223 (81mm) were closely spaced, and their polarizabilities were recovered accurately for low altitude data. However, for the high-altitude data, only U223 (its recovered polarizabilities shown in the middle plot of the bottom row of Figure 6) was correctly detected and classified. U222 failed to resolve. Another large item listed in Figure 6 is U014 (105mm HEAT). The item was correctly classified as TOI, and the prediction of UXO type is ISO large according to the best polarizability match. For the same item, we will show that the low altitude data allow predicting a more accurate classification result.

At this high-altitude survey, none of the TOI smaller than an 81mm mortar has a corresponding detection in the target list submitted to IDA. The detection and classification performance at the selected operating point is listed in **Error! Reference source not found.** 1.

Table 1. IDA generated scoring results for the high-altitude fast base-frequency at the selected operating point.

TOI	40 mm	60 mm	Medium ISO Pipe	81 mm M821 Finned	81 mm M889A1	105 mm M60	105 mm HEAT
Detected, Correctly Classified TOI	0	0	1	7	7	3	4
Detected, Misclassified Clutter	0	1	0	2	1	1	0
Not Detected	1	6	1	0	0	0	0
Total	1	7	2	9	8	4	4

Performance at low altitude

At low altitude (0.5 to 0.75m), a map of the UltraTEM data collected with the fast base-frequency (4F) is shown in Figure 7. The map is annotated with the ground-truth designations of the closest item to each predicted target. Within the IDA determined radius of 3.5m, all TOI have a corresponding target pick which means that the probability of detection is 1.0. Same as the fast base-frequency (4F) data, the probability of detection is 1 for the slow base-frequency (4D) data (the corresponding map is not shown due to the limited space).

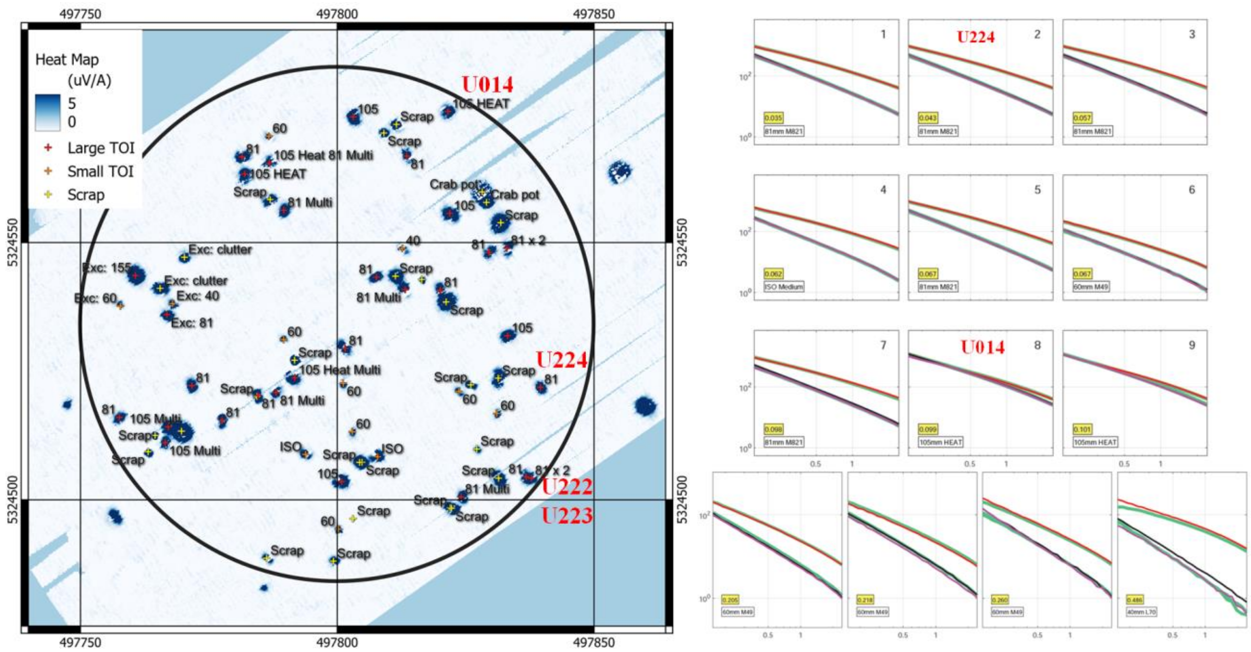

Figure 7. Low altitude blind-grid test with fast-transmitter mode (4F). Left: heat-map of the tmid time-channel and target list. Each anomaly is described from the closest item in the ground-truth provided by IDA. The items marked with "Exc" were dragged out of the survey area and were not used for scoring. Top right: nine recovered polarizabilities of early digs. Bottom: recovered polarizabilities of three 60mm grenades and one 40mm shell.

As a comparison with the high-altitude case, the top-right panel of Figure 7 presents the polarizabilities of a few top-ranked digs for the low altitude data. In contrast to those in Figure 6, the polarizabilities recovered over the 9 targets have excellent matches (highlighted in yellow) to the library ones. In fact, the polarizabilities for all targets, including the 40mm projectile and 60mm mortar (the bottom row of Figure 7), are good matches to the library polarizabilities. Overall, all have L123 match corresponding to targets of interest meeting the performance objective of 0.5. The same performance polarizability match is also achieved for slow transmitter base-frequency (4D) data (Billings et al, 2023). In Figure 7, the two polarizability plots are annotated for targets U224 (81mm) and U014 (105mm HEAT). As compared with the two annotated in Figure 6, the UXO types are correctly predicted for the low altitude data, with library matches of 0.043 and 0.099, respectively.

As an accurate recovery of polarizabilities is achieved for the low altitude data, it is equally important to examine the estimate of target locations. To check the location accuracy, we computed offsets between predicted and the "ground-truth" positions for the low-altitude slow frequency 4D and fast frequency 4F data. Upon some adjustments to WGS-84 coordinates used by PNNL (i.e., a 1.53m correction to the Easting coordinate and a 0.27m correction the Northing coordinate, Billings et al, 2023), Figure 8 (a) shows the corrected offsets where many of the slow frequency 4D and fast frequency 4F positions fall with 50cm range. Only two items in the fast frequency 4F data (in black circles) and four items (in red circles) in the slow frequency 4D data have a residual positional error of greater than 50cm. In addition, Figure 8 (b) shows the relative difference between the slow frequency 4D and fast frequency 4F derived positions. None has a relative difference of greater than 50cm. Given the uncertainties in the positions of both the PNNL ground-truth (which incidentally only provided to within the nearest 10cm) and the good match between the positions derived from the slow frequency 4D and fast frequency 4F datasets, we believe that the location accuracy of inverted positions obtained from the UltraTEM data well meets the objective: i.e., for 90% of inverted positions to be closer than 50cm to the "true" positions.

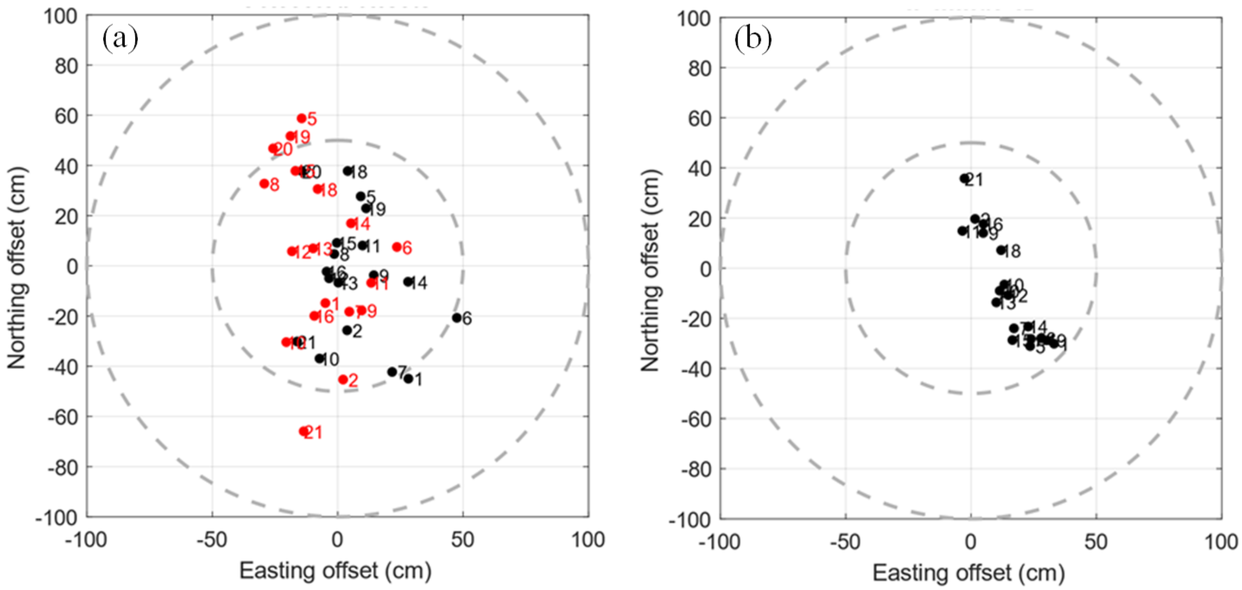

Figure 8. Positions derived from the UltraTEMA-4 platform relative to the PNNL supplied ground-truth. (a) Offsets of 4F and 4D. (b) Location difference between 4F and 4D.

As a summary of the classification performance, Figure 9 shows the receiver operating characteristic curves (ROC) for both the slow and fast-transmitter base frequency data. For the fast frequency 4F data, there are five false positives at demonstrator threshold and only two false positives at best threshold. For the slow frequency 4D data, there are six false positives at demonstrator threshold and only three false positives at best threshold. All TOIs were correctly classified for both data sets. The classification objective has been achieved for both low-altitude datasets: the probability of classification of both dig-lists is one.

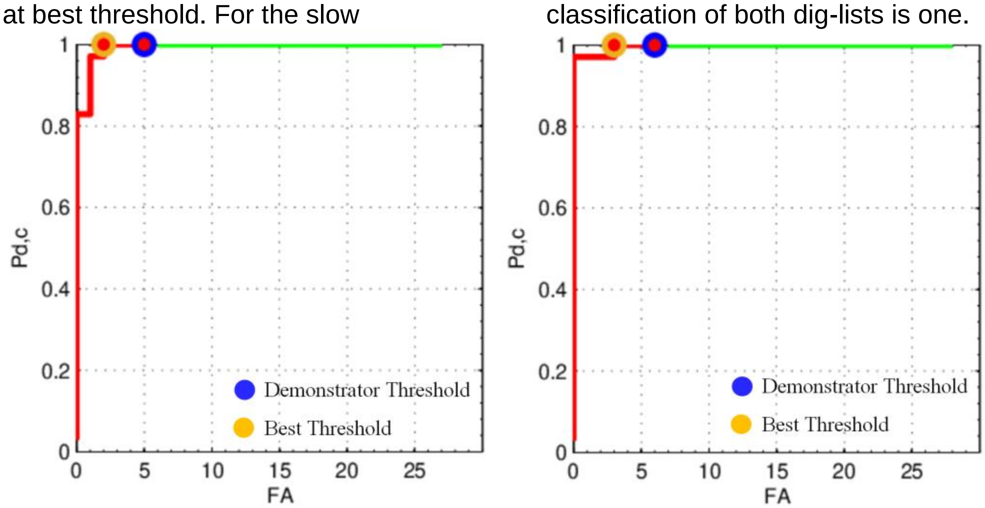

Figure 9. Receiver operating curves of low altitude data: (a) Fast transmitter mode. (b) Slow transmitter mode.

Conclusions

This paper presents the works performed under SERDP MR19-126 and ESTCP MR19-5073 that aim to address the challenges arising from underwater munitions detection and characterization. These challenges are technical and operational, including the effects of conductive seawater on the measured target response and the suitable signal model for processing, the maintenance of sensor positional accuracy for achieving a full surveying coverage, and a stable control of surveying altitude for obtaining sufficient SNR.

In the technical aspects, we have developed a full integral equation technique to model and characterize EMI responses in a multi-layered medium. To mitigate the influence of inaccurate sensor positioning on a recovery of the polarizabilities of a target, we have proposed the modified inversion methods that implicitly and explicitly account for sensor positioning errors. To increase detectability at large standoffs, a synthetic aperture method has been attempted to boost target signals.

In the operational and instrument development aspects, the UltraTEM has had several modifications and improvements in hardware and software. At present, the system is equipped with unique features, including: (1) large transmitter coils and high transmitter dipole moment (e.g., 300 Amp turns for the marine UltraTEM);

(2) configurability for multiple transmitter loops and sensor cubes to address specific applications and environments; (3) extremely rugged and reliable electronics with precision time synchronization; and (4) integration with BTField software, which can be easily configured for new transmitter receiver geometries and can be used for near real-time processing and interpretation of data. By combining these with the results of demonstration of blind test at Sequim Bay, we can draw the following conclusions:

- Within the time range of interest, the dipole signal model used in terrestrial EMI sensing can be effectively utilized for marine detection and characterization.
- Conductive background responses, which can obscure or distort target responses, can be effectively removed by modeling the marine environment as a layered structure or with a properly designed high-pass filter.
- Accounting for errors in sensor positioning is important to accurately recover the polarizabilties of a target through inversion. The IMLI and JETSP methods serve the purpose well.
- Detection of weak targets can be enhanced via the synthetic aperture method that optimally stacks multiple transmitter–receiver measured responses.
- Multiple surveys at 0.5m to 1.5m+ altitude above the sea-bottom demonstrated that the UltraTEM tow-fish is stable to track the sea-bottom profile without significant changes in platform pitch and roll and without large excursions from the intended track. The low-altitude data collected at the fast-transmitter frequency (4F) achieved 100% coverage of the Blind-Grid area. At small standoff distance (0.5 to 0.75m) to the seafloor, we expect the UltraTEM system will allow for collection of high SNR data for production of underwater UXO surveys.
- For each of the two low-altitude blind-grid submissions, all seeded targets have a corresponding target pick which means that the probability of detection is 1.0. The receiver operating characteristic curves (ROC) show that both low-altitude submissions achieve the probability of classification of 1.0 with five or six false positives at demonstrator threshold and only two or three false positives at the best threshold. The location accuracy of the classified targets, as compared to the ground-truth positions, is within 50cm. We have demonstrated that AGC is feasible within the marine environment in situations where the tow-fish can be operated at low altitude (e.g., ~ 0.5m) above the bottom.

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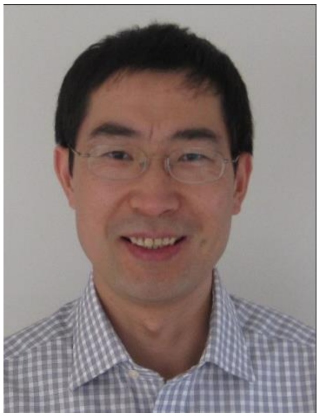
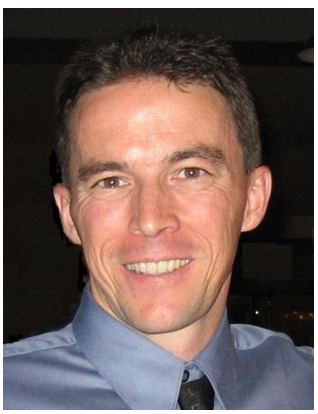
Author Bios



Dr. Lin-Ping Song is a geophysicist at Black Tusk Geophysics. Before he was a Research Associate with the Geophysical Inversion Facility, University of British Columbia, Vancouver, BC, Canada. His primary interests are in developing advanced electromagnetic induction sensing and signal processing techniques for characterizing targets in complex environments, with 18 years of experience working on the UXO detection, localization and classification problems both on land and underwater.



Dr. Stephen Billings has over 27 years' experience working with geophysical sensor data, including 22 years where he has concentrated on improving methods for detection and characterization of UXO. He splits his time working for Black Tusk Geophysics in Canada and Gap Explosive Ordnance Detection in Australia and is an adjunct professor in Earth and Ocean Sciences at the University of British Columbia. He has also been a principal investigator on more than a dozen completed SERDP-ESTCP munitions response projects, ranging from developing and testing classification strategies for magnetic and electromagnetic sensors to developing and certifying new sensor systems.

Dr. Len Pasion is a geophysicist specializing in UXO detection and classification. His current focus is the development and implementation of classification workflows to UXO contaminated sites. He has over 20 years of experience in munitions related classification research and data processing for munitions projects.

David Sinex is a dedicated geophysicist and software developer at Black Tusk Geophysics, with over 15 years of experience in the field. Residing in Victoria, BC, he excels in designing and implementing sophisticated data analysis workflows and software tools. His expertise encompasses electromagnetic modeling, data analysis, GIS systems, and the logistics of large-scale geophysical data processing projects. David's academic achievements include a Bachelor's and a Master's degree in Geophysics from the Colorado School of Mines, fortifying his role as a vital asset to the BTG team and the wider geophysical sector."

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Single-Pass Handheld and Unmanned Ultra-Light Electromagnetic Arrays for UXO detection and Classification

Max Orman-Kollmar[1], Randall Reynolds[1,2], Benjamin Barrowes[2], Michele Maxson[1,2], Caylin Hartshorn[1,2], Fridon Shubitidze[1]

[1]Dartmouth College, Hanover, NH, USA

[2]U.S. Army ERDC Cold Regions Research and Engineering Laboratory, Hanover, NH, USA

Maximilian.A.Orman-Kollmar.TH@dartmouth.edu
Randall.W.Reynolds.TH@dartmouth.edu
Benjamin.E.Barrowes@erdc.dren.mil
Michele.L.Maxson.TH@dartmouth.edu
Caylin.A.Hartshorn.TH@dartmouth.edu
Fridon.Shubitidze@dartmouth.edu

Abstract

The process of detecting, mapping, localizing, and remediating unexploded ordnance (UXO) is both time-consuming and expensive. Cleanup costs for unexploded ordnance are significantly higher for challenging sites, such as those in wooded, rocky, wet, marshy, and rough terrain, which make up more than 50% of the 10 million acres of unexploded ordnance-contaminated sites in the United States [1]. Over the past three decades, extensive research into understanding electromagnetic induction phenomena for detecting subsurface metallic targets with high conductivity and permeability has led to the development, construction, and implementation of advanced bistatic electromagnetic induction systems. These advanced systems incorporate multiple transmitters and receivers, along with sophisticated electromagnetic induction forward, inverse, and classification models. They have provided new capabilities for UXO cleanup efforts by distinguishing potentially hazardous munitions and unexploded ordnance from non-hazardous metal debris. However, most, if not all, current commercial electromagnetic induction systems are bulky, heavy, and unsuitable for challenging terrain. In addition, the standard process involves initial dynamic anomaly detection/selection, followed by cued (static) EMI data acquisition for each detected anomaly, which result the UXO detection and classification processes expensive and time consuming. This paper presents the Ultra-Light Electromagnetic Array system (ULEMA), which the Electromagnetic Sensing Group at Dartmouth College has designed, built, and tested for the detection and classification of subsurface targets. The ULEMA system consists of three small and one large transmitter loops and four tri-axial receivers. This configuration enables the detection and classification of targets in a single pass, eliminating the need for a secondary cued data acquisition. The three smaller transmitters are strategically positioned to illuminate targets from various sides, while the one larger transmitter is designed for detecting and classifying deep targets. The instrument is compact and lighter than many systems currently used, making it suitable for deployment by hand, on unmanned ground vehicles, or unmanned aerial systems. The ULEMA data acquisition system integrates inertial measurement unit and Global Position System data to geolocate anomalies in the measured electromagnetic induction data. The system's detection and classification capabilities are demonstrated across various modes of operation.

Introduction

UXO, the lingering remnants of military training and conflicts, presents significant military and civilian challenges on a global scale. Even within the USA, roughly 10 million acres of land remain contaminated with UXO [2]. However, the magnitude of this problem is significantly exacerbated in Europe, Asia, and the Middle East due to ongoing military training, conflicts, and historical wars. The current Ukraine-Russia conflict has already led to estimations of UXO contamination spanning more than 20 million acres, an area as large as Austria [3].

Over the last three decades, the US government has made significant investments and dedicated efforts toward advancing electromagnetic induction technologies [4-12]. These advancements encompass time-domain electromagnetic induction sensing systems and physics-based data processing methods aimed at detecting, locating, and classifying subsurface metallic targets [13-17]. These sophisticated EMI devices record target responses, offering unparalleled spatial resolution and a wide spectral range that facilitates comprehensive characterization of buried objects. The effectiveness of these advanced EMI sensor technologies in discerning potentially hazardous UXO or other Munitions and Explosives of Concern (MEC) from non-hazardous metal debris has been validated through the US Department of Defense (DOD) Advanced Geophysical Classification Accreditation Program (DAGCAP) [14] and the associated international ISO/IEC 17025 standard.

Despite their capabilities in UXO detection, localization, and classification, the current commercial of the shelf (COTS) systems are focused on ruggedization and achieving classification, leading to some weighing over one hundred pounds, rendering them impractical, especially in rugged terrains such as boulder-strewn landscapes, forested areas, cliffs, and wetlands.

Moreover, most systems necessitate a multi-step process involving 1) dynamic then 2) static data collection, which is more time-consuming and costlier than one-pass classification approaches.

To address these limitations, we introduce the ULEMA [15] for detecting, localizing, and classifying subsurface metallic targets. This system can be handheld [15] or mounted on remote-controlled robots [16] and unmanned aerial systems (UAS) [17]. The ULEMA captures comprehensive target responses in vector form with spatial accuracy and an extensive spectral range, enabling detailed object characterization.

Identifying subsurface targets from geophysical data involves a sequence of three stages:

1) Detection: This initial stage encompasses digital mapping of geophysical data, involving the capture of high-quality data using EMI systems. The quality of data and the responses from targets are directly affected by various factors, including the system's capabilities, data acquisition speed, onboard processing power, as well as the size, shape, and arrangement of the transmitter-receivers.
2) Mathematical inversion: Following data acquisition, this stage utilizes comprehensive physical models to interpret EMI datasets. It estimates intrinsic target features, such as magnetic polarizations, derived from geophysical data.
3) Classification and characterization of targets: In this final phase, the extracted intrinsic parameters are utilized to categorize anomalies, distinguishing between significant targets and non-hazardous items.

Once a target response is recorded, the raw data undergoes preprocessing and inversion to extract intrinsic feature parameters. These features act as inputs for the selected classifier. The inversion process concurrently outputs object positions, orientations, and electromagnetic signatures, including the magnetic dipole polarizability tensor. These electromagnetic signatures, particularly the principal axis of the inverted magnetic dipole polarizability tensor, are then employed to differentiate detected objects, enabling the distinction between UXO and clutter.

Figure 1 - View of ULEMA Array Configuration. The direction of travel is defined along the axis of symmetry of the system, with the transmitter in the front.

ULEMA hardware

The ULEMA system was constructed through a combination of customized and commercially available hardware and firmware. The system comprises a custom-designed transmission (Tx) system responsible for generating a primary electromagnetic (EM) field in the time domain, employing a square wave with a 50% duty cycle. During the on-time phase, which lasts 8.33 milliseconds, the current in the Tx system experiences an exponential rise and then maintains a constant current within the range of 10 to 20 Amperes. This current profile creates a primary magnetic field encompassing any high-conductivity metallic targets present. This magnetic field effectively penetrates inside these targets. After the on-time phase, the Tx current is swiftly interrupted, resulting in a rapid turn-off of the primary magnetic field within the targets. This fast change in the magnetic field induces eddy currents within conductive objects, leading to the generation of a slowly diminishing secondary magnetic field detected by receivers. The secondary magnetic fields give rise to an electromotive force (emf) within each of the four multi-static, multi-axis receiving (Rx) coils, which are amplified, using a custom made two-stage instrumental amplifier, and subsequently measured. These secondary magnetic field measurements are used for the purpose of detecting and classifying subsurface metallic targets.

Each ULEMA system, whether handheld, robot-mounted, or suitable for UAS, comprises two primary components. The first component is the array head, depicted in Figure 1. The second component is the electronics box, discussed below and shown in Figure 2.

The array head incorporates four coplanar transmitter coils and four triaxial receiver coils positioned within the transmitters. The transmitters operate sequentially, firing every 33.32 milliseconds, resulting in seven complete datasets every second, with each complete data set made up of: four transmitters x 12 receivers x 40-time gates. Utilizing the complete data set from all four triaxial receivers and all four transmitters provide a full characterization of metallic targets exposed to primary magnetic fields from various angles. This dense data facilitates the inversion algorithm in extracting both intrinsic and extrinsic parameters from the dynamically collected data. The intrinsic parameters include the effective magnetic dipole moment, which produces size and shape. This capability enables single-pass classification.

The ULEMA array head integrates a lightweight commercial off-the-shelf Global Positioning System (GPS) module, offering real-time kinematic (RTK) positioning accuracy within 1cm at a 10 Hz data rate and off-the-shelf Inertial Measurement Unit (IMU) sensor to monitor the system's orientation.

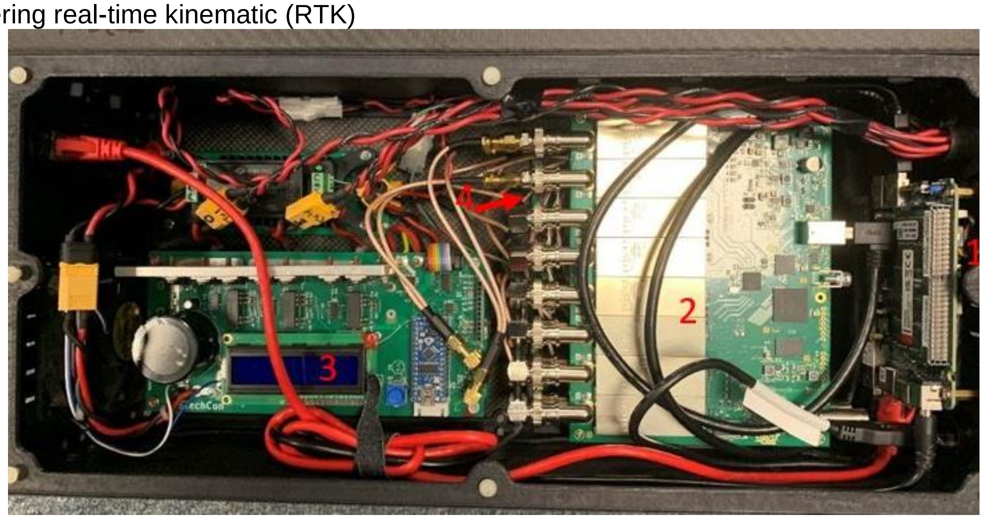


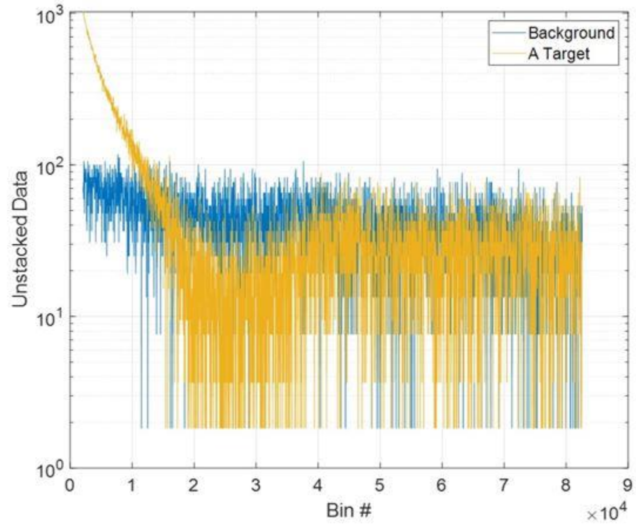
Figure 2 - ULEMA Electronics Box. The major components are (1) the brick computer running the software, (2) the Field Programmable Gate Array (FPGA) handling the incoming data and the outgoing current, (3) the transmitter board sending out the pulsed current, controlling the on and off times which allow for the decaying secondary field to be detectable, and (4) the amplifier boards, which increase the incoming data magnitude to make the responses better distinguishable, positioned directly below the FPGA.

The second primary component within the ULEMA system is the electronics box. Constructed from carbon fiber plates, this box houses several components including data acquisition (DAQ), two-stage amplifiers, transmitter boards, DC-DC power adapters, a mini-PC, and custom-made transmitter boards (depicted in Figure 2). One of the distinctive aspects of these systems is the utilization of a tailor-made Transmitter (Tx) board. This board, developed in collaboration with Dartmouth College and Subsurface Sensing Technologies and Consulting (SSTechCon), LLC, integrates Insulated Gate Bipolar Transistors (IGBTs). These components efficiently handle significant voltage and current levels, maintaining a 50% duty cycle. Alongside a microcontroller, it adeptly manages current polarity switching and synchronizes Tx currents, as illustrated in Figure 3. In addition to the Tx board's robust capabilities, the board maintains a lightweight design and is powered by a simple 22 V battery. The board operates the transmitter loops in a sequential manner, generating currents with a 50% duty cycle of up to 20 A for each transmitter in a span of 33.33 milliseconds. This process, in turn, creates the primary magnetic field required. The entire activation cycle spans 133.33 milliseconds, resulting in data collection occurring at intervals of ~13 cm, achieving a frequency of 7.5 Hz.

The analog EMF signals that are saved from the receiver coils are conditioned, amplified, and then transmitted to the DAQ system. This DAQ system, comprised of FPGA boards operating at a speed of 10 million samples per second, digitizes and transmits these signals to an Intel NUC computer for preprocessing of the raw data.

Our team has designed tri-axial magnetic field sensors proficient in measuring the magnitude and orientation of decaying secondary magnetic fields, all within a lightweight triaxial sensor housing weighing 0.2 lbs. Each sensor consists of a ten-layer PCB employing center-tapped configurations, housing ten 10cm x 10cm coils on each layer, totaling 100 turns and an effective Rx area of 1m x 1m. A two-stage internally developed low-noise amplifier for signal conditioning and amplification has been incorporated.

Once the received data is measured, it is structured into logarithmically spaced time bins, resulting in the generation of transient responses using our in-house developed MATLAB-based DAQ software package. Characterizing these decay patterns is enabled through logarithmic binning of the waveform, condensing the original 83,300 samples per receive channel into 40 bins. Figure 3 illustrates raw and processed signals for both background and target scenarios.



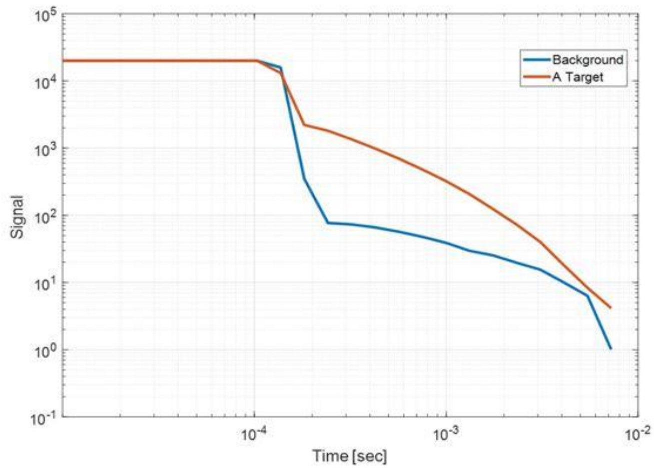


Figure 3 - Examples of raw **(top)** and processed/stacked **(bottom)** signals.

ULEMA systems

ULEMA-Handheld

The Electromagnetic Sensing Group (EMSG) lab has built and evaluated ULEMA systems in three configurations: handheld (ULEMA-H) [15], robot-based (ULEMA-R) [16], and UAS mountable (ULEMA-A) [17]. These systems utilize the same electronic components but differ slightly in Tx coil geometry, sizes, and Rx coil placements. Figure 4 illustrates the ULEMA handheld configuration, comprising three circular coils and one large loop transmitter and four tri-axial receivers. The arrangement of Rx coils is designed to yield data spaced at ~10 cm intervals along the cross-track.

Figure 4 - Full ULEMA Handheld system.

Figure 4 shows the fully assembled ULEMA-H system. A communication link can be mounted on the electronic box, which allows a user to watch the data collection in real-time on a separated screen, isolated from the data collection process. Thus, the sensor can be used in any modality, while the users can monitor it from a safe distance and see potential targets even before the data processing has begun.

ULEMA-A

A minor design adjustment is necessary for deploying ULEMA on UAS platforms. Namely, the system is suspended beneath a UAS, and all electronics are enclosed within the structure of the transmitter coils. The layout of the electronics was carefully arranged to ensure even weight distribution across the array head, promoting stable flight of the UAS, see Figure 5. Furthermore, crossbeams were incorporated at the base of the UAS to enhance stability for attaching the sensor at its designated points.

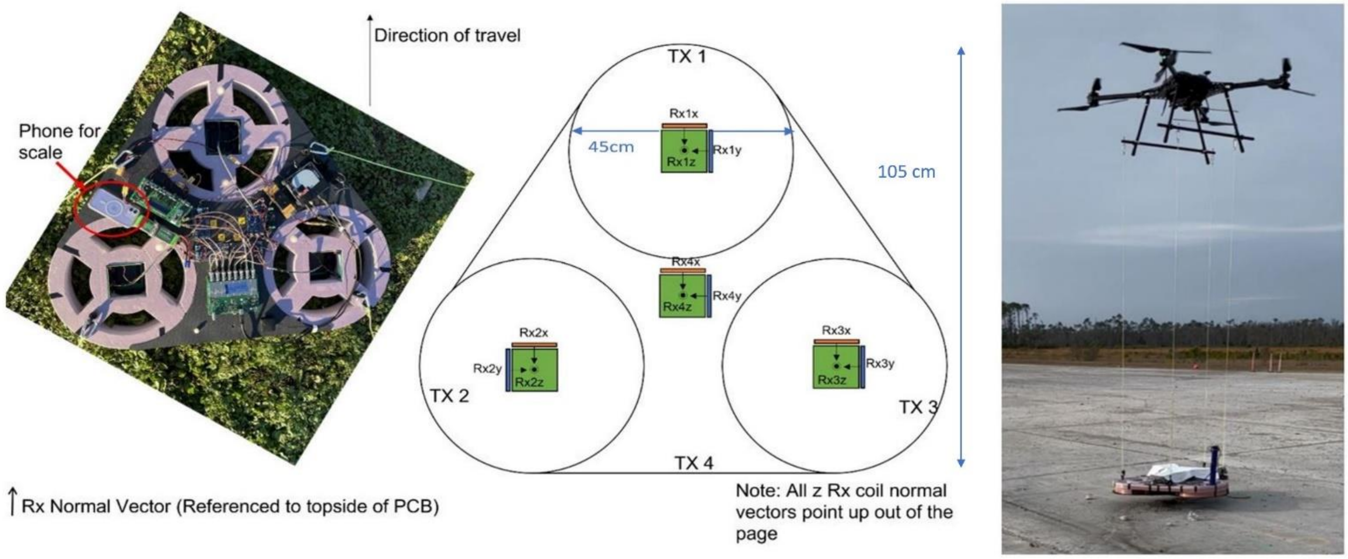


Figure 5 - ULEMA Airborne system. The general layout of the system is shown **(left)**. The system suspended below a Harris HX8 UAS **(right)**. Note the vertical post on the rightmost image, which holds the GPS/IMU sensor.

ULEMA-R

The robotic vehicle-based ULEMA-R system uses identical electronic components and an electronic box. However, it comprises two small (40cm by 40cm), one medium-sized (40cm by 60cm), and one large transmitter loop (wound around the two small and one medium loops). The small and medium-sized loops are engineered to illuminate targets from distinct angles, while the large Tx coil amplifies the detection, localization, and identification of deep targets. Extensive testing has been conducted at both test and blind sites, demonstrating the system's capability to detect and classify targets up to 15x the target's diameter. Figure 6 exhibits the ULEMA-R system along with its detection map.

Figure 6 - ULEMA-R during the data collection **(left)**. ULEMA-R EMI detection map overlaid on the Google map **(right)**.

Results

Testing was conducted both on controlled sites and test locations. The detection depth and classification depths were both confirmed before the systems were tested on blind test sites.

Test-Stand: Detection Depth

EMI systems, when operating in cued mode, are limited to detecting and classifying objects at offsets of approximately less than 11 times their diameter. To address this limit, the ULEMA systems were purposefully designed and constructed for the specific task of identifying deep subsurface targets using single-pass datasets. Overcoming the 11x rule was possible through updates to the custom-made amplifiers and quiet transmitter board used, which allowed for lower noise and better signal to noise ratio (SNR). Additionally, the high sample rate of 10 million samples per second allowed for more data collection and cleaning. As seen in Figure 3, the processed data shows that data decay can be seen for 5 decades, which is possible due the high sampling rate and averaging of the data in each time gate. Figure 7 shows the process of data collection and the recorded signals relative to data points for a horizontal 155mm projectile positioned beneath the ULEMA system.

To ascertain the detection depth of ULEMA systems, EMI response data from a 155mm projectile was gathered. The sensor was placed on a non-conductive raised platform, and the 155mm projectile was placed directly underneath on an adjustable surface. Starting from a 137cm offset, the system recorded static data above the target for 2-3 seconds. The target was then removed and the surface lowered. Once the surface was lowered (in 10cm increments at first, then in 5cm increments at larger offsets), the target was reinserted for another 2-3 seconds and data were recorded at the new height.

Figure 7 displays the recorded data (depicted by blue lines) for the 155mm projectile positioned at various depths. The data indicates that at shallow depths, the measured data exhibits decay following the 1/distance^5 (fifth) power law, whereas for deeper targets, the signal decays according to the 1/distance^6 (sixth) power law. For targets closer than 1.5x the maximum transmitter length (in this case, around 1.5m), the primary magnetic field decays as 1/distance^2. Because the 155mm projectile was over 2x its maximum distance away from the Rx coils, the secondary signal emanating from it decays as 1/distance^3. The product of the two decays gives 1/distance^5. As the target gets further away from the transmitter, the primary magnetic field decays as 1/distance^3, with the decay product becoming 1/distance^6. The distance measurement is calculated from the bottom of the array to the closest point of the targets. Even at 205cm depth, which is 13x the 155mm projectile's diameter, the signal is distinguishable from the observed noise of approximately 1x10^{-4} V/A. The results underscore that the signal consistently remains well above the noise level. Additionally, the signal exhibits a decay behavior between the 1/d^5 and 1/d^6 decay models, further corroborating the system's effectiveness in detecting targets at varying depths. Data was also collected for a BLU-26 submunition, shown in Figure 8. The Blu-26 submunition is about 70mm in diameter, and it is clearly visible at even 85cm deep, over 12x the diameter.

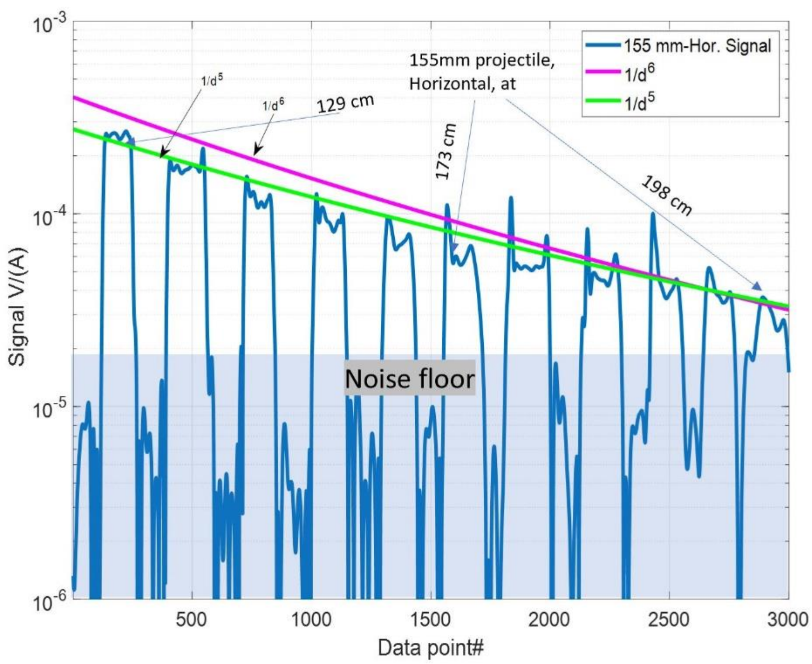


Figure 7 - ULEMA-R Detection depth for a horizontal 155 mm projectile horizontal in test-stand. The noise floor is shown for comparison **(left)**. The test stand set-up is shown as well **(right)**.

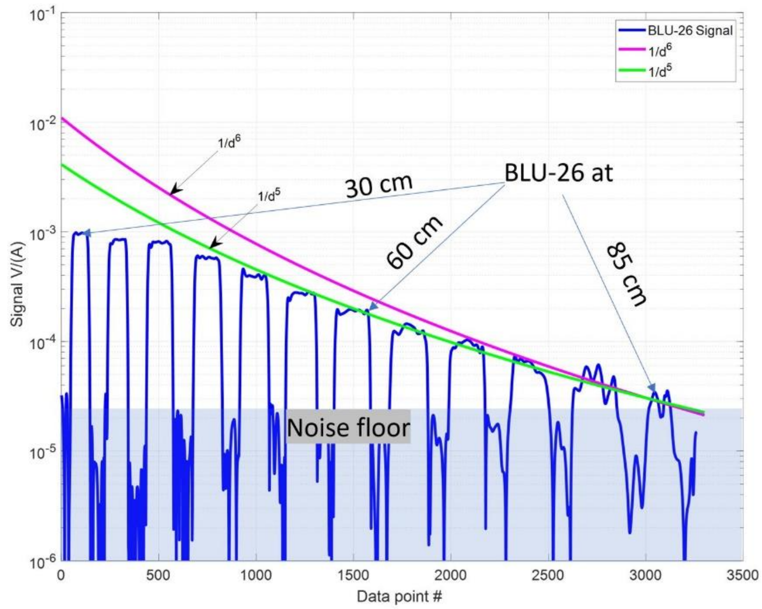
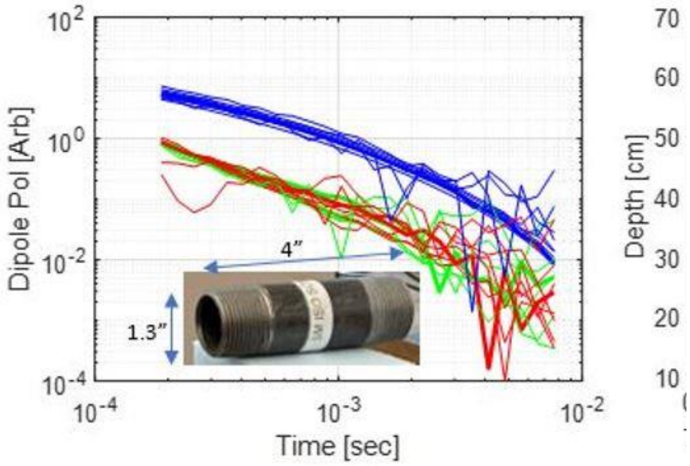


Figure 8 – ULEMAR Detection depth for BLU-26 submunition, with noise floor for comparison **(left)**. The test stand set-up is shown as well **(right)**.

Classification depth

The ULEMA system is designed for both deep target detection and classification. To demonstrate the systems' limitations in classification depth, initial studies were conducted in a laboratory setting using a small industry-standard object (ISO) measuring 4 inches in length and 1.3 inches in diameter. The analysis covered both vertical and horizontal orientations at various depths.



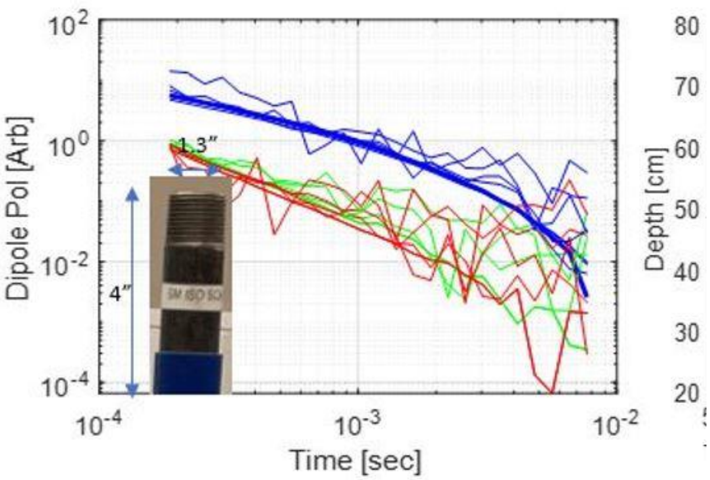


Figure 9 shows inverted polarizabilities corresponding to different depths, with the right side illustrating the inverted depth relative to the target's diameter. These findings indicate that the ULEMA systems adeptly determine the positions of targets up to depths 20x their diameter, while successfully extracting effective polarizabilities.

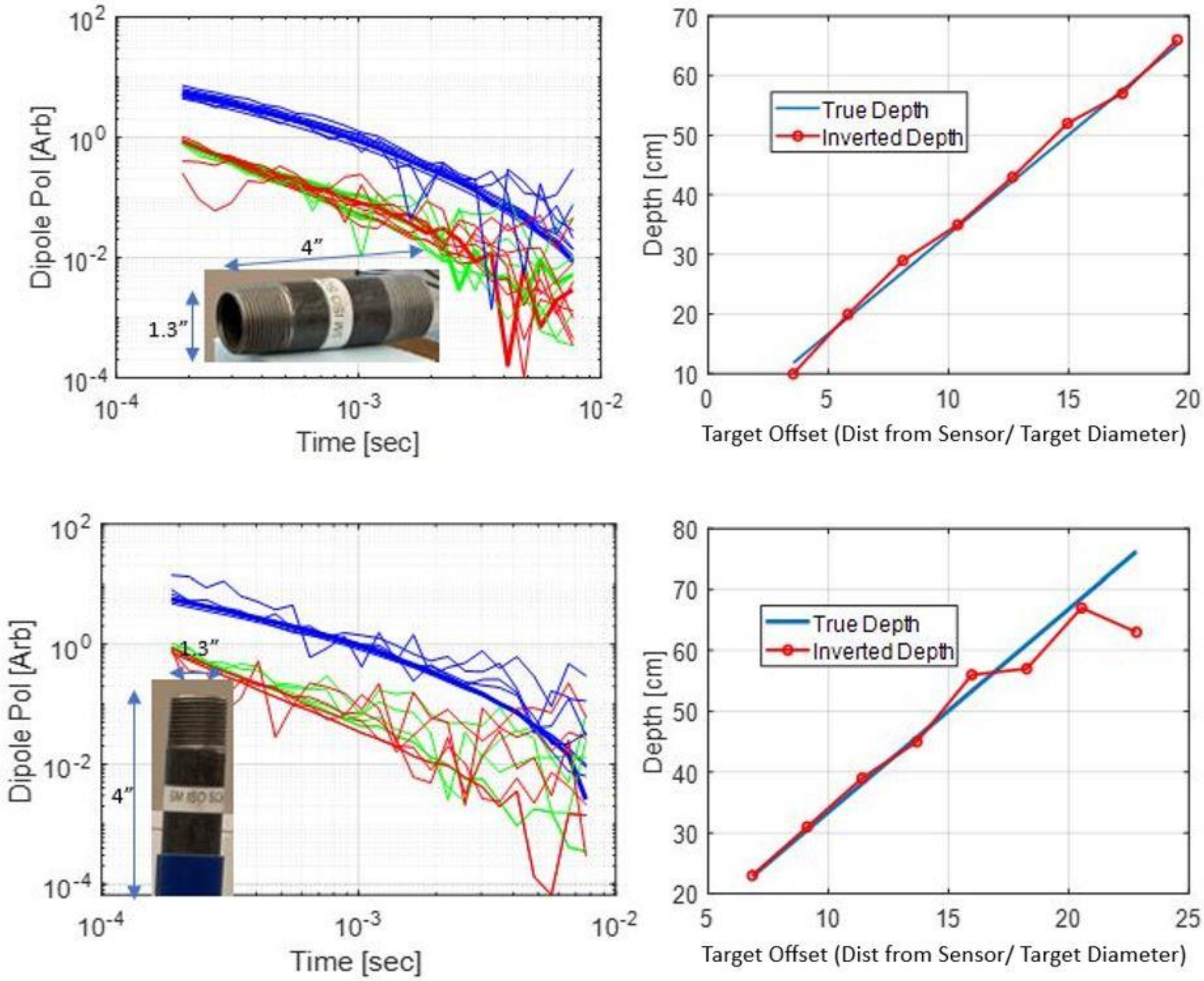


Figure 9 - ULEMA-R classification depth for a small horizontal **(top row)** and vertical **(bottom row)** ISO. The **left** column: inverted effective polarizabilities, blue, green, and red lines are primary, secondary, and tertiary effective polarizabilities, respectively. The r**ight** column**:** the inverted depth versus ratio true depth to target diameter.

To illustrate the performance of ULEMA systems in detecting and classifying deep subsurface targets under-real field conditions, Figure 10 displays the EMI signals detected above a buried, horizontal 155mm projectile. These detection signals were measured with the single-pass ULEMA-R systems in dynamic mode. Subsequently, advanced forward and inverse EMI models, such as combined orthonormalized volume magnetic sources and a differential algorithm, were employed to process the measured signals and extract the target's intrinsic and extrinsic parameters for each single-pass data set. The inverted depth, measured from the array center to the center of the 155mm projectile, is 168cm and consistent with the actual burial depth of the target. Additionally, the extracted polarizabilities align with those found in the library, shown in Figure 10. These results demonstrate that the single-pass ULEMA system is capable of practical classification in field operating conditions.

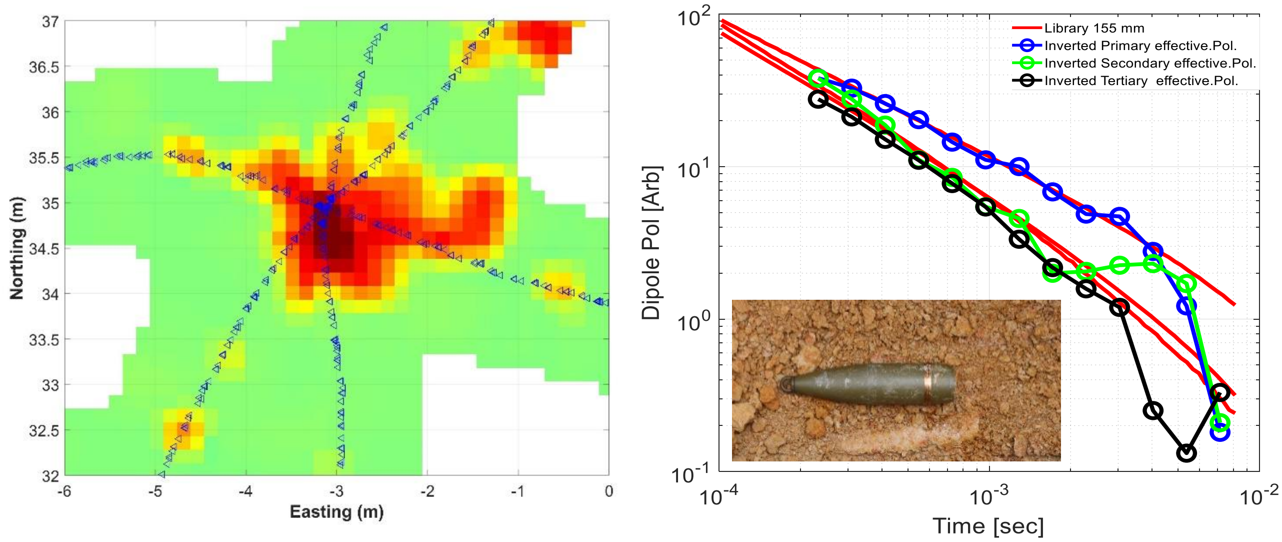


Figure 10 – ULEMA-R local detection map. Blue triangles indicate the path along which the sensor was moved over the area (**left**) and comparisons between extracted effective polarizabilities for library and buried 155 mm projectiles (**right**).

Tyndall Air Force Base

For ULEMA Airborne (ULEMA-A), data collection and testing were performed at Tyndall Air Force Base (Figure 11). Various UXO surrogates were placed inside 1.5m deep craters on the surface of the runway. Targets used mimicked 155mm and 105mm projectiles, as well as rockets and smaller munitions. Several data collection runs were performed. One run had GPS coordinates of the targets in the UAS mission planning software for the sensor to collect dynamic data while flying directly over the four targets at 1m above ground level. The other data collection runs had the UAS traverse to a GPS coordinate, with the operator manually lowering the system over each target for 20 seconds of static data collection.

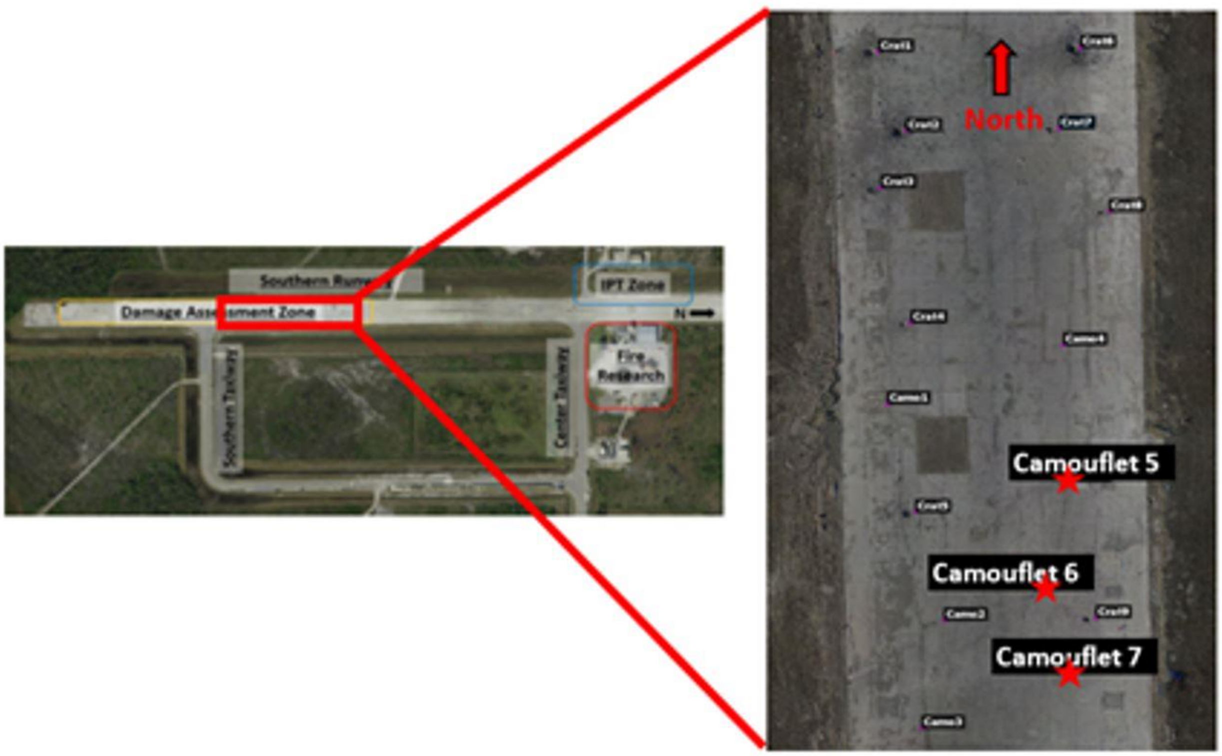


Figure 11 – Tyndall Air Force Base test site.

Figure 12, shows a detection heatmap of the dynamic data collection run. All four targets are clearly visible along the flight path. The dynamic data were processed and inverted, which extracted the polarizabilities of each target. The extracted polarizabilities were compared to a set of library values, with the closest match reported as the best estimate as shown in Figure 13. The dynamic data were used to extract the polarizabilities demonstrating the capability for target classification with a single pass. The thick lines in Figure 13 represent the target polarizabilities from a previously collected library database, and the thinner lines represent the extracted polarizabilities. The extracted polarizabilities match well with the library values.

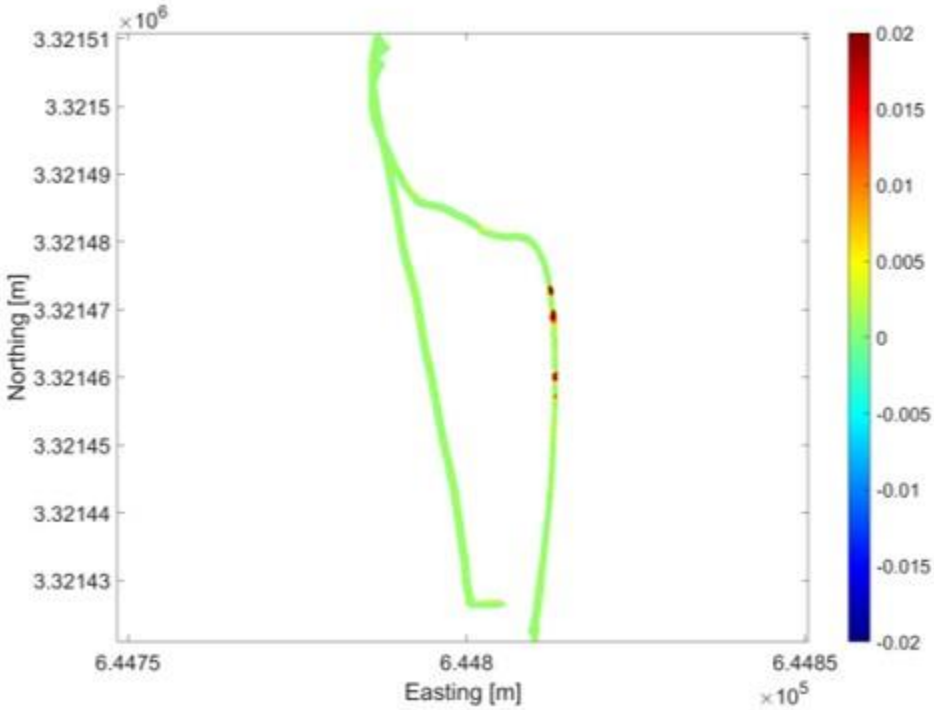


Figure 12 - Detection heatmap for Tyndall test area.

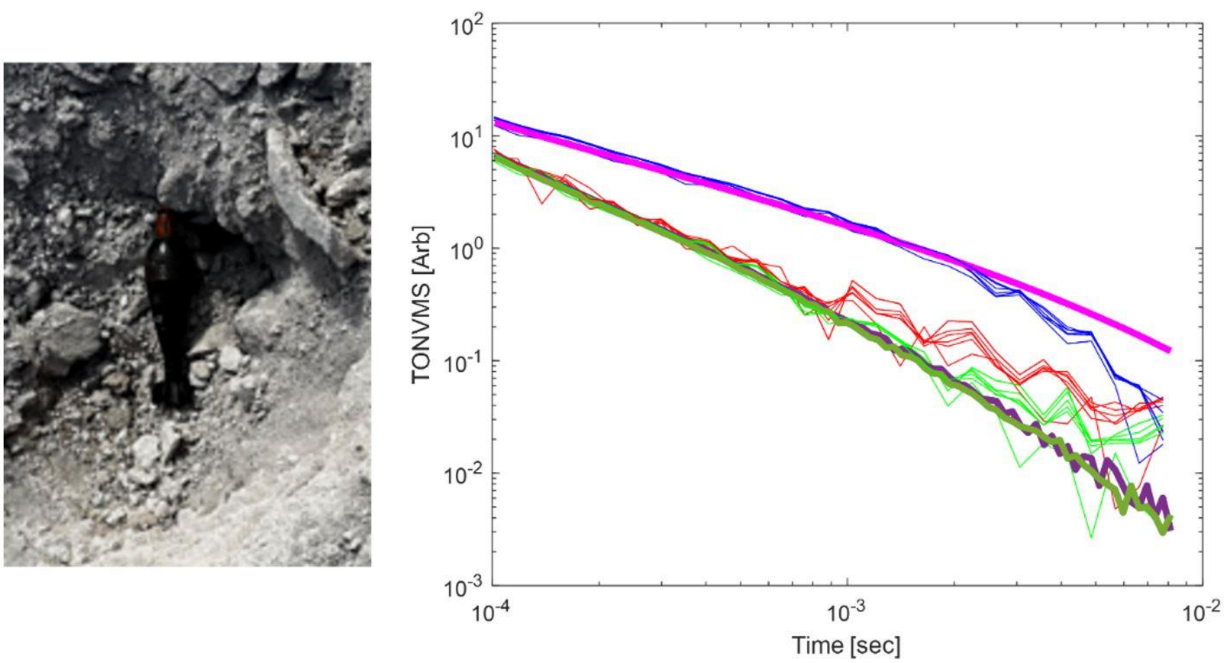


Figure 13 - 81mm projectile in crater **(left)**. The extracted polarizabilities from the single-pass collection. The thick lines represent the library polarizabilities, while the thin lines represent the inverted polarizabilities **(right)**.

ULEMA Studio software package

The EMI software package ULEMA-Studio, shown in Figure 14, has been designed, built, and tested to process ULEMA data sets and to meet DAGCAP requirements [14]. This software integrates functionalities such as data acquisition, sensor function testing, data pre-processing, data inversion, and automated and manual classification. Additionally, the software allows users to expand the DoD library by introducing new target entries. ULEMA-Studio facilitates the creation of site-specific synthetic data, allowing assessment of classification performance. Our

DoD library encompasses a diverse collection of more than four hundred munitions items ranging from 20mm projectiles to MK84 bombs and includes similar munitions items that vary in size and shape. This library was created using EMI data obtained from laboratory and actual live UXO settings and is compatible with DAGCAP-library.

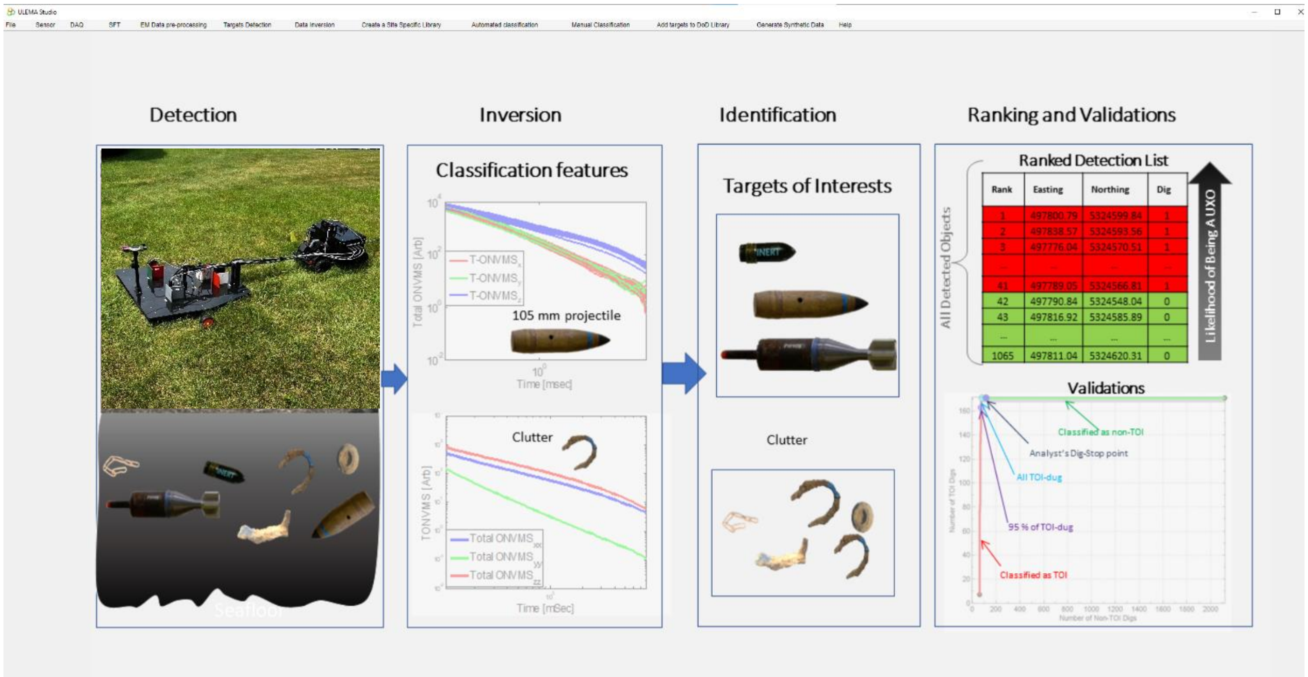


Figure 14 - ULEMA – Studio GUI.

The initial phase of data preprocessing involves filtering the raw EM data to remove background noise. This process of background removal is executed for each time channel. Subsequently, the background-corrected data are gridded to generate a detection map, where users have the flexibility to select a detection threshold. Once defined, the software identifies peaks surpassing the detection threshold, designating each as a detected anomaly. The software automatically selects data points surrounding each detected anomaly, which then undergo an inversion process using advanced forward and inverse EMI models [11]. The result of this inversion process includes determining the locations and magnetic polarizability tensor elements. The coordinates resulting from inversion are converted from a local to a global coordinate system. This conversion is facilitated by the GPS and IMU data associated with each EMI data point. The inverted polarizabilities serve as classification features, which are compared against the entries in the library. This comparison between the source's polarizabilities and those in the library yields classification confidence statistics, Figure 14, which are used to rank the sources according to likelihood of being a target of interest.

Conclusion

The ULEMA systems have been developed to address the challenges of subsurface detection and classification in difficult terrain, including densely wooded, wet, and rugged landscapes. The core components of ULEMA systems, including the Tx/Rx head and DAQ box, are designed for multi-modality applications. Compact and lightweight, the ULEMA instrument is adaptable for manual deployment, or integration with unmanned ground vehicles, and aerial systems. The data acquisition system incorporates IMU and GPS hardware to map and geolocate anomalies identified in measured EMI data. These systems produce high-quality single-pass EMI datasets, enabling characterization and precise localization of subsurface targets. The ULEMA Studio package has been specifically created for ULEMA data acquisition, pre-processing, inversion, target classification, DoD library updates, and synthetic data generation [19]. The data collection and processing workflows adhere to the DAGCAP general procedures [14]. Future endeavors will focus on DAGCAP validation of the ULEMA-Studio and ULEMA systems for application within MMRP.

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Acknowledgements

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Author Bios

Max Orman-Kollmar was born in New York City and received his double-majored in Engineering Physics with a concentration in Physics as well as in Middle Eastern Studies with a focus on Arabic language and literature from Dartmouth College in 2020. He subsequently received his BE in Mechanical Engineering from the Thayer School of Engineering in 2021, as well as his Engineer in Training license the following summer. He is currently pursuing his PhD at Dartmouth College in control theory and electromagnetics, working on autonomous electromagnetic sensor design and integration.

Randall Reynolds was born in New Haven, CT. He received a BS in Mechanical Engineering from the University of Vermont in 2014. Afterwards, Randall served as a Building Controls Engineer at the University of Vermont for 1 year and then as a Research/Mechanical Engineer at White River Technologies for the next 5 years. Currently, Randall works as an Electronics engineer at the Cold Research and Engineering Laboratory (CRREL). He has 8+ years of experience working with electromagnetic sensors including data collection, data processing, data quality control and sensor development. He has worked with Magnetometers, Time Domain Electromagnetic Induction (EMI) and Frequency Domain EMI for Unexploded Ordinance (UXO) detection, utility mapping and other remote sensing applications.

Ben Barrowes received the Ph.D. degree in 2004 fromthe Massachusetts Institute of Technology, Cambridge, MA. He was named top high school math student in the state of Utah (1991), was awarded an NSF graduate fellowship (1999), was a Director's funded Postdoc at Los Alamos National Laboratory (2004) and was named Innovator of the Year for the Army Corps of Engineers (2019). Currently, he is a physicist with the US Army ERDC Cold Regions Research and Engineering Laboratory and is the author or coauthor of over two hundred scientific publications. His research interests center on electromagnetic wave theory and modeling with applications including electromagnetic induction methods for detecting and classifying subsurface objects, novel fusion energy generation, and the intersection between modern technology and political science.

Ms. Maxson has undergraduate degrees in both mathematics and physics and a masters in geoscience. She started her career in private industry working as a LiDAR data analyst. She moved to the federal sector working with the United States Army Corps of Engineers focused on near surface geophysics and the problem of remediating unexploded ordinance. She is now working toward her PhD at Dartmouth College in Electrical Engineering focusing on advanced geophysical classification systems and their associated algorithms. Ms. Maxson's research is the design and implementation of algorithms for both time and frequency domain electromagnetic induction sensors. She is the recipient of multiple awards for her research including the 2018 ERDC Program Development Award for her work with the Unconventional Countermeasures Program and the 2023 NATO SET Panel Young Scientist Award for her work with the Ultra-Light Electromagnetic Array (ULEMA).

Caylin Hartshorn served on active duty in the United States Marine Corps as a digital wideband equipment operator from 2009 to 2013. After leaving all military service he attended the University of Missouri - Kansas City (UMKC) where he received his B.S. in electrical and computer engineering (ECE). Caylin began his civilian federal service with the U.S. Army Corps of Engineers in 2018 when he joined Rock Island District. He worked at Rock Island until 2020, when he accepted his current position as an electrical engineer at the U.S. Cold Regions Research and Engineering Laboratory (CRREL) located in Hanover, NH. At CRREL, Caylin is part of an electromagnetic sensing research group that specializes in subsurface classification and detection, such as UXOs, IEDs, permafrost, voids, and civil works utility infrastructure. He currently attends Dartmouth College, Thayer School of Engineering, where he is pursuing his PhD in electrical engineering.

Fridon Shubitidze (A’98–M’04) earned a Diploma in radio physics (M.S.) from the Sukhumi branch of Tbilisi State University (TSU), Sukhumi, Republic of Georgia, in 1994. He obtained a Cand.Sci. (Ph.D.) degree in radio physics with a specialization in applied electromagnetics from TSU in 1997.

Beginning in 1994, Shubitidze served as a Member of the Research Staff at the Laboratory of Applied Electrodynamics within the Department of Physics, TSU. Simultaneously, he held a position as a Senior Teacher at the Department of Physics and Mathematics, Sukhumi branch of TSU, eventually becoming an Associate Professor in 1998. Between 1998 and 1999, he undertook a Postdoctoral Fellowship at the National Technical University of Athens, Greece, where he conducted research involving computer simulation of electrostatic discharge, electromagnetic compatibility's electrodynamic aspects, numerical modeling of conformal antennas, electromagnetic wave scattering, field visualization, object identification through scattered field analysis, wave propagation studies through anisotropic, plasma, and chiral media, and innovative numerical methodologies.

In the period from June to August 2005, he held the role of a Visiting Scientist at the Department of Earth and Ocean Science, University of British Columbia, Vancouver, BC, Canada. Presently, Shubitidze serves as a Research Professor at the Thayer School of Engineering, Dartmouth College, Hanover, N.H., and a senior research physicist, at White River Technologies. His primary research interests lie in the development of electromagnetic sensing technologies, numerical modeling concerning both forward and inverse electromagnetic scattering problems, the application of magnetic nanoparticle hyperthermia and phage lysates to reprogram tumor microenvironment for cancer treatment. A native of the Republic of Georgia, Shubitidze was honored with the Medal of Honor by the country's President in 2019, acknowledging "his personal contributions to the advancement of science and the creation of modern technologies." In additions, Dr. Shubitidze and his group received the Munitions Response Project-of-the-Year Award given by the Strategic Environmental Research and Development Program in 2011 for developing and demonstrating advanced EMI models and algorithms for UXO detection and classification.

Electromagnetic Induction Data Driven Synthetic Seeding: An Effective Approach to Augment Quality Control on Advanced Geophysical Classification Projects

Jonathan S. Miller, Michael Gunnels, Fridon Shubitidze
White River Technologies, Inc.
Lebanon, N.H.

Abstract

The effectiveness of advanced Electromagnetic Induction (EMI) sensor technologies to discriminate potentially hazardous Unexploded Ordnance (UXO) or other Munitions and Explosives of Concern (MEC) from non-hazardous metal debris has been established through the implementation of the US Department of Defense (DOD) Advanced Geophysical Classification Accreditation Program (DAGCAP) and the associated international ISO/IEC 17025 standard. A central principle of the DAGCAP program is the application of a blind seeding process on all Advanced Geophysical Classification (AGC) projects. To verify the AGC technology used on a project has detected and correctly classified all MEC, inert or proxy items are buried in undisclosed locations throughout the site to test the AGC process. To meet DAGCAP standards, the contracted Geophysical Classification Organization (GCO) performing AGC must classify 100 percent of these blind seeds or perform a Root Cause Analysis (RCA) for those that are not. While blind seeding is an effective process for ensuring the integrity of the classification decision, it can be costly, particularly for underwater UXO sites, due to the time required to bury and accurately survey a large sample of seeds throughout a site. A cost-effective way to increase the size of the seeding program is to use synthetic seeds, which incorporate the modeled signal from seed items into the EMI survey data acquired at the site. This method can significantly increase the number of seeds to better establish the operating envelope of the AGC technology given site-specific conditions such as environmental noise, terrain, and geology.

Introduction

One could make the case that blind seeding is the keystone of the DAGCAP program. It is a way to ensure that the AGC technology is performing as expected on a project. Because many Munitions Response (MR) sites contain a relatively small percentage of MEC compared to non-hazardous items, it can be difficult to ascertain the effectiveness of AGC decisions with intrusive investigation of native objects alone. By emplacing seeds at or near the maximum operating depth, seeding not only guarantees a statistically relevant sample size, but also demonstrates the technology is achieving the expected operating envelope. For these reasons, blind seeding was a critical component for achieving regulator acceptance of AGC technology during the inception of the DAGCAP program.

Blind seeding is implemented through two programs on AGC projects. The Quality Assurance (QA) program is performed by either the Government or a third-party contractor. These “validation” seeds are designed to verify that the GCO is implementing their quality system correctly. The quality system defines a set of standard operating procedures that guide all phases of work from site preparation to data collection to data processing to intrusive investigation. Validation seeds are emplaced at sub-maximal depths to demonstrate that if the GCO follows these procedures correctly, they are guaranteed to identify the seeds correctly.

The Quality Control (QC) program is implemented directly by the GCO contractor through the means of an internal firewall that segments the seeding team from the rest of the project team. QC seeds are designed to test both the GCO’s quality system and the AGC technology operating envelope. Accordingly, QC seeds are buried at various depths throughout the vertical boundary of the site, including seeds placed at or near their maximum expected depth of classification.

Effective QA can be accomplished with a relatively small number of validation seeds. Because these seeds are not intended to be as challenging nor to test the AGC technology under all conditions encountered at a site, validation seeds need only be placed at a rate equivalent to one seed encountered per survey team per day. QC, on the other hand, would benefit significantly from a larger number that tests the technology throughout the range of conditions that may be encountered on a site. Because environmental factors such as noise (e.g., powerlines), terrain, and geology can vary considerably throughout a site, verifying the AGC system operating envelope with all these variables may require a much larger distribution of QC seeds.

Synthetic Seeding

One way to boost seeding sample size without the cost associated with burying and surveying seeds throughout a site is to use synthetic seeds. Synthetic seeding is accomplished by combining real survey data with synthetically generated signals from seed objects using electromagnetic dipole-based models. To fully understand this approach, we must first consider the 3D electromagnetic sensor concept.

Advanced 3D EMI sensors incorporate an array of multi-axis transmitters and receivers to provide high spatial and temporal resolution of anomalies created by buried metal objects. This combination of multi-directional transmit and receive elements produces a spatially and temporally rich data set that contains information about how the subsurface object responds to the transmitter magnetic fields in both space and time. Specifically, the transmitter primary magnetic fields induce eddy currents within a target. These induced eddy currents generate a target response in the form of a secondary, time-varying magnetic field. As the transmitter fields impinge on the object in different directions, the target responses can be represented by the magnetic polarizations along the object's principal axes (i.e., one large longitudinal and two smaller lateral for axially symmetric objects such as UXO). The responses of these principal axes to the impinging magnetic fields are known as the time-dependent electromagnetic polarizabilities of the object (Figure 15) and they are used to characterize physical attributes such as diameter, wall thickness, aspect ratio, and material composition.

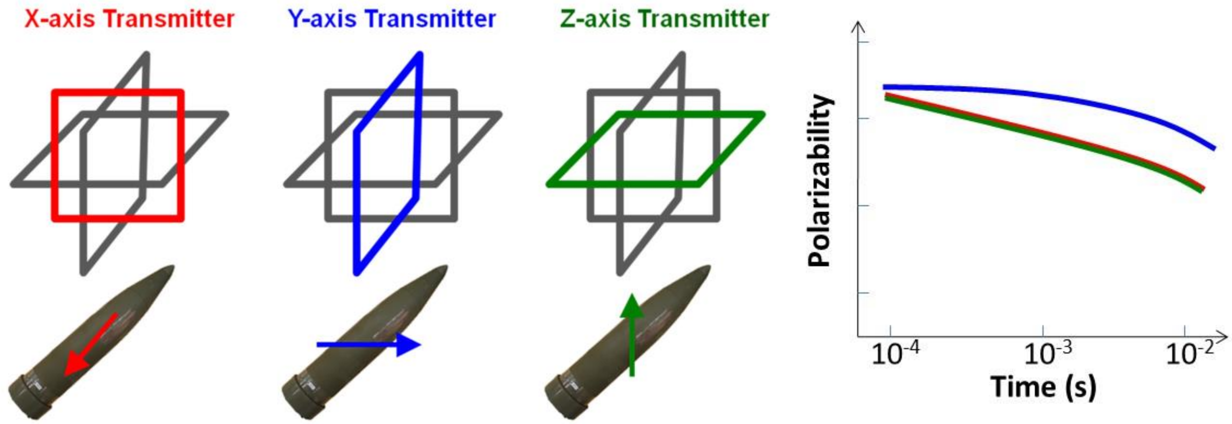

Figure 15. LEFT: Each transmitter creates a unique polarization of the buried metal object that is determined by the direction of the magnetic field impinging on it. RIGHT: The overall response of the object to the transmitters can be deconstructed into principal components described by a set of three time-dependent principal electromagnetic polarizabilities.

Much as the principal electromagnetic polarizabilities of an object can be derived from the object's response signal recorded in survey data, the reverse is also true. The electromagnetic forward model used to derive the polarizabilities from inversion of the data can also be applied to derive the signals generated by the object from the polarizabilities. This process is the basis for synthetic seeding.

Determining the Operating Envelope

As part of DAGCAP, the DoD has catalogued an extensive library of polarizability signatures derived from several hundred different munitions commonly found on current or former DoD installations. These library polarizabilities can be used to generate site-specific data driven synthetic data corresponding to any item in the library catalog. As an example of this process, we can consider the case of a 37mm projectile signature. Using the library polarizabilities for this item, we can effectively synthetically seed a site with a large sample size of 37mm projectiles placed virtually at a range of depths, locations, and orientations.

Figure 16 presents a grid of dynamic AGC sensor data comprising overlapping transects. Initially, we designate positions, depths, and orientations for our synthetic 37mm seeds within a global coordinate system on the grid. Subsequently, in the immediate vicinity of each synthetic seed location, we use the sensor's positions and orientations to compute the primary magnetic field at the synthetic seed's location. We then determine the induced magnetic dipole using library polarizabilities. We calculate the induced voltage at the sensor receivers for each transmitter coil. This process is performed at each sensor location to generate a signal based on the library polarizabilities that is contingent upon the seed's location and orientation with respect to the sensor. Finally, the signals generated from the library polarizabilities are added to the raw data. We then reprocess the synthetically seeded data files using the standard classification workflow. In this manner, we capture the effects of site-specific factors such as environmental noise and geologic response on the classification results. The classification workflow applies project-specific processing procedures to the synthetically seed data, verifying appropriate selection of data processing parameters.

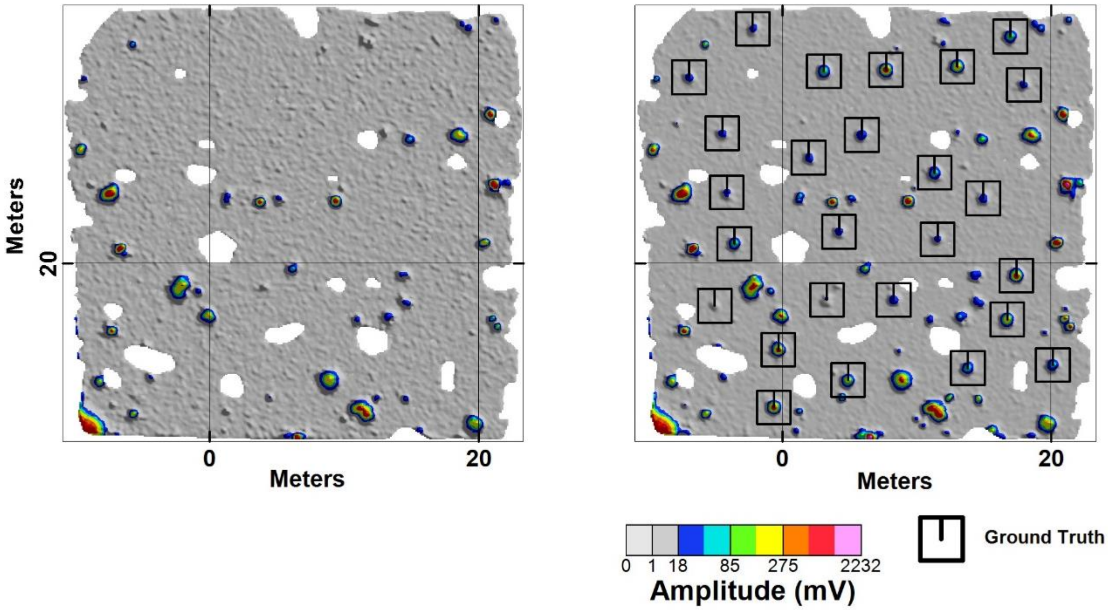

Figure 16. LEFT: Gridded dynamic AGC survey data acquired at a site. RIGHT: Grid map after synthetic 37mm projectile seeds (black squares) are emplaced. Seeds range in depth from 15 cm to 60 cm.

After inverting the seeded data, we can compare the polarizabilities for each seed to the library from which the seed signature was derived. A library match statistic is a value between 0 and 1 that indicates how closely a set of polarizabilities matches a library signature. Values close to 0 indicate a low confidence that the item is the library target while values close to 1 indicate a high confidence that the item is the library target. Typically, a confident classification decision can be made that the item is the library target when the match statistic is above a range of 0.8 – 0.9. A value in this range is selected per project as the target selection threshold. Targets above this threshold are selected for intrusive investigation and targets below this threshold are rejected as clutter. Library match values above this threshold indicate that the item is classified as the library target while values below this threshold indicate the item is not classified as the library target. Using a target selection threshold, we can determine whether the seed items can be correctly classified as the library target (37mm projectile) with a high confidence. This library match process quantifies the effects of environmental factors on classification of the seed by demonstrating the conditions in which the seed is no longer classifiable (i.e., it produces a library match below the threshold). Figure 17 shows an example of a synthetic 37mm seed library match.

Using the library match analysis, synthetic seeding provides confirmation that the operating envelope (i.e., required classification depth for a specific target of interest) can be achieved under the variety of conditions that may be encountered at a site. Conditions that may affect the depth of classification include site geology (i.e., elevated background response), environmental noise (e.g., power lines), terrain-induced noise, or saturated response areas (i.e., localized high target density regions).

Site-Specific Factors

Synthetic seeding is particularly useful for identifying site-specific factors that may limit the ability to achieve the planned operating envelope and for deriving data driven classification performance statistics. Physical seeding may not effectively capture the effect of environmental variability on AGC performance due to a limited sample size. The larger number afforded by synthetic seeding is more likely to capture corner-case scenarios (i.e., scenarios in which overlapping conditions such as high target density and elevated background combine to limit operating performance). Synthetic seeding can be a tool that not only identifies these conditions, but also provides a means for testing and verifying remedies to these challenges.

An example of this verification process is demonstrated using powerline noise interference. Powerlines and nearby low frequency, high power communication systems commonly interfere with EMI sensors by elevating background noise levels. Noise levels can vary significantly depending on the powerline height, depth, or time of day (load on the lines). Several filtering methods are available to reduce the effect of powerline noise, and results can be evaluated to ensure effective noise reduction without effect to detection and classification.

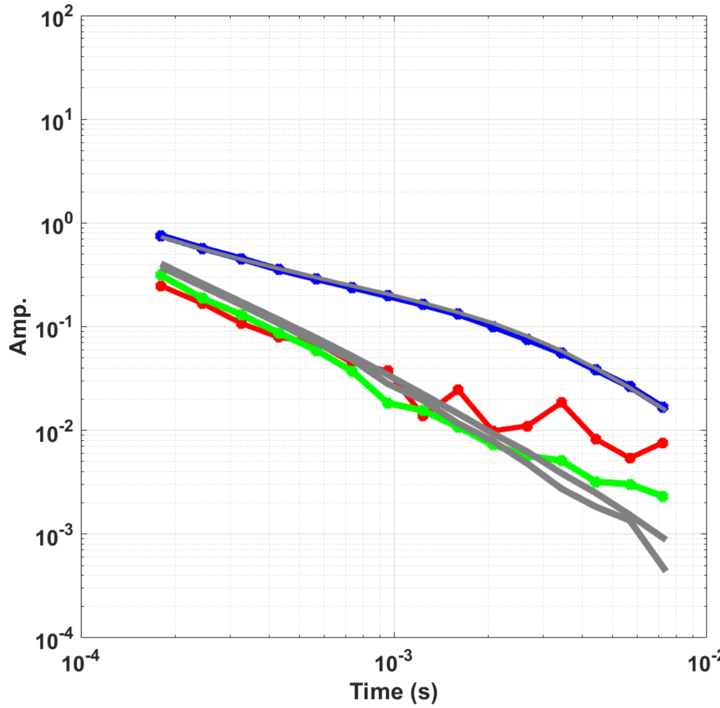

Figure 17. Library match showing the polarizabilities obtained from a synthetic 37mm seed (blue, red, and green lines) compared to the library polarizabilities (grey lines) for this item.

Figure 4 shows an example of powerline noise interference and the implementation of a filter to reduce these effects. In this case, we applied synthetic seeds to the data to evaluate the performance of the filter for improving classification in these conditions. We synthetically seeded the raw data with a distribution of 37mm projectiles and determined the library match for each seed after applying both the standard classification workflow and a site-specific workflow that implemented a powerline filter. We compared the classification results from the standard approach to the filtered approach and determined that the filter significantly improved the operating envelope for this target of interest.

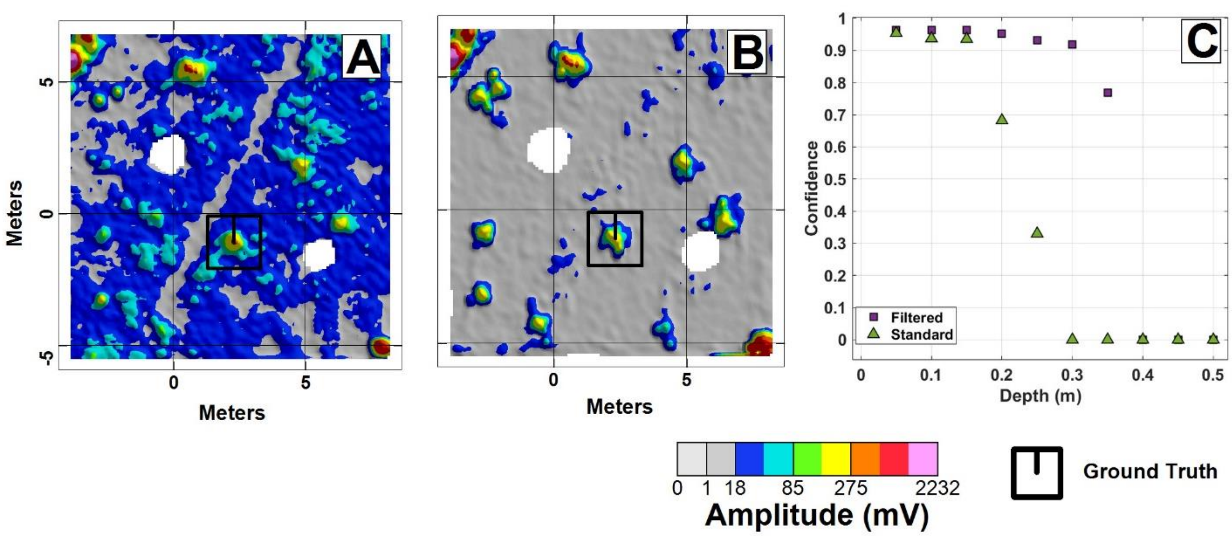

Figure 18. Example of powerline interference. A: Map showing the presence of elevated background noise due to a powerline running southwest to northeast through the grid. The map shows the gridded vertical component data. Due to the rotational direction of the powerline field, the vertical component data show elevated noise near the powerline, but not directly underneath because the noise there is almost entirely oriented in the horizontal plane. Ground truth for a seed location is shown as the black square. B: Noise levels are significantly reduced by applying a powerline noise filter. Note the seed's anomaly now produces a much higher signal-to-noise ratio. C: Classification confidence based on library match for synthetic seeds processed using the standard (triangles) and filtered (squares) methods. Without the filter, the seeds produce a high confidence match to a depth of only 0.15 m. Applying the filter, the high confidence match depth is extended to 0.30 m. A confidence value of 0 means that the seed signal is indistinguishable from noise.

Another challenge at many sites is the presence of magnetic geology that can produce an elevated and spatially variable background response. Separating the background response from the target response is a critical step in effective AGC. Without correct identification and removal of the background response, the background response may get mixed with the target signal and result in incorrect classification of a target.

Background identification and removal in AGC is typically performed using two methods: 1) static removal where the background response from one location is subtracted from other sensor data across the site (applies to both static and dynamic sensor data); and 2) dynamic removal where background response is determined from a highly localized region within the site and subtracted from sensor response within that region (applies only to dynamic sensor data).

Static removal is effective when the background response is relatively constant throughout the site; however, this method can be problematic when background response is high and highly variable as is commonly the case at sites with magnetic geology. In these conditions, the dynamic background removal approach may be more effective. As the dynamic background response window is applied to different regions throughout the site, the background is constantly updated to reflect the local response. A window length is selected based on the characteristics of the site. Longer windows are closer to static removal in that they apply one background correction to a larger area. A long window may be desirable for sites with little background variability. Shorter windows may be better suited for sites with high background variability because they are more sensitive to background changes over a smaller area. The potential drawback of a shorter window is the possibility of including a greater proportion of target signal with background response and, therefore, incorrectly over-leveling the data.

Synthetic seeds can be used to verify the optimal selection of a background removal approach for a site. For example, proper implementation of synthetic seeds can confirm the background removal window length effectively removes the background without removing target signals resulting in misclassification. Consider the data presented in Figure 19. The maps show a region of elevated background response due to magnetic geology. Each map displays the effect of applying a different length background leveling window to the data. Prior to performing the background leveling, synthetic seeds are placed at a range of depths in the elevated background region. Performing classification on the leveled data allows us to determine the effect of window length on the maximum operating depth.

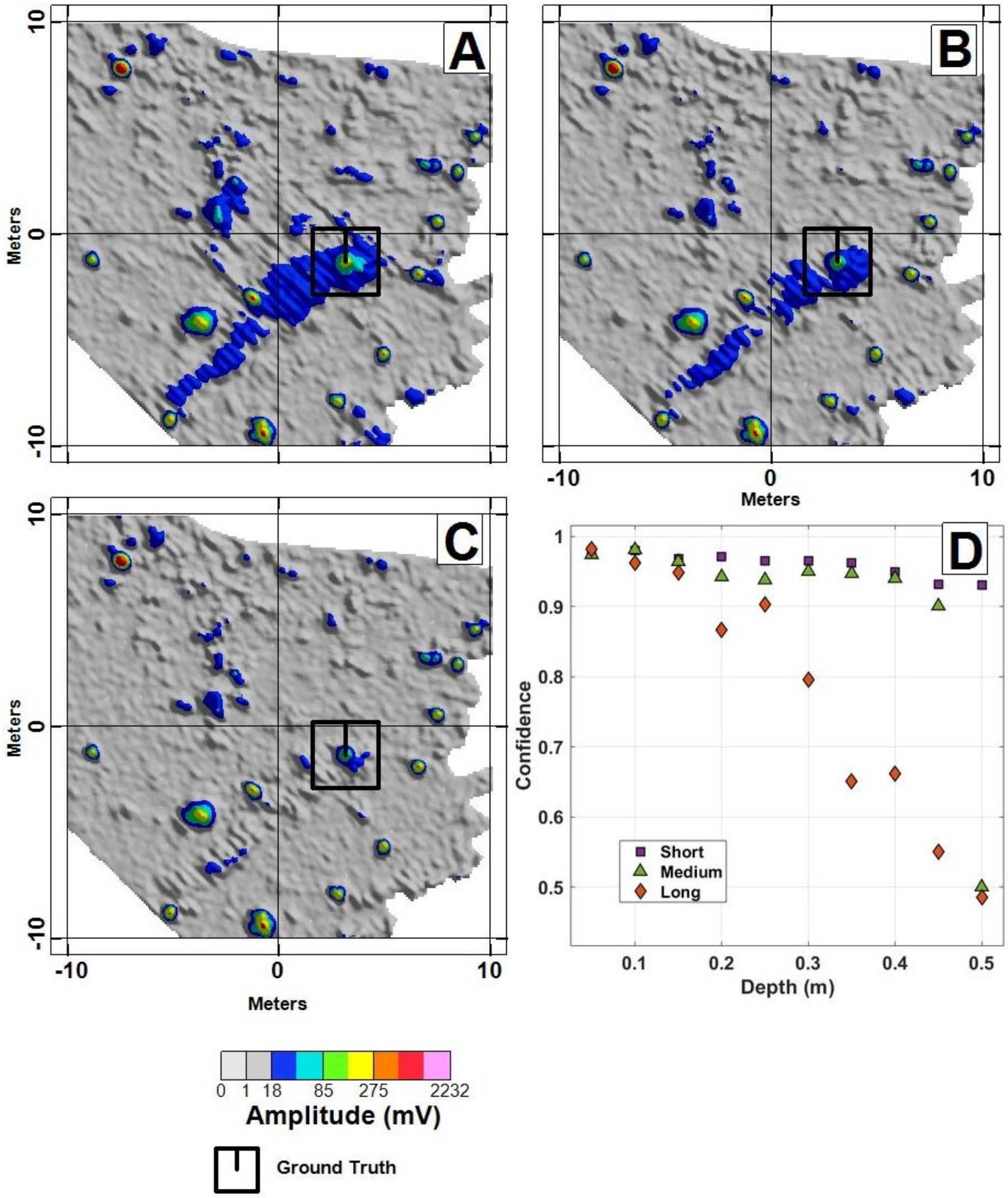

Figure 19. Data corresponding to a 37mm projectile synthetic seed buried at a range of depths at a site with elevated background response. The location of the synthetic seed is shown with the black square on each map. A: Gridded data leveled using a "long" filter length. Applying this window length is similar to performing static background leveling. B: Gridded data leveled using a "medium" filter length. C: Gridded data leveled using a "short" filter length. Note that as the filter window length decreases, the background response (blue region in center of map) decreases, and the seed anomaly becomes more distinct. D: Classification results corresponding to the three filter window lengths. The long filter (diamonds) provides high confidence classification to a depth of only 0.25 m, while the medium (triangles) and short (squares) filter lengths provide high confidence classification to depths of 0.45 m and 0.50 m, respectively.

Conclusions and Recommendations

Data driven synthetic seeding is an effective tool for supplementing QC measures on AGC projects. It provides a cost-effective method to capture the effects of site-specific factors on data quality, and to quantify and verify the performance of processing techniques used to mitigate these effects. Additionally, synthetic seeding can be used to generate extensive site-specific datasets for post-AGC assessment purposes.

While synthetic seeding captures many of the attributes of physical seeding, there are certain aspects of AGC that are better evaluated by emplacement of physical seeds. For example, it is possible to acquire AGC data with positional errors that would not be identified with synthetic seeding. Therefore, synthetic seeding is best suited as a method to augment and not replace the physical seeding program.

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Author Bios

Jonathan Miller
White River Technologies, Inc.
115 Etna Road, Bldg. 3 Ste 1
Lebanon, New Hampshire 03766
miller@whiterivertech.com

Jonathan Miller is a Senior Engineer at White River Technologies. He obtained a B.S. degree in Physics from Bates College and an M.S. degree in Mechanical Engineering from the University of Vermont. His research interests include application of magnetic and electromagnetic sensing to detection, subsurface characterization, and infrastructure monitoring. He is currently performing several projects involving integration of these sensor modalities with a variety of platforms.

Michael Gunnels
White River Technologies, Inc.
115 Etna Road, Bldg. 3 Ste 1
Lebanon, New Hampshire 03766
gunnels@whiterivertech.com

Michael Gunnels is an R&D Geophysicist at White River Technologies. He obtained a B.S. degree in Geology from Central Michigan University and an M.S. degree in Geophysics from the University of Missouri. His interests include efficient processing of magnetic and electromagnetic data, algorithm development / testing, and data fusion / visualization. He is currently working on algorithm development and assisting in commercial EM processing work.

Fridon Shubitidze, Ph.D.
White River Technologies, Inc.
115 Etna Road, Bldg. 3 Ste 1
Lebanon, New Hampshire 03766
shubitidze@whiterivertech.com

Fridon Shubitidze is a Senior Research Physicist at White River Technologies and a Research Professor with the Thayer School of Engineering, Dartmouth College, Hanover, NH. He received the degree of Diploma radio physicist (M.S.) from the Sukhumi branch of Tbilisi State University (TSU), Sukhumi, Republic of Georgia, in 1994 and the Cand.Sci. (Ph.D.) degree in radio physics (applied electromagnetics) from TSU in 1997. His current work interests focus on development of advanced EM sensing technologies (from 0 Hz up to GHz) for detecting and classifying buried explosive hazards on land and in underwater environments. In 2011, Dr. Shubitidze and his group received the Munitions Response Project-of-the-Year Award given by the Strategic Environmental Research and Development Program for developing and demonstrating advanced EMI models and algorithms for UXO detection and classification.