



Final Report

ESTCP Project MR-201612

**Implementing Advanced Magnetic Gradiometric Algorithms
Within Geosoft's Oasis montaj Software Platform**

December 2018

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LIST OF ACRONYMS

AECOM	Architecture, Engineering, Consulting, Operations, and Maintenance
ATR	Automated Target Recognition
CWP	Coalition Warfare Program
DCL	Detection, Classification and Localization
LSG	Laser Scalar Gradiometer
MAGMA	Magnetic Gradiometric Algorithms
MCM	Mine Countermeasures
MR	Munitions Response
MRS	Munitions Response Site
NSWC PCD	Naval Surface Warfare Center, Panama City Division
ONR	Office of Naval Research
PMA	Post Mission Analysis
REMUS	Remote Environmental Monitoring UnitS
TREX	Target Reverberation Experiment
UUV	Unmanned Underwater Vehicles
UXO	Unexploded Ordnance

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ABSTRACT

INTRODUCTION AND OBJECTIVES

The US Navy has been developing passive magnetic gradiometers for use in underwater mine hunting for decades, including sensor hardware, vehicle integration and detection algorithm development. Currently, analyzing the data from these systems has been the purview of a small number of analysts, making the dissemination of data collected from munitions response sites problematic. This project sought to create a toolbox within Geosoft's Oasis montaj software package that would allow import of raw data from these gradiometers as well as access to the robust detection algorithms developed and being used by the Navy. This will increase usability of these sensors and data products, as well as developing trust in the results being presented and provided to remedial program managers.

TECHNOLOGY DESCRIPTION

The Laser Scalar Gradiometer (LSG) is a prototype passive magnetic gradiometer designed for underwater mine countermeasures surveys, built by Polatomic Inc. in collaboration with the US Navy. This system and its successors, mounted on unmanned underwater vehicles, are capable of detecting ferrous targets such as mines and discarded munitions. Oasis montaj is the industry standard software package for analyzing magnetic survey data and the new toolbox designed specifically for this sensor will make future analysis open to a wider audience.

PERFORMANCE AND COST ASSESSMENT

Comparing the original algorithm implementation to the Oasis montaj toolbox has shown that they both yield quantitatively very similar results, which is the primary metric of success. These new software tools will be available to the community, similar to other unexploded ordnance tools created in partnership with the Department of Defense, so software costs will be low. The cost of sensor and vehicle hardware is high, but comparable to other survey equipment already in use.

IMPLEMENTATION ISSUES

The only implementation issues for this technology pair are acquiring the hardware and software required. It is likely that an organization interested in using magnetic sensors to survey for unexploded ordnance will already be using Geosoft's Oasis montaj and should thus have access to the software tools developed here. The remaining concern will be in acquiring an appropriate magnetic gradiometer and unmanned underwater vehicle or data from one already being used. A related concern would be any raw data formatting and/or sensor geometry differences between platforms between software upgrades within Geosoft Oasis montaj.

PUBLICATIONS

L. Vaizer et al, *Algorithm for Automatic Detection, Localization and Characterization of Magnetic Dipole Targets Using the Laser Scalar Gradiometer*, 2016, ESTCP Website

EXECUTIVE SUMMARY

INTRODUCTION

The US Navy has been developing passive magnetic gradiometers for use in underwater mine hunting for decades, including: sensor hardware, vehicle integration and detection algorithm development. Currently, analyzing the data from these systems has been the purview of a small number of analysts, making the dissemination of data collected from munitions response sites problematic. As these systems get more utilization on munitions response sites, it will be important to provide additional non-Navy personnel with the capability to process and analyze the gradiometric data. Geosoft's Oasis montaj, one of the common software packages for analyzing magnetic data for remediation, does not currently possess the complete set of tools used to properly analyze magnetic gradiometer data from these systems, limiting the munitions response community's ability to properly leverage data from these magnetic gradiometers as they find increased usage on underwater munitions sites.

OBJECTIVES

The objective of this project is to create a toolbox within Geosoft's Oasis montaj software package that would allow import of raw data from these gradiometers as well as access to the robust detection algorithms developed and being used by the Navy. This will increase usability of these sensors and data products, as well as developing trust in the results being presented and provided to remedial program managers.

A selection of algorithms and software tools developed at the Naval Surface Warfare Center, Panama City Division (NSWC PCD) will be properly packaged and combined with appropriate tools already available within Oasis montaj to allow for magnetic gradiometric data collected from these systems to be analyzed and displayed in a manner similar to other electromagnetic unexploded ordnance detection systems currently in use, allowing a much wider audience to analyze the data.

The toolbox will be demonstrated by using existing data collected over many years of in-water testing and validation. Intermediate data products from both the original implementation and the Oasis montaj tools will be compared to make certain individual steps in the workflow have been created correctly while final source detection lists will be compared to verify that the overall product is generating comparable results. Only fully tested and stable tools, the primary set used to import data and generate targets lists are being implemented, as experimental tools would be more prone to failure and inconsistent results.

TECHNOLOGY DESCRIPTION

The LSG and follow-on sensors are prototype passive magnetic gradiometers designed for underwater mine countermeasures surveys, built by Polatomic Inc. in collaboration with the US Navy. The original LSG system and its successors, mounted on unmanned underwater vehicles, are capable of detecting ferrous targets such as mines and discarded munitions (**Figure 1**).



Figure 1 – Prototype LSG sensor mounted on a REMUS600 being deployed in the field.



Figure 2 – Prototype single axis gradiometer mounted on a REMUS100.

Oasis montaj (see **Figure 3**) is the industry standard for analyzing magnetic survey data. The toolbox created under this project is designed for the LSG system and will make future analysis open to a wider audience.

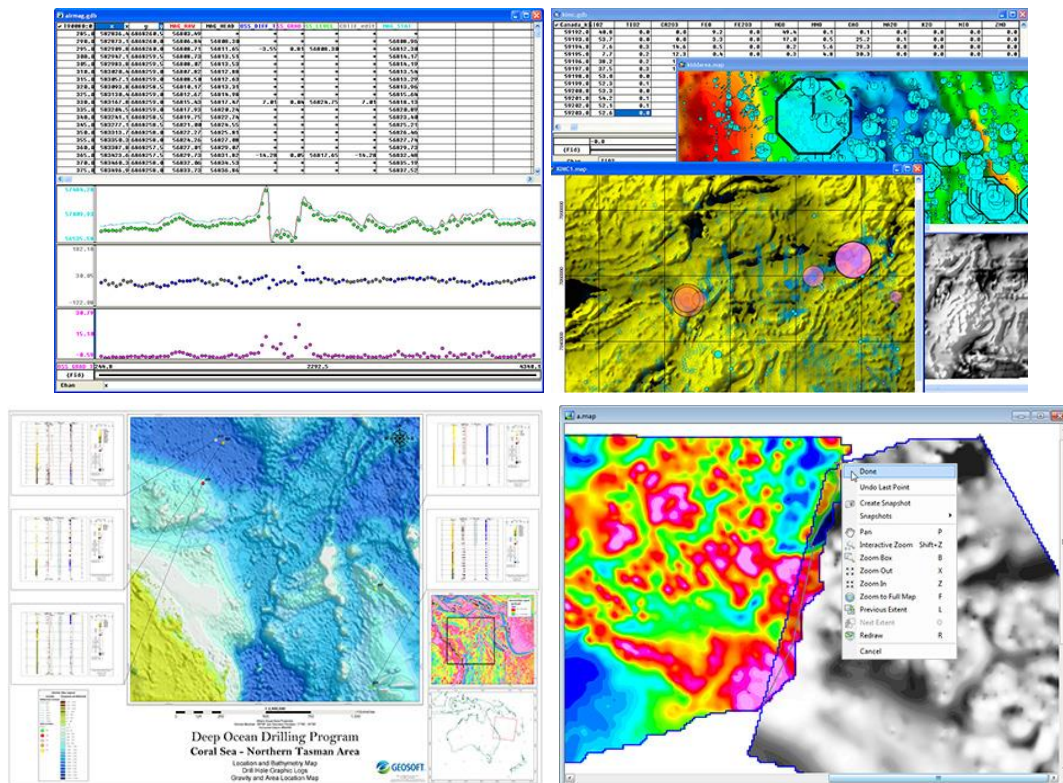


Figure 3 – Examples of various stock Oasis montaj interfaces and data products.

PERFORMANCE

The Navy's ability to detect underwater ferrous items of interest with high confidence has been repeatedly demonstrated during testing over the last 20 years and so the focus of this project was ensuring that the new implementation generates comparable results. Comparing the original algorithm implementation to the Oasis montaj toolbox has shown that they both yield quantitatively very similar results, which is the primary metric of success. The similarity was determined to be 95.54% for anomalies clearly distinguishable from background noise and 90.46% similar for all anomalies. The comparative analysis encompassed almost 100 datasets from 5 unique work products (2013 Fort Story, 2016 Dahlgren, 2016 Panama City, 2017 Dahlgren, 2017 San Diego), each with varying degrees of complexity

The new software tools developed for this project will be available to the community, similar to other unexploded ordnance tools created in partnership with the Department of Defense, so software costs will be low. These tools, developed under ESTCP project # MM-0131 (2009), are currently available free of charge to Geosoft users from the US UXO community, comprising US government employees, UXO contractors and regulators working for the DoD on UXO projects.

COST ASSESSMENT

Magnetic gradiometers mounted to UUVs are capable of operating in locations inaccessible to standard tow body setups and in many cases closer to the bottom, allowing for increased discrimination of targets. In addition, high accuracy dipole detection algorithms further reduce false alarms. In total, the combined benefit of these technology solutions is to reduce survey time and the number of contacts requiring follow-up remediation resulting in long term cost savings. However, it is true that the cost of such sensors and vehicle hardware is high, albeit comparable to other survey equipment already in use. The cost of conducting a survey with this type of hardware is also comparable to other underwater survey methodologies, which is understood to be more expensive than land based surveys.

IMPLEMENTATION ISSUES

There are two main requirements to implement the technology under the current configuration:

- **Software requirements** – Geosoft's Oasis montaj (v9.4 as of June 2018) and the implemented MAGMA toolbox once it is publicly released with the next version.
- **Hardware requirements** – The primary technology requirement is a 3 channel gradiometer, specifically the LSG from Polatomic Inc. and a REMUS600 UUV

The software is not considered a true limitation as everyone in the industry has access to a Geosoft license for DoD deliverable requirements and the MAGMA toolbox has no extra cost. The true limitation is the access to the hardware, not due to public availability but due to significant capital costs. However, the MAGMA toolbox can be used on datasets acquired by the Navy and provided to the contractor. Future interests for the project include modifying the toolbox for standardizing import formats and increasing geometric flexibilities to leverage a wider array of commercially available systems (e.g. Polatomic magnetic sensors, Geometrics G882 Array) in order to remove all implementation issues observed under the current configuration.

1.0 INTRODUCTION

1.1 BACKGROUND

Semi-automated target recognition (ATR) algorithms developed for magnetic gradiometer anomaly detection, classification and localization (DCL) have been successfully demonstrated to localize mine and unexploded ordnance (UXO)-like targets through simulation, land-based experimentation, and extensive in-water experimentation, testing and surveying. To date, the signal processing and analysis for Navy-developed magnetic gradiometers has been accomplished using custom algorithms developed for these specific systems, requiring specific personnel to accompany these sensors in order to process the collected data. As these systems get more utilization on Munitions Response Sites (MRSs), it will be important to provide additional personnel with the capability to process and analyze the gradiometric data. Geosoft's Oasis montaj, one of the common software packages for analyzing magnetic data for remediation, does not currently possess the complete set of tools used to properly analyze magnetic gradiometer data from these systems, limiting the Munitions Response (MR) community's ability to properly leverage these magnetic gradiometers as they find increased usage on MRSs.

NSWC PCD has spent several decades developing complex magnetic gradiometric algorithms (MAGMA) capable of accurately detecting, classifying and localizing relatively small ferrous targets of interest laying both proud on the seabed as well as fully buried. These algorithms have been designed specifically to operate using data collected from a suite of laser pumped helium-cell magnetometer systems developed by Polatomic Inc. (i.e. the Laser Scalar Gradiometer [LSG] and its successors), but can be generalized for different gradiometer setups using accurate geometrical information about the sensor setup.

Currently, these gradiometric sensors are mounted on commercially available unmanned underwater vehicles (UUVs) (i.e. Remote Environmental Monitoring UnitS (REMUS)) and are finding increased use in underwater MRSs throughout the United States. Magnetic data collected with these systems are capable of detecting a wide array of unexploded ordnance regardless of burial and have proven extremely useful in reducing the number of clutter contacts detected solely using acoustic sensors. Versions of these sensors, developed with the aid of the Office of Naval Research (ONR) and NSWC PCD, have transitioned into Navy acquisition programs, but even they do not have access to the entire array of processing tools developed for these sensors.

The Oasis montaj MAGMA toolbox developed under this project will make these tools available to a much wider audience and will increase confidence in the data products generated by these novel systems and their related algorithms, which will be important as more underwater MRSs are surveyed using these systems. By offering up these tools to a wider audience, input from others will help to further refine and improve the existing offering as the number of users and sites implemented continually increases. The ultimate goal of implementing advanced MAGMA within Geosoft's platform aligns with ESTCP's mission to realize market cost savings through industry-wide implementation of technological advances.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of this project was to create a software toolbox available from within Geosoft's Oasis montaj geophysical analysis software package, similar to the land based UXO detection tools developed by the Army. A selection of algorithms and software tools developed at NSWC PCD were properly packaged and combined with appropriate tools already available within Oasis montaj. Additionally, a few new (primarily display or minor correction) tools were added to be specifically tailored for the user. The end goal was to allow for magnetic gradiometric data collected from these systems to be analyzed and displayed in a manner similar to other electromagnetic unexploded ordnance detection systems currently in use by the DoD.

The toolbox was demonstrated by using existing data collected over a five-year period (2013-2017) of in-water data acquisition by NSWC PCD. Intermediate data products from both the NSWC PCD MAGMA implementation and the Oasis montaj tools were compared to make certain individual steps in the workflow have been created correctly while final source detection lists will be compared to verify that the overall product is generating comparable results. Only fully tested and stable tools, the primary set used to import data and generate targets lists are being implemented, as experimental tools would be more prone to showcase inconsistent results.

1.3 REGULATORY DRIVERS

ONR, NSWC PCD and others are continuing to develop magnetic sensors for use on UUVs for MCM, UXO detection, and other underwater work and it is vital that the larger community potentially getting access to this data be able to better process and understand the products being developed. As more underwater UXO sites get pushed towards remediation, it is very likely these types of systems will be fielded at an increased rate.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

Magnetic gradiometers for MCM have been in development since around the turn of the century. One MCM gradiometer being actively used by the Navy includes the LSG sponsored by ONR Code 32. Various tools / algorithms for DCL have been developed at NSWC PCD over the last decade. The effort is working to package an appropriate set of tools for implementation within Geosoft's Oasis montaj so that LSG data can be analyzed by a larger audience using software tools certified by agencies responsible for MR as well as those tools developed by the Navy for MCM.

These sensors use laser-pumped helium cells to measure the scalar magnetic field (via the Larmor precession frequency) to an absolute accuracy of better than 0.001%, making them more accurate than many contemporary magnetometers. Currently the detection limits of these sensors are not determined by the underlying physics nor the sensor technology itself, but rather the noise generated by the host platform (i.e. REMUS100 and REMUS600). A smaller single axis prototype contains two total-field sensors that generate a single magnetic gradient, which allows only magnetic anomaly detection, but not localization, to be determined using a single pass over an object. The LSG contains four total-field sensors that generate three unique magnetic gradients, allowing for detections, classifications and localizations to be determined in a single pass only. See **Figure 1** and **Figure 2** for images of these two systems.

Below is a rough timeline of LSG development at NSWC PCD.

- 2005: Under a Small Business Innovation Research program, the LSG 3-axis magnetic gradiometer delivered to Navy by Polatomic, Inc.
- 2008: Buried Mine Identification system including LSG, Marine Sonics sidescan sonar, and Pike Electronic Still Camera on a REMUS600 UUV was demonstrated at AUV Fest 2008.
- 2010: Demonstration of embedded magnetic ATR for LSG data at 2010 VSW-N Technology Demo.
- 2011: MCM S&T Demonstration of embedded magnetic/acoustic/optical data fusion of various ATR software. Magnetic localizations were fused with sidescan snippets, allowing for operator review after the mission.
- 2015: LSG magnetic data fusion with acoustic data from separate synthetic aperture sonar at Pax River 2015 ONR S&T Demo.
- 2016: Edgetech SBP and dual frequency sidescan replaces Marine Sonics sonar
- 2016: LSG performed UXO surveys near Eckernförde, Germany as part of multinational collaboration for the Coalition Warfare Program (CWP).
- 2017: LSG performed UXO surveys in San Diego as part of multinational collaboration for the CWP.

The general approach to detecting and classifying a ferrous object with LSG is (see **Figure 4**):

1. Calculate parameters for motion compensation of non-target signals arising from system rotations in the local Earth's magnetic field (based on data collected from an initial system calibration routine)

2. Calibrate several coefficients within the algorithm to account for changes in the Earth's magnetic field at different locations
3. Examine the time series data for obvious data quality issues (e.g. sensor malfunction, losing laser lock near a large ferrous object etc.)
4. Merge the sensor data with the vehicle's navigation data
5. Prepare data for subsequent analysis, including filtering to eliminate high frequency artifacts that are not of interest
6. Motion compensate to eliminate signals arising from rotation through the Earth's magnetic field
7. For the four-channel LSG, calculate three independent total-field magnetic gradients, providing the equivalent of three of five independent tensor magnetic gradients required to uniquely solve the underlying magnetic field equations
 - a. Since the smaller prototype has two total field sensors, only a single gradient can be calculated. This makes it possible to generate detections but not localizations
8. Search for a set of one or more magnetic dipoles that fit a segment of data

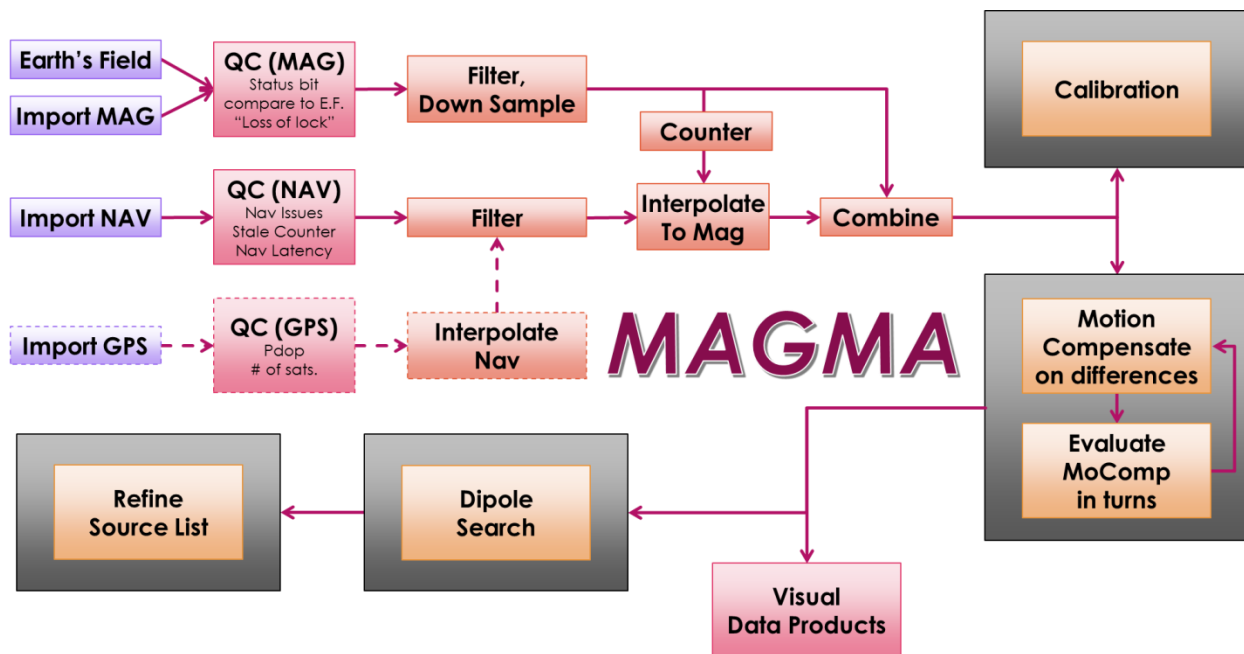


Figure 4 – Overview of MAGMA workflow. Black boxes indicate NSWC PCD section while other portions are built using existing or modified Oasis montaj tools.

These algorithms and software tools have been written in C and have been successfully operated within several Microsoft Windows environments as well as the Linux environment deployed on-board the AUVs themselves. The algorithms deployed on the vehicle are designed to operate autonomously while the vehicle and sensor are collecting data; however improved results are always possible with additional post mission analysis (PMA) once data has been downloaded from the vehicle. A primary limitation of these algorithms is their restricted availability beyond their creator which this project seeks to remedy.

On the software side, Geosoft Inc. was established in 1986 with a focus on exploration and earth sciences, making the explorer data experience simple, natural and powerful by providing

software for mapping and modelling the Earth's subsurface, and technology for managing large exploration datasets. Geosoft's flagship software, Oasis montaj provides a powerful suite of modelling and analysis tools for advanced understanding of the Earth's subsurface and subsea environments (see **Figure 5**). Oasis montaj is the market-leading software for UXO surveys, with UXO extensions that provide a full suite of tools to locate and analyse UXO targets based on magnetic (total field and gradiometer) and electromagnetic (EM61) data. A single workflow, incorporating Geosoft's UXO tools, goes from survey planning to target identification.

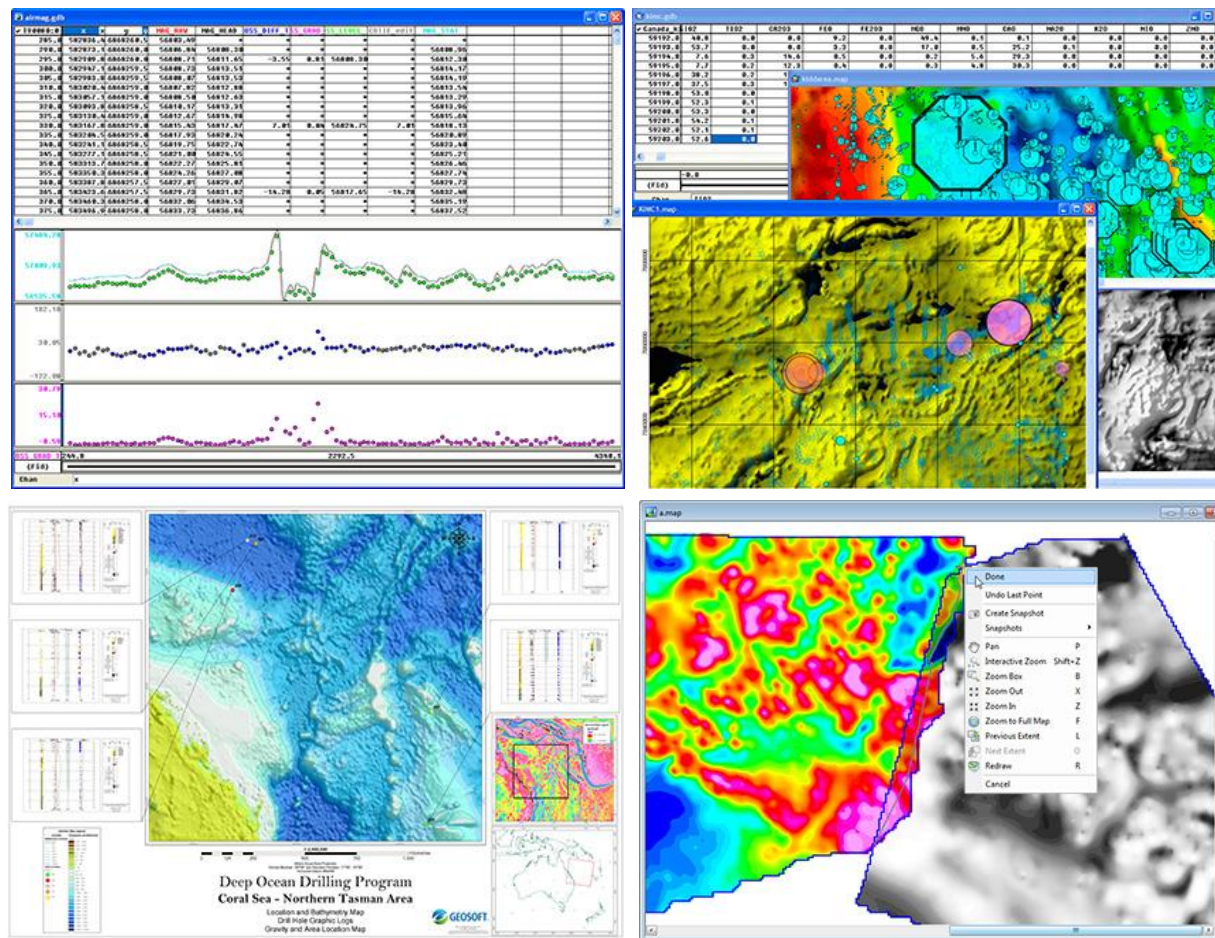


Figure 5 – Examples of various stock Oasis montaj interfaces and data products.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The LSG sensor and the associated suite of algorithms have been demonstrated to be effective in locating ferrous objects regardless of burial, making them a powerful tool for both MCM tasks as well as MR work. The sensitivity of gradiometers, like other magnetic sensors, is highly dependent on range and target size, with typical detection distances on the order of several meters. The LSG has been demonstrated over mine and UXO target fields in various underwater experiments, including the “Munitions Detection using Unmanned Underwater Vehicles with Advanced Sensors,” ESTCP Project Number MR-201103 in June 2011 and the “Target Reverberation Experiment (TRES)” sponsored jointly by SERDP and ONR in June 2013 where the smaller single axis prototype was also successfully demonstrated. The LSG has collected extensive sets of relevant data from five MR surveys conducted for NAVFAC over the period from April 2012 to August 2013, covering several thousand acres over a wide array of environments, including the waters near NSA Panama City, NWS Earle, and MCB Quantico. The associated DCL algorithms were successfully operated on all of these data sets in order to localize thousands of ferrous objects of various shapes and sizes.

Geosoft’s Oasis montaj software package is mature and has been in use for many years for land based UXO remediation. In aquatic environments, the software is seeing increased usage as well. In 2013, Geosoft released its UXO-Marine software extension specifically for working with magnetic and gradient data for UXO detection and basic analysis in the underwater environment. It is anticipated that the proposed workflow development will complement the existing UXO-Marine workflows. Since the large community of users already use Geosoft workflows for analysis, processing, and map-view presentations of standard magnetic, gradiometer and other geophysical data sets, imbedding NSWC PCD’s DCL algorithms into Oasis montaj for use on MRS is the most logical step forward.

3.0 PERFORMANCE OBJECTIVES

Table 1 – Performance metrics for successful demonstration

Performance Objective	Metric	Data Required	Success Criteria
-----Quantitative Performance Objectives-----			
Number of Targets Detected	Number of targets output by the toolbox vs. the number output by the original algorithm implementation	Target list from both toolbox and original design using the same data set	>95% similarity in number of detected targets
Location Accuracy	Location of targets as calculated by both methods	Target locations as calculated by both methods	<1m difference in calculated positions
Magnetic Moment Accuracy	Size and orientation of determined moments as calculated by both methods	Moment size and orientation (based on unit vector) as calculated by both methods	<0.5 Am ² difference in calculated moment <5° difference in calculated orientation (vertical and horizontal)
-----Qualitative Performance Objectives-----			
Ease of use		Feedback from operator experienced in preexisting land based UXO detection techniques available within Oasis montaj	

3.1 – OBJECTIVE: TARGETS DETECTED

All methods of calling the gradiometric detection algorithms should yield the same target list, with the first target metric under consideration being simply the number of targets generated. Later metrics will ensure the target metadata is also appropriately recreated.

3.1.1 – METRIC

Compare the number of targets generated by the new Oasis montaj toolbox to the number generated using the original method.

3.1.2 – DATA REQUIREMENTS

Using an example data set collected over an appropriate UXO site, we will first compare the number of targets generated using each technique.

3.1.3 – SUCCESS CRITERIA

The objective will be met if there is at least a 95% similarity between the number of targets generated in each fashion.

3.2 – OBJECTIVE: LOCATION ACCURACY

All of the metadata associated with each target should be identical regardless of how the gradiometric algorithms are called, with the most important being the location of each target.

3.2.1 – METRIC

Compare the position of each target generated using each method to ensure that each method is generating comparable locations.

3.2.2 – DATA REQUIREMENTS

Using an example data set collected over an appropriate UXO site, we will compare the locations of each target generated. Latitudes/longitude numbers will be converted into local UTM when necessary.

3.2.3 – SUCCESS CRITERIA

The objective will be met if the calculated locations are within 1 meter of each other.

3.3 – OBJECTIVE: MAGNETIC MOMENT ACCURACY

All of the metadata associated with each target should be identical regardless of how the gradiometric algorithms are called, with the second most important being the information associated with the magnetic moment vector, including size and unit vector orientation.

3.3.1 – METRIC

Compare the size and orientation of each target's magnetic moment generated using both methods to ensure that each method is generating the same dipole fits.

3.3.2 – DATA REQUIREMENTS

Using an example data set collected over an appropriate UXO site, we will compare the dipole moment information of each target generated. Moment unit vectors will be converted to horizontal and vertical orientations (relative to North and horizontal respectively).

3.3.3 – SUCCESS CRITERIA

The objective will be met if the calculated moments are within 0.5 Am² and the calculated orientations are within 5° of each other.

3.4 – OBJECTIVE: EASE OF USE

The usability of the new Oasis montaj toolbox will be compared to existing Oasis montaj tools.

3.4.1 – DATA REQUIREMENTS

A third party partner (AECOM) not directly engaged in the toolbox or algorithm development yet familiar with using Oasis montaj UXO detection tools will evaluate the toolbox workflow and documentation to ensure quality of implementation matches existing paradigm.

4.0 SITE DESCRIPTION

4.1 SITE SELECTION

A suitable set, or sets, of data will be compiled from existing UXO surveys executed with the LSG system that can be analyzed by both the new toolbox and the existing techniques. Data known to contain a reasonable number of detections is crucial so that there will be sufficient statistics to compare against. Also, data with quality issues was chosen to exercise the various QA/QC checks being implemented into the toolbox. Datasets were thus chosen to exercise different portions of the MAGMA toolbox, including:

- Portions of the Chesapeake Bay near Fort Story, VA (2013, see **Figure 6**)
 - Clean, well behaved data, all 4 channels operating as expected
- Potomac River sites near Dahlgren, VA (2016, no figure)
 - Preliminary UXO effort with mixed performance, good for QC Testing
- St. Andrews Bay site near Panama City, FL (2016, see **Figure 7**)
 - Well behaved data collection over planted target field
- Potomac River sites near Dahlgren, VA (2017, see **Figure 8**)
 - Follow on UXO effort with better performance than prior survey
- Pacific Ocean and San Diego Bay sites near San Diego, CA (2017, see **Figure 9**)
 - Extensive data set over three-week period

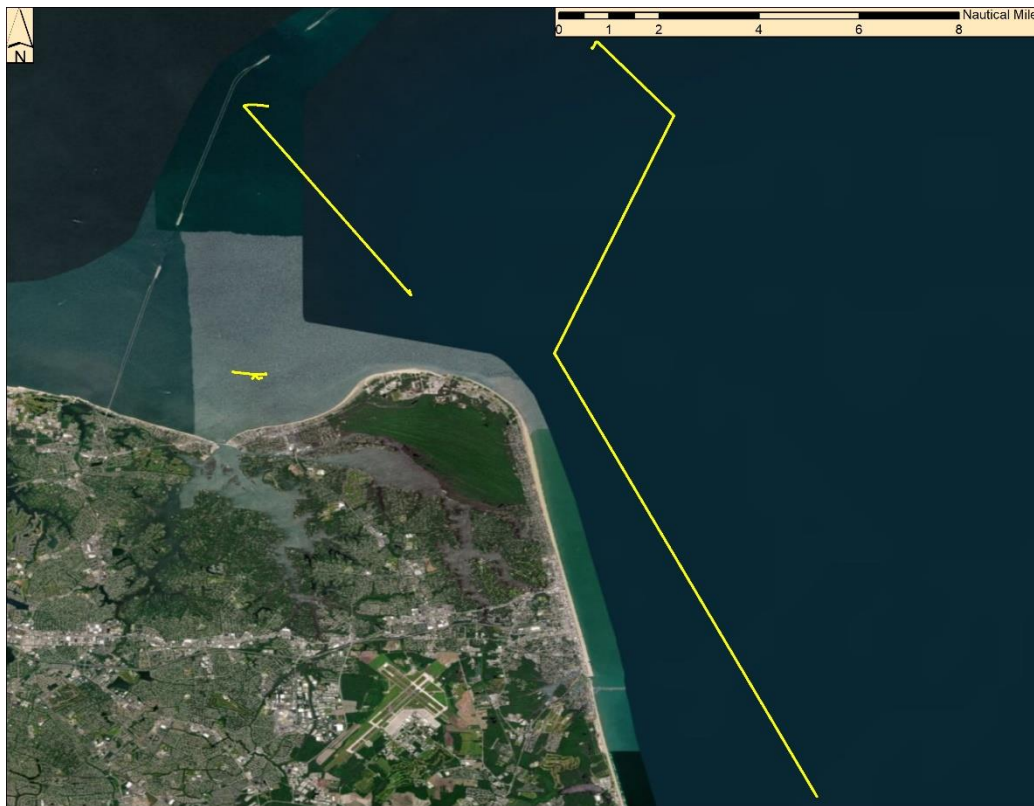


Figure 6 – Overview of LSG UUV tracklines near 2013 Virginia Beach, VA survey.

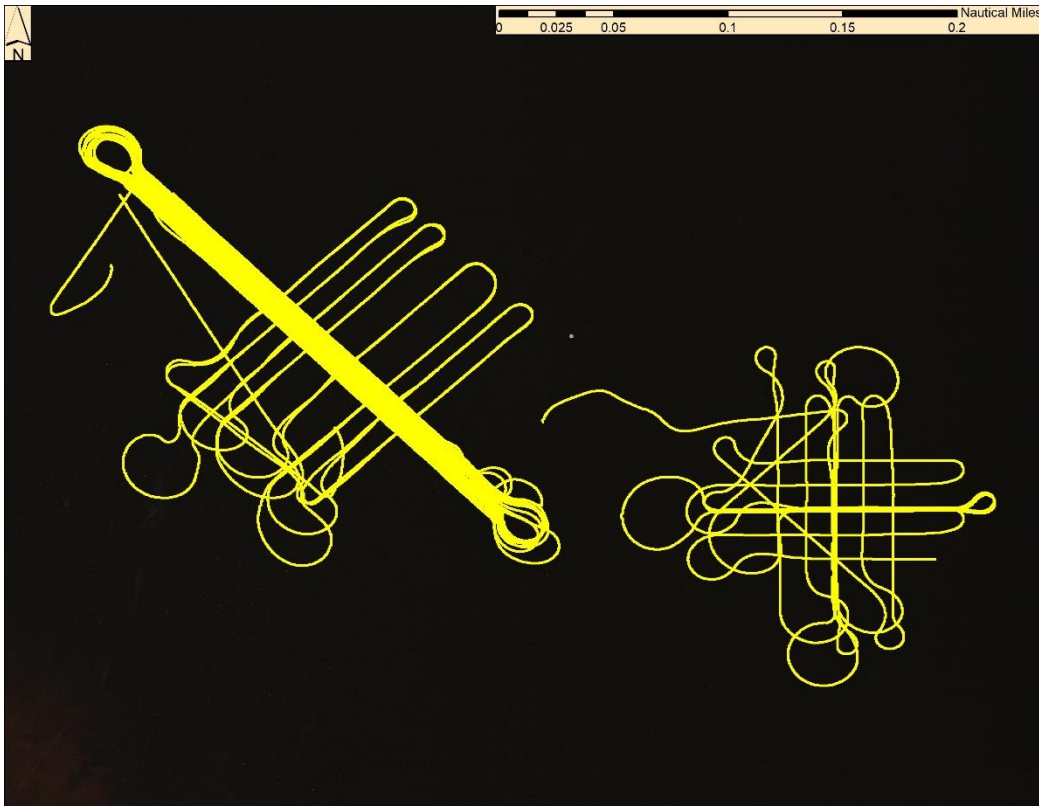


Figure 7 – Overview of LSG UUV tracklines near 2016 Panama City, FL survey.



Figure 8 – Overview of LSG UUV tracklines near 2017 Dahlgren, VA survey.



Figure 9 – Overview of LSG UUV tracklines near 2017 San Diego, CA survey.

4.2 SITE HISTORY

Data collected in the Chesapeake Bay and the Potomac River was obtained during NSWCCD led MR survey work on behalf of NAVFAC, over documented UXO sites. Data collected near Panama City was obtained during data collection experiments over planted fields and while UXO simulants were part of the experiments, no real UXO was present. Data collected near San Diego was obtained during both a Coalition Warfare Program (CWP) experiment on behalf of the Naval International Program Office as well as a NAVFAC MR survey. Both planted targets and UXO are present in the datasets.

5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

This project used existing data to test the accurate implementation of the MAGMA toolbox. NSWC PCD has been involved in many MR efforts over different UXO sites, including but not limited to Panama City, FL, San Diego, CA, West Point, NY, Dahlgren, VA, Quantico, VA and the Baltic Sea near Germany to name a few. From all these sites, NSWC PCD provided full data suites (e.g., raw, merged, motion compensated, source list) from five data collection events across four sites. As introduced under site selection, each collection event acquired LSG data with unique characteristics. All available data was supplied for testing and as many datasets as possible were run through the Oasis toolbox looking for issues and validating the results against the original MAGMA implementation.

The original MAGMA code has been validated over many years of successful surveys, both in support of UXO remediation and over planted target fields, so the primary purpose of this algorithm testing is not the accuracy of the algorithm results, but rather the side-by-side repeatability of the two different implementations. Data streams will be quantitatively compared at various points along the process to verify that the primary steps all behave the same (e.g. Import, Merge, Filter, Dipole Search etc.).

5.2 DATA PREPARATION

Target List Generation

Identical copies of the data were passed to both the original algorithm implementation as well as to the newly developed toolbox. The resulting target lists are used for comparison to determine if the toolbox is producing the same results as the original method. Should the toolbox fail to generate an appropriate list of detections, the point of failure will be identified and rectified.

Target Metadata Comparisons

Target specific metadata will be compared using computation tools such as Excel and Matlab. ArcGIS or Oasis montaj will also be used for visually representing the different targets.

- Location accuracy can be compared by looking directly at the calculated latitude and longitude or converting the coordinates into UTM and determining an offset in meters.
- Magnetic moment size can be compared directly while moment vector orientation will most easily be compared by transforming the unit vector into vertical and horizontal angular separations, for example angle relative to North and angle relative to the horizontal plane.
- Other metadata, such as estimated burial can be compared as well to further verify proper functionality of the new toolbox.

6.0 DATA ANALYSIS AND PRODUCTS

6.1 PREPROCESSING

Raw data collected from all UXO sites surveyed with the LSG has been stored at NSW PCD. Raw magnetic data in binary DAT files with corresponding raw navigation data in binary STS files (same filename for ease of reference) are available for reprocessing. See Reference 1 for details, but in summary each algorithm implementation imports the raw data files by using a counter stored in each to line up the data streams before filtering and merging into the final raw dataset. This set is motion compensated using the Tolles-Lawson technique before creating the four total field measurements to determine three magnetic differences (akin to gradients) which are then passed along for target selection. The individual stages of the data processing workflow (i.e. Import, Merge, Motion Compensated) were all verified between the Oasis montaj implementation and the original NSW PCD implementation to ensure proper functionality.

6.2 TARGET SELECTION FOR DETECTION

To allow for larger targets, three time windows are used to scan through the datasets, fitting the difference values to dipoles of different size. See **Figure 10** for an example. The characteristics of the dipole fit, combined with navigational information from the vehicle yield information on the targets location, orientation and magnetic moment. The final target lists were compared against each other to ensure the final results match.

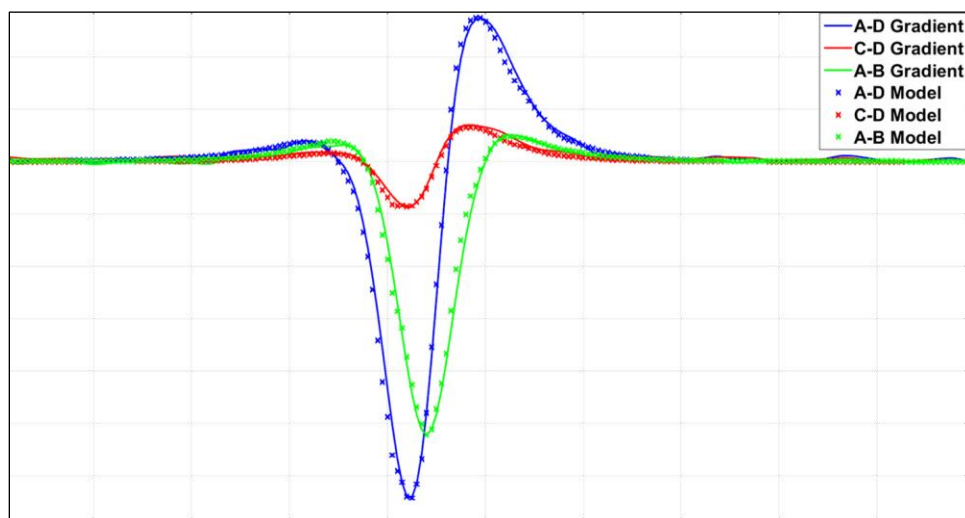


Figure 10 – Time series data showing both measured and modelled signature.

6.3 WORKFLOW EXAMPLES

The Oasis montaj toolbox (**Figure 11**) is easy to use and follows the process shown in **Figure 4**. Data is first Imported, which will search through a selected folder for DAT and STS files (**Figure 12**) to create individual MAG, INS and GPS geodatabases. These databases are then Quality Checked (**Figure 13**), searching for sections of data not suitable for target detection. Data that passes the Quality Checks are allowed to be Merged using binary masks (**Figure 14**) into a new MERGED geodatabase. Typically, once per survey, a multidirectional calibration run is done in

deep waters away from targets (both surface or bottom) that will feed into the Motion Compensation algorithm. Data from the calibration run, listed as Calibrate rather than Search, can be run through the Calculate Coefficients step to generate a list of Tolles-Lawson coefficients that will be called by the Apply Motion Compensation (**Figure 15**) that reduces the effects of Earth's field on the dataset. Note that in the absence of a calibration run, 0's will be assumed for the coefficients, allowing motion compensation to occur regardless. A new data set of compensated total field values is added to the MERGED geodatabase and then used by the Find Sources tool (**Figure 16**) to hunt for targets of interest, stored in a SOURCES geodatabase.

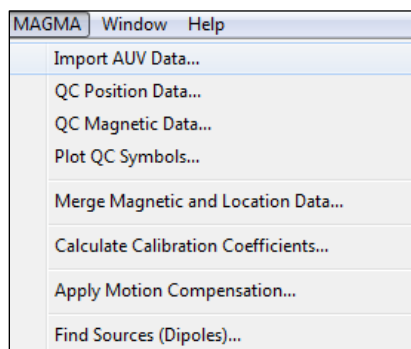


Figure 11 – Main menu of the Oasis montaj MAGMA toolbox.

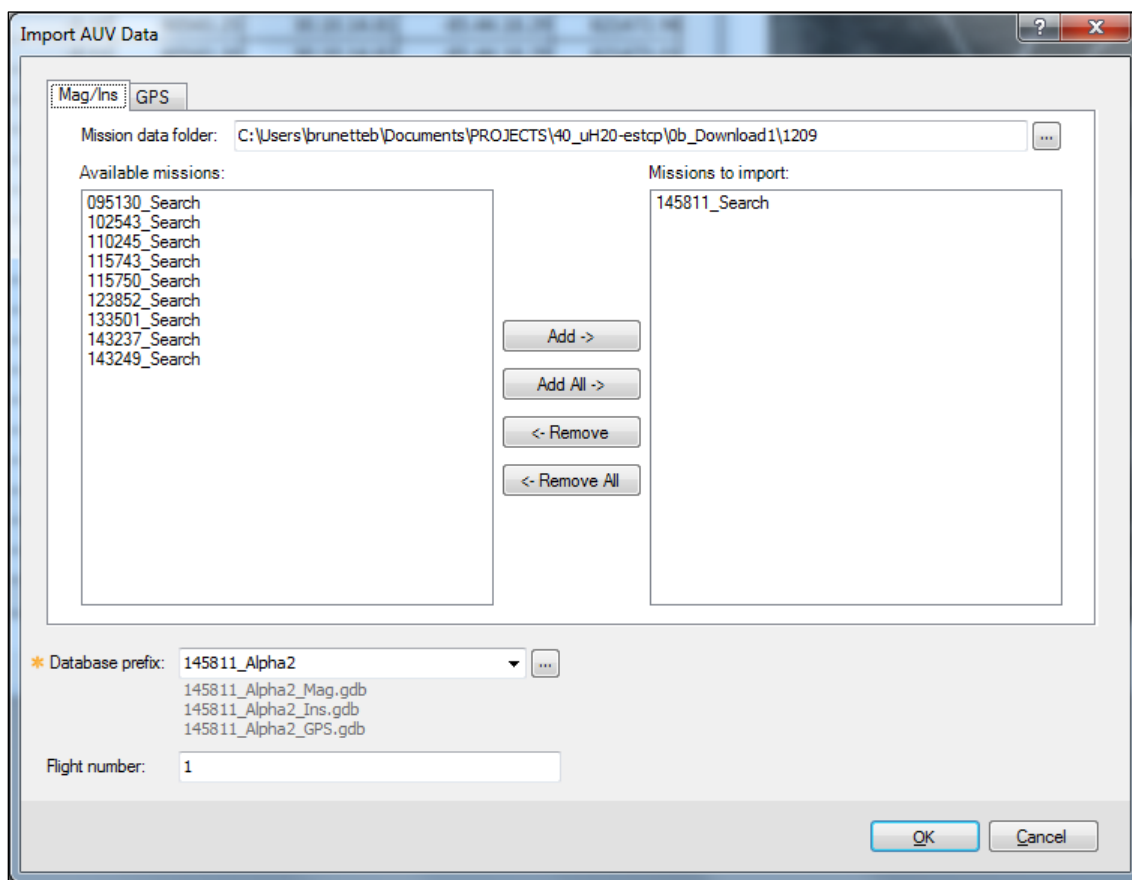


Figure 12 – Import AUV Data tool.

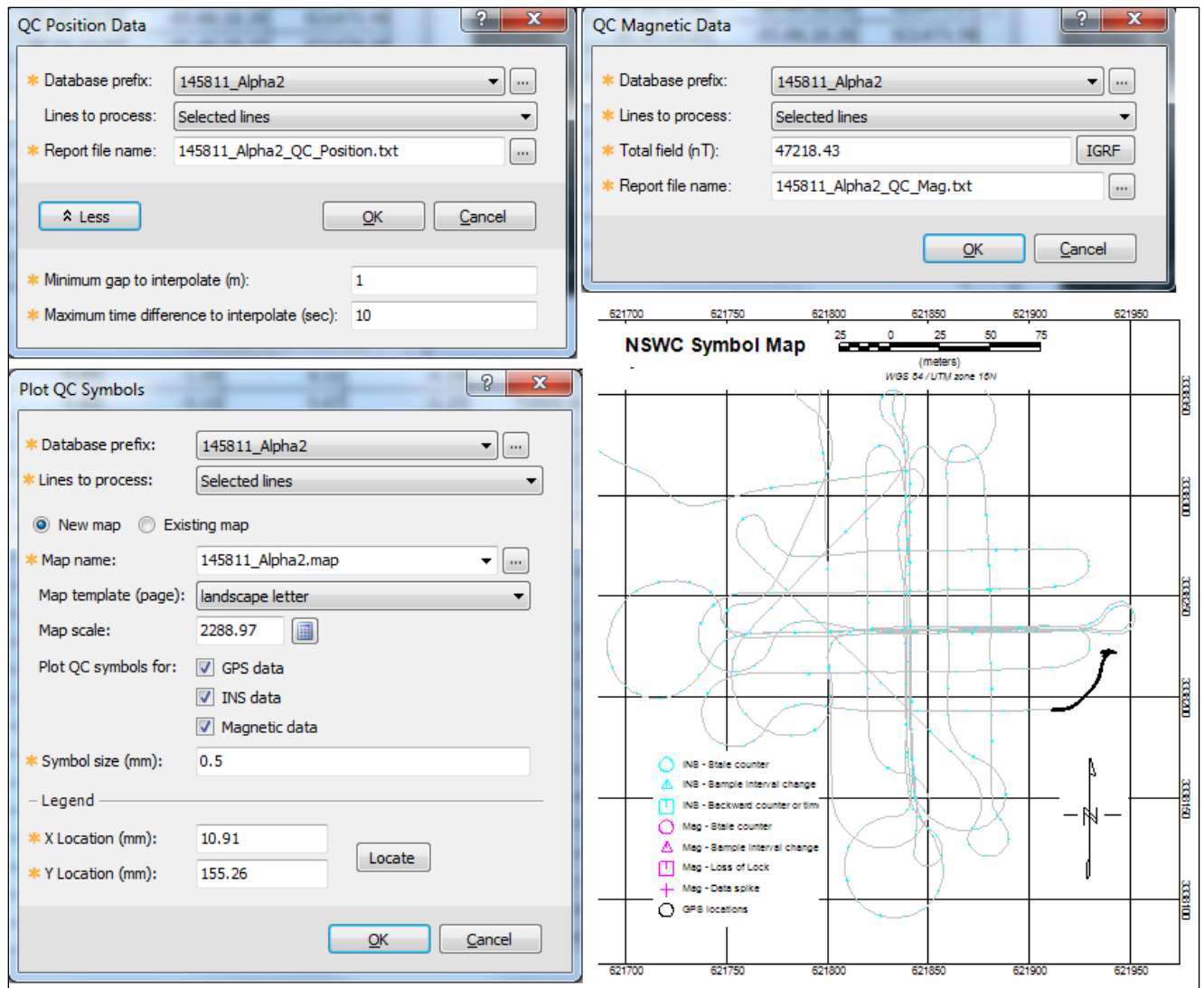


Figure 13 – Quality Check Data tools, Magnetic on left, Position on right. A map can be populated with QC Symbols using the Plot QC Symbols tool on bottom.

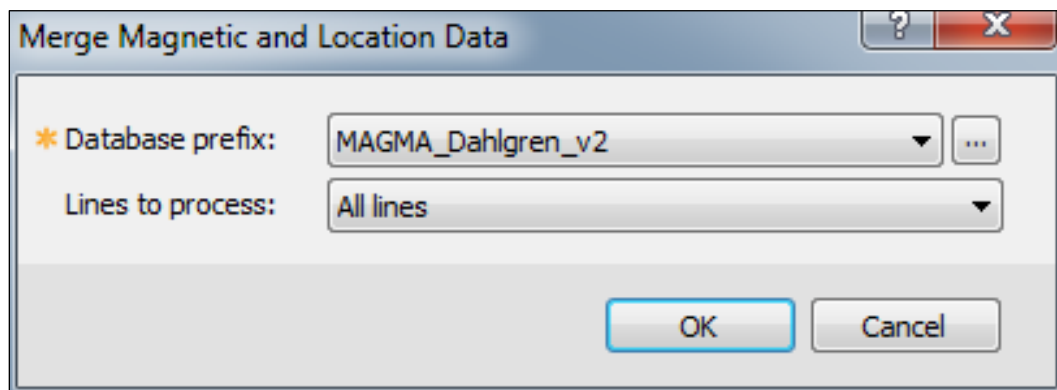


Figure 14 – Merge Magnetic and Location Data tool.

The image shows two stacked software dialog boxes. The top dialog, titled 'Calculate Calibration Coefficients', contains the following fields: 'Database prefix' (MAGMA_Dahlgren_v2), 'Mission to process' (L144445_Calibrate), 'Declination (deg)' (-10.85), 'Inclination (deg)' (65.05), 'Total field (nT)' (50813.9), and 'Output calibration coefficient file' (MAGMA_Dahlgren_v2_Coefficients.t). It includes an 'IGRF' button and 'OK'/'Cancel' buttons. The bottom dialog, titled 'Apply Motion Compensation', contains: 'Database prefix' (MAGMA_Dahlgren_v2), 'Lines to process' (All lines), 'Declination (deg)' (-10.85), 'Inclination (deg)' (65.05), 'Total field (nT)' (50813.9), 'Input calibration coefficient file' (MAGMA_Dahlgren_v2_Coefficients.t), and 'Output RMS signal file' (MAGMA_Dahlgren_v2_MoComp_Resi). It also includes an 'IGRF' button and 'OK'/'Cancel' buttons.

Figure 15 – Calculate Calibration Coefficients and Apply Motion Compensation tools.

The image shows a software dialog box titled 'Find Sources (Dipoles)'. It contains the following fields: 'Database prefix' (MAGMA_Dahlgren_v2), 'Lines to process' (All lines), 'RMS signal file' (empty), 'Declination (deg)' (-10.85), 'Inclination (deg)' (65.05), and 'Total field (nT)' (50813.9). It includes an 'IGRF' button and 'OK'/'Cancel' buttons.

Figure 16 – Find Sources tool, the final step in target detection.

7.0 PERFORMANCE ASSESSMENT

7.1 – INITIAL DATA CHECKS

Prior to testing the final target lists, the initial workflow stages were verified to be functioning in a similar fashion by comparing the intermediate data inputs and outputs.

Knowing that these portions are being handled correctly, means the data being passed to the Motion Compensation algorithms and Detection algorithms is identical. It has been noted that the original MAGMA implementation breaks the data into small chunks when doing initial filtering, based on memory limitations when first implemented. Oasis montaj does not do this, so longer missions experience slight offsets in imported magnetic data, however since this is a simple DC offset, there should be no effect on final target detections. This simple DC offset effect is exemplified by **Figure 17** below, which shows two example data sets from cleanest data sets (Fort Story 2013). The top image is a short file with 100% agreement while the bottom image is a longer file and shows sign of the simple DC offset, in this case approximately 40 nT.

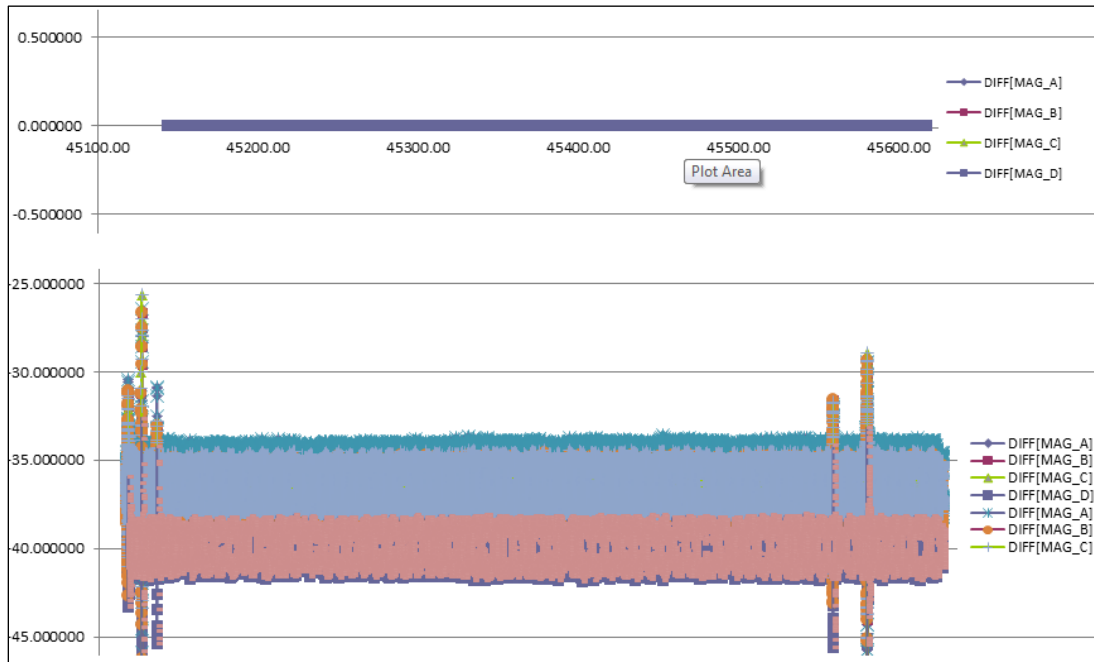


Figure 17 – Amplitude differences between NSWC and Geosoft Datasets at Initial Stage.

Further, subtle differences in the calculation of Earth’s magnetic field can lead to differences in the motion compensation coefficients, making the motion compensated data difficult to compare to the same level of fidelity as the raw imports. These subtle differences are also expected to be the cause of small differences in the final target list.

7.2 – OBJECTIVE: TARGETS DETECTED

As reminder, this objective is simply a count comparison of the number of targets listed in the anomaly source lists between same datasets processed within Oasis montaj and those delivered for comparison from NSWC using their internal MAGMA routines. (See Table 2)

Table 2 – Target Sources Count Summary

MRS (Year)	NSWC total	GEOSOFT total	% Diff total	NSWC small ¹	NSWC ADJ total ²	% Diff ADJ total	Effective Difference
Fort Story (2013)	190	185	2.7%	6	184	-1.1%	None
Dahlgren (2016)	243	211	14.1%	55	188	-20.3%	Geosoft more
Panama (2016)	224	261	-15.3%	4	220	-33.8%	Geosoft more
Dahlgren (2017)	774	832	-7.2%	69	705	-31.6%	Geosoft more
San Diego (2017)	1185	841	34.0%	353	832	-1.8%	None
Total (2013-2017)	2616	2330	11.6%	487	2129	-16.3%	Geosoft more

¹Small targets selected by NSWC yet not selected by GEOSOFT, and defined by low amplitude, size, and confidence characteristics in the source solver summary.

²NSWC ADJ removes the small targets to provide a more accurate representation of anomaly count repeatability.

The synopsis from **Table 2** is that for the data sets from Fort Story and San Diego, there is no effective difference after removal of the lower amplitude, smaller size, and lower confidence targets. For the remaining sites, the Geosoft runs reported a higher anomaly count by about 25%. The discrepancy leads to potential anomaly density overestimates. Therefore, the performance goal of achieving 95% anomaly count similarity was achievable for 2 of the 5 sites, while the remaining 3 sites anomaly counts would be overestimated. The overestimated is a preferred outcome (i.e. conservative approach) if the anomaly source counts don't align more accurately.

7.3 – OBJECTIVE: LOCATION ACCURACY

As reminder, this objective is a more comprehensive comparison of the exact locations (with < 1-meter tolerance) of targets in the anomaly source lists between same datasets processed within Oasis montaj and those delivered for comparison from NSWC. (See **Table 3**)

Table 3 – Target Sources Location Accuracy Summary

MRS (Year)	Small misses ¹	% small misses	Targets in common	BIG misses ²	% BIG misses	Targets in common	Effective Difference
Fort Story (2013)	6	3.16%	96.84%	11	5.87%	94.13%	Minimal
Dahlgren (2016)	55	22.63%	77.37%	14	6.17%	93.83%	Small Targets
Panama (2016)	4	1.79%	98.21%	11	4.54%	95.46%	Minimal
Dahlgren (2017)	69	8.91%	91.09%	29	3.61%	96.39%	Minimal
San Diego (2017)	353	29.79%	70.21%	59	5.82%	94.18%	Small Targets
Total (2013-2017)	487	9.36%	90.64%	124	4.54%	95.46%	Minimal

¹Small target locations not in common (i.e., missed) between NSWC PCD and GEOSOFT. As in **Table 2** above, these targets were defined by low amplitude, size, and confidence characteristics in the source solver summary.

²Big target locations not in common (i.e., missed) between NSWC PCD and GEOSOFT. Contrary to small misses, these targets were defined by larger amplitude, size, and confidence characteristics in the source solver summary.

The summary from **Table 3** is three-fold: first, Dahlgren and San Diego have a large number of small targets via percentage of their respective site totals of 23% (55/243) and 30% (353/841) respectively; second, due to more common occurrence of the small targets there are fewer targets (by percentage) in common between NSWC and Geosoft analyses for these two sites; and third, once the effect of these targets were accounted for the commonality reached 95%.

7.4 – OBJECTIVE: MAGNETIC MOMENT ACCURACY

As reminder, this objective is a more comprehensive comparison of the anomaly parameters (with less 0.5 Am² moment variation and 5° orientation variation) of targets in the anomaly source lists between same datasets processed within Oasis montaj and those delivered for comparison from NSWG using their internal MAGMA routines. (See **Table 4**)

Table 4 – Target Sources Moment and Orientation Accuracy Summary

MRS (Year)	Moment misses ¹	% M misses	Targets in common	Orient misses ²	% L misses	Targets in common	Effective Difference
Fort Story (2013)	28	15.74%	85.26%	12	6.32%	93.68%	Minimal
Panama (2016)	59	26.34%	73.66%	22	9.82%	90.18%	Minimal
Total (2013-2017)	87	21.00%	79.00%	34	8.21%	91.79%	Minimal

¹Target moments not in common (i.e., missed) between NSWG and GEOSOF. Misses are defined as moments not within 0.5-Am². While examining the misses, almost all moments are within 10% of each other.

²Target orientations not in common (i.e., missed) between NSWG and GEOSOF. Misses are defined as moments not within 5°. While examining the misses, almost all moments are within 10° of each other.

The summary from **Table 4** demonstrates that moment (M) and orientation (L) characteristics from the anomaly source lists show inconsistencies exceeding the anomaly source location accuracy achievements (**Table 3**). However, if the misses were defined by more of a reasonable metric of 10% / 10° for moment / orientation performance would be required in order to match the anomaly property results and meet the positional achievement of 95% of anomalies reviewed.

Thus, the ultimate performance metric, comparing the final target locations output from the Oasis montaj source solver to the results exported from the original toolbox developed by NSWPCD, was found to be achieve the desired results. The comparative analysis encompassed almost 100 datasets from 5 unique work products (2013 Fort Story, 2016 Dahlgren, 2016 Panama City, 2017 Dahlgren, 2017 San Diego), each with varying degrees of complexity.

7.5 – OBJECTIVE: EASE OF USE

After reviewing the user's notes, inclusive of basic process flow shown **Figure 4**, and with a rudimentary familiarity with field procedures, filenames, and file types acquired, the use of Geosoft to process the files from raw machine files to generating a list of source targets was fairly straight forward. The software does not allow a lot places for severe user error, does provide clear error messages, and does generate feedback via basic QC / QA inspections. There are not any perceived hurdles for use to process data acquired using the LSG system. If any other system within the Navy's fleet or publicly available is desired, the software does not have this sort of flexibility at this time. This is the most desired and needed next step; flexibility of format of input and different types of sensor geometry platforms. But from ease of use, what is provided is an excellent start.

8.0 COST ASSESSMENT

8.1 COST MODEL

Approximate cost of a REMUS600 and Polatomic Inc. LSG is approximately \$1.5M. Survey costs for NSWCD and other Navy organizations have been observed to be far removed from those incurred by contracting organizations, and in addition the focus of this project is data analysis rather than overall survey costs, making an overall cost model inappropriate for this particular technology solution.

8.2 COST DRIVERS

The primary cost drivers that need to be considered are the procurement cost of an appropriate UUV and sensor. Software licensing should also be considered, but it is generally assumed that parties interested in geophysical survey techniques will likely already possess an Oasis montaj license. UUV shipping/operating costs are comparable to tow body operations.

8.3 COST BENEFIT

Magnetic gradiometers mounted to UUVs are capable of operating in locations inaccessible to standard tow body setups and in many cases closer to the bottom, allowing for increased discrimination of targets. In addition, high accuracy dipole detection algorithms further reduce false alarms. In total, the combined benefit of these technology solutions is to reduce survey time and the number of contacts requiring follow-up remediation resulting in long term cost savings.

9.0 IMPLEMENTATION ISSUES

There are two main requirements to implement the technology under the current configuration:

- **Software requirements** – Geosoft’s Oasis montaj (v9.4 as of June 2018) and the implemented MAGMA toolbox once it is publicly released with the next version.
- **Hardware requirements** – The primary technology requirement is a 3 channel gradiometer, specifically the LSG from Polatomic Inc. and a REMUS600 UUV

The software is not considered a true limitation as everyone in the industry has access to a Geosoft license for DoD deliverables requirements and the MAGMA toolbox has no extra cost. The true limitation is the access to the hardware, not due to public availability but due to significant capital costs. However, the MAGMA toolbox can be used on datasets acquired by the Navy and provided to the contractor. Future interests for the project include modifying the toolbox for standardizing import formats and increasing geometric flexibilities to leverage a wider array of commercially available systems (e.g. Polatomic magnetic sensors, Geometrics G882 Array) in order to remove all implementation issues observed under the current configuration.

10.0 FUTURE CONSIDERATIONS

The current implementation allows for processing of LSG data, which is the primary sensor choice for most recent UXO surveys by the Navy. It is recommended that

- Future efforts expand the current processing to include different sensor geometries
 - LSG with less than the full 3 difference channels
 - Smaller single axis prototype
 - Follow-on successors to the LSG
 - Arbitrary gradiometers, e.g. the White River Technology and Geometrics G882 Array gradiometers being investigated by the Navy and private contractors
- Simplified magnetic data structures (e.g. based on H5 formats) be implemented that can store magnetic and navigation data, sensor information (e.g. name, geometry etc.). Data stored in this manner will simplify the import steps, since the user would be required to pre-generate these common data files from raw data. Geometry information store within the data structure will also simplify the processing, since each file will contain the necessary geometry rather than the user needing to supply it during PMA.
- Advanced processing techniques, such as cylinder classification and cable following algorithms, can be added to the processing chain and validated.

11.0 REFERENCES

1. L. Vaizer et al, *Algorithm for Automatic Detection, Localization and Characterization of Magnetic Dipole Targets Using the Laser Scalar Gradiometer*, 2016, ESTCP Website
2. L. Vaizer, J. Lathrop, and J. Bono, *Localization of Magnetic Dipole Targets*, in Proceedings of MTS/IEEE OCEANS 2004, November 2004.
3. S.H. Bickel, *Small Signal Compensation of Magnetic Fields Resulting from Aircraft Maneuvers*, in IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-15, No. 4, July 1979.

APPENDICES

APPENDIX A: POINTS OF CONTACT

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Brian Brunette	AECOM	brian.brunette@aecom.com	Toolbox testing

APPENDIX B: CHESAPEAKE BAY SURVEY RESULTS

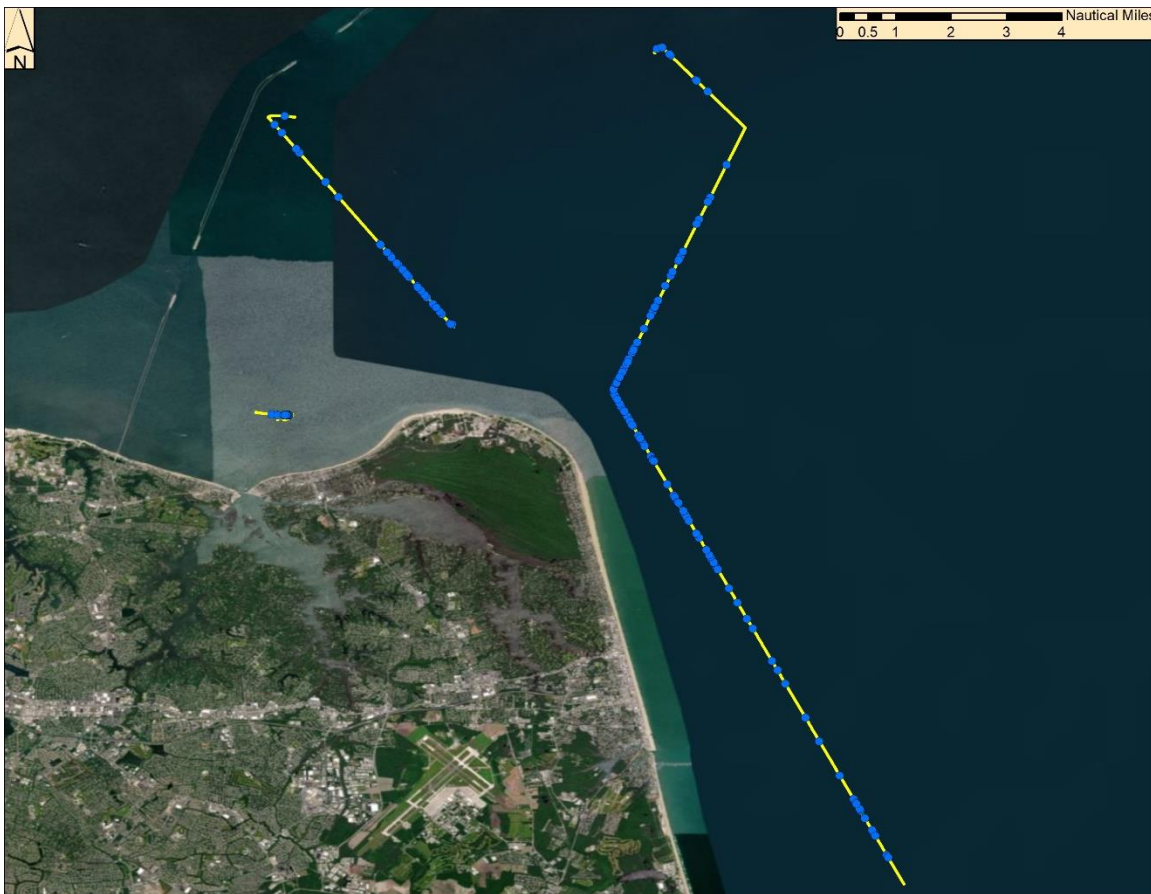


Figure 18 – Tracklines and contacts from the 2013 Chesapeake Bay UXO survey.

Table 5 – Example high confidence targets from the 2013 Chesapeake Bay UXO survey.

TargetID	latitude	longitude	depth	moment	burial	SNR	Conf. #
LSG4C_20130726d_6	36.856847	-75.933115	11.5	41	-1	21.1	10
LSG4C_20130726d_4	36.886942	-75.950927	9.7	11	-0.5	5.6	10
LSG4C_20130726d_5	36.884873	-75.949688	9.5	10	-0.3	2.6	10
LSG4C_20130726d_1	36.930715	-75.976878	16.5	1.6	-0.5	2.3	10
LSG4C_20130726d_3	36.922347	-75.971918	12.9	1.3	-0.3	1.8	10
LSG4C_20130726d_2	36.923205	-75.972423	12.7	0.5	0.2	1.5	10
LSG4C_20130726f_1	36.930865	-76.083298	10.2	21	-0.3	1.2	10
LSG4C_20130726f_3	36.930652	-76.079373	9.8	74	0.2	75.4	9.99
LSG4C_20130726d_7	36.934220	-75.978940	19.6	61	-1.4	24.8	9.99
LSG4C_20130726d_9	36.811905	-75.906588	12.8	150	-1	14.7	9.99
LSG4C_20130726c_1	36.930688	-76.078942	9.8	5	0	14.4	9.99
LSG4C_20130726d_8	36.839882	-75.923088	11.9	4.2	-0.5	5.8	9.99
LSG4C_20130726f_2	36.930668	-76.078915	9.8	4.7	0.2	5.2	9.99
LSG4C_20130726d_10	36.933767	-75.978657	17.2	3.2	0.7	3	9.99

DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.

LSG4C_20130726d_11	36.923623	-75.972713	13.1	6.4	-0.2	1.9	9.99
LSG4C_20130726d_12	36.928682	-75.975628	17.1	22	-2.2	2.3	9.98
LSG4C_20130726d_13	36.921890	-75.971662	12.5	2	-0.1	2.4	9.97
LSG4C_20130726a_2	36.930643	-76.079455	10.1	78	0.2	130	9.96
LSG4C_20130726c_3	36.930670	-76.079393	9.8	76	0	98.5	9.96
LSG4C_20130726f_4	36.930638	-76.078510	10	15	0	41.4	9.96
LSG4C_20130726c_2	36.930648	-76.078535	9.8	15	0	21	9.96
LSG4C_20130726d_14	36.924617	-75.973255	13.5	11	-0.2	20.1	9.96
LSG4C_20130726a_1	36.930652	-76.079185	10.1	1.3	0.1	1.4	9.96
LSG4C_20130726f_5	36.930605	-76.078728	9.4	5.3	0.6	2.6	9.94
LSG4C_20130726a_3	36.930677	-76.078290	10.2	81	0	8.6	9.92
LSG4C_20130726d_15	36.874382	-75.943498	9.8	2.4	0	3.7	9.92
LSG4C_20130726d_16	36.854113	-75.931500	11.4	3.4	-0.7	1.9	9.92
LSG4C_20130726a_4	36.930647	-76.078597	8.6	10	1.6	41.7	9.91
LSG4C_20130726d_17	36.887427	-75.951248	9.9	15	-0.8	12.4	9.91
LSG4C_20130726d_18	36.832808	-75.918955	12.2	63	-0.8	5.7	9.9
LSG4C_20130726d_19	36.935428	-75.979685	20	180	-0.9	84.7	9.87
LSG4C_20130726d_20	36.934762	-75.979282	19.8	15	-1.2	3.7	9.85
LSG4C_20130726b_1	37.040483	-75.967725	2.3	74	6.8	19.2	9.83
LSG4C_20130726d_21	36.878662	-75.946063	13.3	9.8	-3.7	0.9	9.8
LSG4C_20130726b_2	37.027740	-75.952382	9.3	9.7	-0.6	4	9.78
LSG4C_20130726c_4	36.930700	-76.078228	9.5	35	0.3	136.9	9.77
LSG4C_20130726d_22	36.934573	-75.979188	19	25	-0.6	8.6	9.76
LSG4C_20130726a_5	36.930700	-76.078598	10	0.8	0.3	4.1	9.76
LSG4C_20130726d_23	36.866580	-75.938900	10.2	20	-0.2	41.2	9.75
LSG4C_20130726b_3	37.040888	-75.966092	11.2	17	-1.4	6.1	9.75
LSG4C_20130726c_5	36.930623	-76.078750	9.8	5.6	0.1	18.2	9.74
LSG4C_20130726d_24	36.936832	-75.980497	20.2	5	0	7.2	9.73
LSG4C_20130726d_25	36.805387	-75.902643	12	23	-0.6	6.1	9.73
LSG4C_20130726d_26	36.927833	-75.975155	15.2	20	-0.6	17.1	9.72
LSG4C_20130726d_27	36.812097	-75.906672	11.9	7.7	-0.3	6.1	9.71
LSG4C_20130726d_29	36.923790	-75.972773	13.1	5.1	-0.2	4.8	9.7
LSG4C_20130726d_28	36.936102	-75.980073	19.9	1.4	-0.2	3.1	9.7
LSG4C_20130726d_30	36.900662	-75.959078	11.1	37	-2.3	9.8	9.69
LSG4C_20130726d_31	36.927417	-75.974893	14.5	3.3	-0.1	1.5	9.67
LSG4C_20130726a_6	36.930700	-76.079700	10.3	1.6	-0.1	3.9	9.65
LSG4C_20130726c_6	36.930687	-76.078773	9.8	1.4	0.1	3.9	9.65
LSG4C_20130726d_33	36.884343	-75.949422	9.7	1.8	-0.3	2.9	9.65
LSG4C_20130726d_32	36.929593	-75.976210	15.9	1.5	-0.4	2.3	9.65
LSG4C_20130726c_7	36.930678	-76.079123	9.8	0.9	0.1	2.8	9.64
LSG4C_20130726d_34	36.921380	-75.971388	12.5	9.1	-0.3	2.1	9.64

APPENDIX C: PANAMA CITY RESULTS

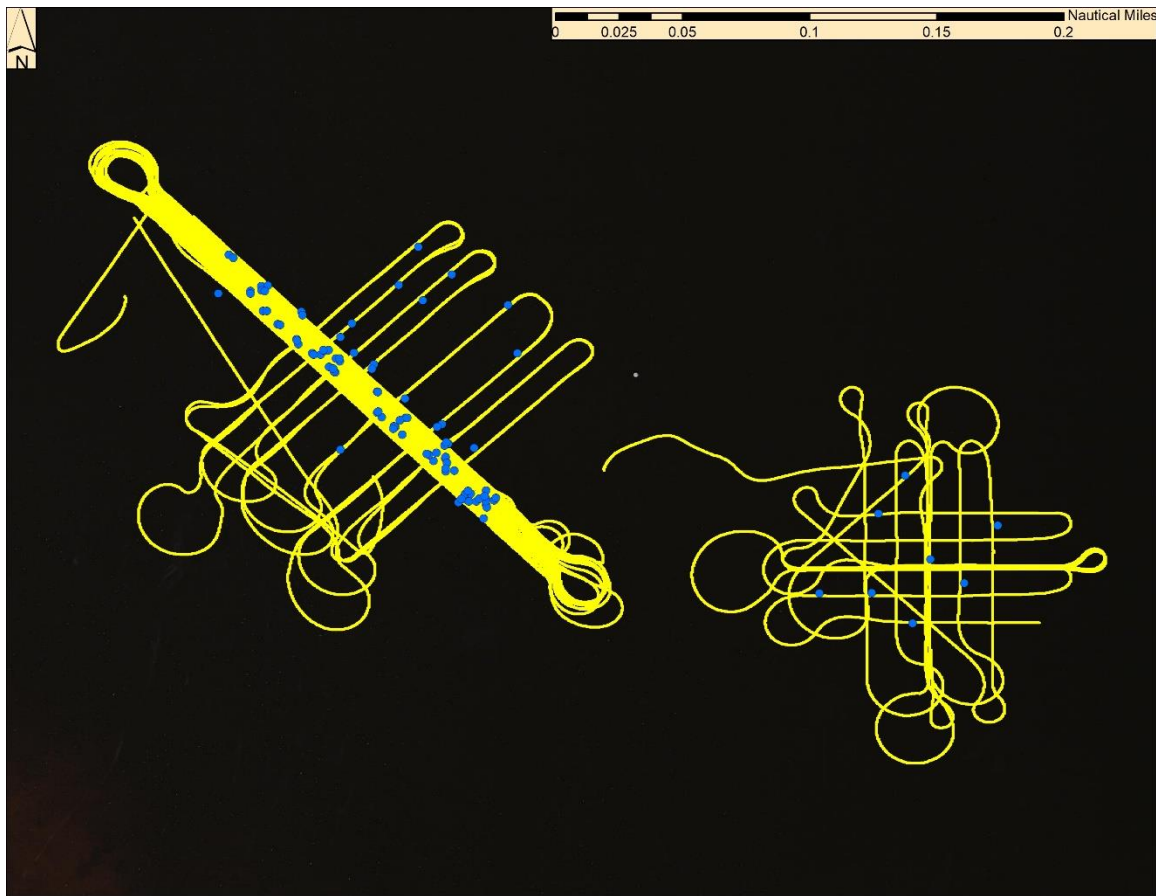


Figure 19 – Tracklines and contacts from the 2016 Panama City sensor checkout survey.

Table 6 – Example high confidence targets from the 2013 Chesapeake Bay UXO survey.

TargetID	latitude	longitude	depth	moment	burial	SNR	CN
LSG4C_20161209b_4	30.169847	-85.73765	10.3	110	-0.7	55.2	10
LSG4C_20161209b_3	30.170555	-85.738237	10.7	84	0	49.4	10
LSG4C_20161209c_4	30.171055	-85.738725	11.3	55	-0.5	48.6	10
LSG4C_20161209c_3	30.171218	-85.738993	11.1	60	-0.3	44	10
LSG4C_20161209b_5	30.171245	-85.738997	10.9	78	0	25.4	10
LSG4C_20161209b_1	30.170823	-85.73858	10.7	13	0.1	20.5	10
LSG4C_20161209b_2	30.169865	-85.73753	9.1	15	0.6	12.8	10
LSG4C_20161209c_1	30.169908	-85.737523	9.7	9	0	11.1	10
LSG4C_20161209c_2	30.171432	-85.73918	10.9	2.3	0	2.8	10
LSG4C_20161209a_1	30.170213	-85.73777	10.7	130	-0.3	120.5	9.99
LSG4C_20161209c_10	30.170553	-85.738232	10.7	73	-0.1	50.5	9.99
LSG4C_20161209c_7	30.17125	-85.738952	9.1	58	1.8	40.3	9.99
LSG4C_20161209c_8	30.169905	-85.737642	10.5	78	-0.8	31.8	9.99
LSG4C_20161209a_3	30.170342	-85.73781	10.7	85	-0.1	30.9	9.99

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LSG4C_20161209c_5	30.170705	-85.738525	10.5	27	0	18.8	9.99
LSG4C_20161209a_2	30.171002	-85.7384	10.8	11	0.2	14.3	9.99
LSG4C_20161209c_9	30.170827	-85.738555	10.4	10	0.3	12.7	9.99
LSG4C_20161209c_6	30.171197	-85.739068	10.6	3.5	0.1	5	9.99
LSG4C_20161209c_11	30.170147	-85.737912	10.3	14	-0.2	14.7	9.98
LSG4C_20161209c_13	30.170383	-85.73804	10.5	72	0	48.6	9.97
LSG4C_20161209c_12	30.170223	-85.737783	10.4	110	-0.1	15.4	9.97
LSG4C_20161209a_4	30.170733	-85.738257	10.9	82	-0.1	14.7	9.97
LSG4C_20161209b_6	30.171213	-85.739067	10.4	8.4	0.5	2	9.96
LSG4C_20161209b_7	30.170383	-85.73805	10.2	68	0.2	7.8	9.95
LSG4C_20161209b_8	30.17014	-85.737897	10.2	18	-0.1	7.1	9.95
LSG4C_20161209d_1	30.169457	-85.734608	11.1	7.2	-0.7	1	9.95
LSG4C_20161209c_14	30.170425	-85.73823	10.3	5.3	0	5.8	9.94
LSG4C_20161209a_5	30.17068	-85.73851	10.5	27	0	15.9	9.93
LSG4C_20161209a_6	30.170508	-85.738052	10.8	92	-0.1	19.2	9.91
LSG4C_20161209c_15	30.169838	-85.737525	9	9.7	0.6	12	9.91
LSG4C_20161209b_9	30.170417	-85.738237	10.4	6.2	0	4.5	9.91
LSG4C_20161209b_10	30.170807	-85.738663	10.4	8.5	0.2	9.1	9.9
LSG4C_20161209d_2	30.169757	-85.734948	11.1	2.2	-0.2	3.8	9.89
LSG4C_20161209c_16	30.170328	-85.738127	10.5	3	-0.3	3.5	9.85
LSG4C_20161209d_3	30.169038	-85.734725	8.9	1.1	0	1.7	9.85
LSG4C_20161209d_4	30.1693	-85.734387	10.3	54	0.1	8.4	9.84
LSG4C_20161209c_17	30.170798	-85.738652	10.6	10	-0.1	3.7	9.84
LSG4C_20161209b_11	30.170718	-85.738552	10.5	29	0	7.1	9.83
LSG4C_20161209c_18	30.169843	-85.73747	9.8	11	-0.1	3.9	9.83
LSG4C_20161209c_19	30.170052	-85.737787	10.7	11	-0.8	6.4	9.82
LSG4C_20161209b_12	30.170772	-85.738507	10.5	2.4	0.2	3.7	9.82
LSG4C_20161209c_20	30.170892	-85.738762	10.6	11	0.1	6.4	9.81
LSG4C_20161209b_13	30.170032	-85.737788	10	13	0.1	2.9	9.81
LSG4C_20161209a_8	30.170913	-85.738477	10.1	6.7	0.8	1.4	9.8
LSG4C_20161209a_7	30.170187	-85.7376	8.2	3.6	2	1.1	9.8
LSG4C_20161209b_14	30.170898	-85.738765	10.6	12	0.1	15.2	9.78
LSG4C_20161209c_22	30.169837	-85.737585	11.7	46	-2.1	5.1	9.78
LSG4C_20161209c_21	30.170773	-85.738483	10.4	2.7	0.2	4.2	9.78
LSG4C_20161209a_9	30.171503	-85.737967	12.6	44	-1.4	6.2	9.76
LSG4C_20161209b_15	30.170155	-85.737848	11.1	19	-0.8	1.7	9.73
LSG4C_20161209b_16	30.170368	-85.738088	10.9	53	-0.4	23	9.72
LSG4C_20161209a_10	30.170038	-85.73773	10.7	9.4	-0.8	6.5	9.72
LSG4C_20161209c_23	30.170993	-85.738873	10.7	9.5	0	4.9	9.69
LSG4C_20161209d_5	30.169237	-85.734992	10	6.5	-0.9	3.4	9.69

APPENDIX D: DAHLGREN RESULTS



Figure 20 – Tracklines and contacts from the 2017 Potomac River UXO survey.

Table 7 – Example high confidence targets from the 2017 Potomac River UXO survey.

TargetID	latitude	longitude	depth	moment	burial	SNR	CN
LSG4C_20170924e_1	38.276215	-76.905225	6.2	7.8	0.1	2.7	10
LSG4C_20170925e_4	38.243107	-76.842987	6.1	6.9	0.2	48	9.99
LSG4C_20170925e_3	38.245918	-76.848043	7	9.4	-0.2	11.6	9.99
LSG4C_20170926e_1	38.268333	-76.896858	8.4	12	-0.6	10.6	9.99
LSG4C_20170921a_1	38.391673	-77.074983	6.9	5.4	-0.3	7.4	9.99
LSG4C_20170924c_1	38.27009	-76.88929	7.6	8.5	0.1	5.7	9.99
LSG4C_20170925e_1	38.245425	-76.847782	7.4	6.3	-0.6	5.7	9.99
LSG4C_20170925e_5	38.245378	-76.846815	6.7	14	0	3.3	9.99
LSG4C_20170925e_2	38.247688	-76.85043	7.7	2.1	-0.7	2.8	9.99
LSG4C_20170924e_3	38.27989	-76.90669	5.7	8.6	-0.1	14.6	9.98
LSG4C_20170925e_6	38.247757	-76.851625	7.9	7.2	-0.6	9.5	9.98
LSG4C_20170924e_4	38.275333	-76.903352	5	3.4	1.7	6.1	9.98
LSG4C_20170921b_1	38.389522	-77.07775	7.3	2.3	-0.7	4	9.98
LSG4C_20170926d_1	38.252368	-76.826468	10.9	4.4	-1.5	4	9.98

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LSG4C_20170924f_1	38.269412	-76.89169	7.8	0.7	-0.4	3.7	9.98
LSG4C_20170924e_2	38.275215	-76.903085	6.9	3.5	-0.1	3.4	9.98
LSG4C_20170924a_1	38.277815	-76.904892	6.4	20	-0.3	0.8	9.98
LSG4C_20170925e_7	38.244318	-76.84507	6.5	17	0	45.5	9.96
LSG4C_20170921d_1	38.387128	-77.080152	5.7	9.8	-0.1	39.6	9.96
LSG4C_20170925e_8	38.244822	-76.847343	7.7	15	-0.8	18.2	9.96
LSG4C_20170921c_1	38.389292	-77.077328	7.3	4.5	-0.6	4.5	9.96
LSG4C_20170924e_5	38.278303	-76.909617	5.1	9.7	0.4	10	9.95
LSG4C_20170924b_1	38.275485	-76.901863	6.2	0.4	0.3	2	9.95
LSG4C_20170926e_2	38.26777	-76.900122	9.7	60	-2	8	9.93
LSG4C_20170924d_1	38.270127	-76.889252	7.5	6	0.2	2.7	9.93
LSG4C_20170926e_3	38.26717	-76.901105	8.2	8.2	-0.5	2	9.93
LSG4C_20170925e_10	38.247838	-76.851763	7.9	30	-0.6	17.5	9.92
LSG4C_20170925e_9	38.246512	-76.849595	7.5	17	-0.4	7.4	9.92
LSG4C_20170921e_2	38.387945	-77.07498	3.7	3.9	-0.1	5.5	9.92
LSG4C_20170921e_1	38.3879	-77.07533	5	5.1	-1.4	3.7	9.92
LSG4C_20170925e_12	38.246592	-76.844665	6.4	24	-0.2	54.4	9.91
LSG4C_20170925e_11	38.24715	-76.850142	7.8	3.5	-0.8	2.7	9.91
LSG4C_20170921e_3	38.38681	-77.077622	3.3	2.9	0.1	3.9	9.9
LSG4C_20170925e_13	38.247388	-76.850773	7.2	4	-0.1	2.3	9.9
LSG4C_20170926e_4	38.265975	-76.89852	7.4	5.8	0.3	15.8	9.89
LSG4C_20170921e_4	38.38872	-77.0733	5	4.1	-1.2	1.7	9.89
LSG4C_20170925e_14	38.247932	-76.849105	6.8	4.6	0.1	3.7	9.88
LSG4C_20170924g_1	38.36404	-76.98898	20.9	57	-2.1	4.3	9.86
LSG4C_20170924a_2	38.278445	-76.906382	5.5	8.5	0.3	2.9	9.86
LSG4C_20170925e_15	38.243753	-76.842562	6.5	1.4	-0.4	1.9	9.86
LSG4C_20170924e_6	38.275922	-76.904618	7	9.2	-0.7	1.5	9.85
LSG4C_20170924a_3	38.27261	-76.89488	8.1	29	0.1	101.7	9.84
LSG4C_20170926e_5	38.266448	-76.897342	7.2	29	0.3	24.7	9.84
LSG4C_20170924c_2	38.278375	-76.904347	5.6	3.5	0.4	5.1	9.84
LSG4C_20170921b_2	38.389502	-77.07901	6.5	3.8	-0.3	3.2	9.84
LSG4C_20170926e_6	38.267895	-76.895948	8.1	1.2	-0.5	0.6	9.83
LSG4C_20170921c_2	38.389582	-77.076418	6.7	6.9	-0.1	12.6	9.82
LSG4C_20170921c_3	38.389707	-77.078883	3.3	4.1	2.6	6.9	9.82
LSG4C_20170924a_4	38.277055	-76.904283	6.4	2.3	-0.2	3.4	9.82
LSG4C_20170921a_2	38.39123	-77.07592	6.1	2.4	0.3	1.3	9.82
LSG4C_20170921a_3	38.388818	-77.08134	4.1	18	1.5	6.7	9.81
LSG4C_20170924e_7	38.278038	-76.909007	5.6	2.1	0	5.8	9.81
LSG4C_20170924c_3	38.277703	-76.902913	5.7	5.6	0.3	3.9	9.81
LSG4C_20170926e_7	38.267147	-76.895212	8.2	7.9	-0.7	2.7	9.81

APPENDIX E: SAN DIEGO RESULTS



Figure 21 – Tracklines and contacts from the 2017 San Diego UXO survey.

Table 8 – Example high confidence targets from the 2017 San Diego UXO survey.

TargetID	latitude	longitude	depth	moment	burial	SNR	CN
LSG4C_20171113c_6	32.664003	-117.150048	4.3	58	-0.2	156.9	10
LSG4C_20171113d_8	32.666622	-117.149765	5.7	110	-1.1	108.6	10
LSG4C_20171113a_1	32.66918	-117.133353	4.4	70	-0.5	105.3	10
LSG4C_20171112g_3	32.682157	-117.194152	9.5	300	-1.8	73.4	10
LSG4C_20171114b_2	32.700768	-117.23373	19.8	78	-0.2	71	10
LSG4C_20171107d_3	32.695045	-117.230158	15.9	190	-1.1	67.8	10
LSG4C_20171107d_1	32.697628	-117.230037	15.9	160	-0.6	65.3	10
LSG4C_20171114b_1	32.699535	-117.235883	16.8	130	-0.2	57	10
LSG4C_20171113b_5	32.664745	-117.152005	4.1	23	-0.5	51.3	10
LSG4C_20171107c_5	32.693457	-117.228872	15.3	97	-0.6	50.2	10
LSG4C_20171112d_4	32.671312	-117.188622	11.1	43	-0.1	46.7	10
LSG4C_20171113c_4	32.667628	-117.1519	4.2	19	-0.6	42	10
LSG4C_20171107a_3	32.69313	-117.228208	16.3	210	-1.7	38.6	10
LSG4C_20171113a_9	32.664597	-117.138712	4.2	19	-0.4	37.9	10

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LSG4C_20171107a_5	32.694787	-117.228118	16.9	22	-0.3	34.4	10
LSG4C_20171113b_1	32.660062	-117.149078	4.6	29	-0.8	33.7	10
LSG4C_20171113c_3	32.662255	-117.148912	5	19	-0.7	30.1	10
LSG4C_20171113a_2	32.661507	-117.142355	4.7	39	-1.2	29.1	10
LSG4C_20171113d_6	32.668683	-117.15192	2.1	57	1.8	28.2	10
LSG4C_20171113d_5	32.66009	-117.146203	4.9	16	-0.5	27.3	10
LSG4C_20171112h_1	32.671578	-117.205122	8.6	37	0	26.8	10
LSG4C_20171111h_4	32.663963	-117.181322	13.9	28	-0.9	25.6	10
LSG4C_20171107a_1	32.697108	-117.228135	15.4	68	-0.9	25	10
LSG4C_20171112b_5	32.664975	-117.18855	13.2	21	-0.2	24.5	10
LSG4C_20171113a_8	32.66767	-117.135115	4	7.8	-0.3	24.2	10
LSG4C_20171112b_2	32.66103	-117.189123	14.6	26	-0.5	23.8	10
LSG4C_20171113a_10	32.664252	-117.152608	3.1	3.9	-0.2	21.5	10
LSG4C_20171112b_3	32.670858	-117.181258	10.2	23	0.1	21.4	10
LSG4C_20171113b_8	32.666787	-117.1528	4.7	23	-1.1	20.7	10
LSG4C_20171111h_3	32.664577	-117.181632	15.1	74	-1.9	19	10
LSG4C_20171107c_7	32.697402	-117.228622	16.9	200	-1.7	18	10
LSG4C_20171112d_5	32.664687	-117.19393	12.7	25	-0.8	17.9	10
LSG4C_20171113c_5	32.665768	-117.151403	4.3	6.4	-0.3	17.8	10
LSG4C_20171112d_2	32.666835	-117.194777	11.3	21	-0.3	16.4	10
LSG4C_20171111c_4	32.665695	-117.174635	10.9	12	0	15.8	10
LSG4C_20171113d_3	32.661365	-117.146302	5.4	14	-0.9	15.6	10
LSG4C_20171113c_2	32.669288	-117.15375	4.5	5.6	-0.4	15.2	10
LSG4C_20171112a_2	32.66472	-117.182318	13.1	10	-0.2	14.6	10
LSG4C_20171111b_1	32.662358	-117.175507	12.7	21	-0.7	13.7	10
LSG4C_20171112f_1	32.670155	-117.197247	10.5	33	-0.4	13.6	10
LSG4C_20171113a_6	32.66472	-117.152723	3.7	6.6	-0.3	13.6	10
LSG4C_20171113d_9	32.66872	-117.151172	4.6	6	-0.3	13.6	10
LSG4C_20171107a_2	32.693557	-117.228098	15.6	77	-0.8	13.4	10
LSG4C_20171113b_2	32.66441	-117.151988	4.7	8.3	-1.2	13.1	10
LSG4C_20171111f_1	32.661112	-117.18205	16.1	62	-1.6	12	10
LSG4C_20171112d_8	32.671853	-117.188235	11.3	21	-0.5	11.9	10
LSG4C_20171112g_1	32.674692	-117.198805	9.3	6.6	-0.3	11.3	10
LSG4C_20171112g_2	32.67647	-117.196075	9.2	8.4	-0.4	10	10
LSG4C_20171114b_3	32.698267	-117.235352	17.9	41	-1.3	10	10
LSG4C_20171107d_2	32.695158	-117.229105	15.1	24	-0.7	9	10
LSG4C_20171111e_4	32.663083	-117.179533	14.3	19	-1.3	9	10
LSG4C_20171113a_7	32.671118	-117.130042	8.6	25	-0.4	9	10
LSG4C_20171114c_1	32.69893	-117.235608	18.5	38	-1.5	8.8	10
LSG4C_20171113c_7	32.667797	-117.152042	4.8	11	-1.2	8.6	10

APPENDIX F: MAGMA TOOLBOX HELP MENUS

NSWC Help System

This NSWC-MAGMA Help system contains help topics for custom software developed by Geosoft for Naval Surface Warfare Center, Panama City Division (NSWC-PCD).

Introduction to NSWC-MAGMA

This extension to Oasis montaj supports NSWC PCD's Magnetic Gradiometric Algorithms (MAGMA) workflow, providing an automatic algorithm that detects, localizes and characterizes magnetic targets from the measurements collected by the Laser Scalar Gradiometer (LSG) residing onboard an Autonomous Underwater Vehicle (AUV) (Vaizer 2004, Vaizer 2016). Magnetic sensors such as the LSG provide information that is independent of acoustic measurements and can thus be used to improve target classification.

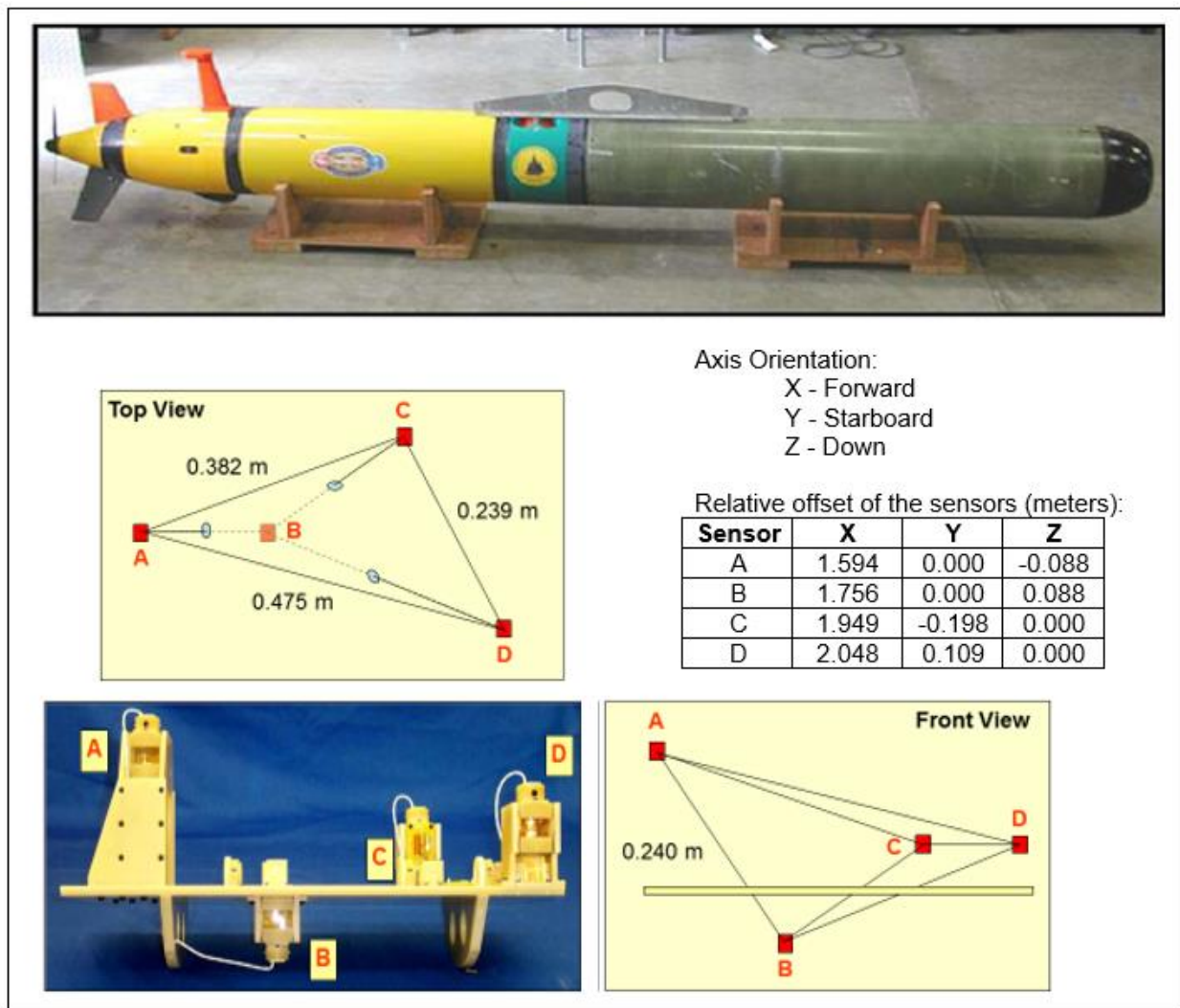


Figure 22 – REMUS600 AUV with LSG sensor payload located in the (green) forward section (top). LSG sensor assembly (middle & bottom).

The LSG, developed by Polatomic Inc. for mine countermeasures using funding from the Office of Naval Research (ONR), shown in Figure 1, features four high sensitivity laser pumped Helium cells that measure the magnitude of the local magnetic field by measuring changes in the Larmor precession frequency. Mounted in the forward section of the AUV, these cells are arranged in such a way as to allow three nearly orthogonal scalar-field differences (gradients). Using differences in the magnetic field cancels the effects of distant sources of magnetic noise and helps with target resolution. The sensor's position and orientation are provided by the AUV's Inertial Navigation System (INS).

LSG measures the magnitude of the magnetic field magnitude at the four cells at regular intervals as the AUV navigates the survey area. A magnetic source will appear point-like if the sensor is not too close to the source (farther than once or twice the dimensions of the target) and can be approximated as a dipole. The target detection and inversion algorithm operates on overlapping segments of data which are compensated for platform motion noise. The MAGMA algorithm attempts to fit segments of measured data with a minimal number of magnetic dipoles by iteratively adding dipoles, optimizing their positions and removing unnecessary dipoles. The algorithm requires no user involvement in the target localization process.

Survey Method

When collecting data for MAGMA there are three types of missions:

- Calibration,
- Search or Survey, and
- GPS Iridium.

Calibration is a mission conducted prior to Search surveys in a local area. It is used to determine and verify appropriate corrections for the magnetic data, such as directional (i.e., heading) and from the vehicle interactions (i.e., motion compensation). Although the heading corrections will change slightly and be re-calculated between missions, once the motion compensation data is collected, the application will be re-utilized for all Search surveys.

The calibration mission data is collected in deep water, with at least 15 meters of water below the sensor. The mission contains several legs of data, with each leg is separated by about 30 degrees to form the shape of a clover-leaf pattern. Legs should be approximately 200 metres long, with data collected in both directions.

Search or survey missions are the detection and classification surveys, most commonly conducted in a series of parallel transects to cover the survey area. Multiple search/survey missions may be required to fully cover the entire survey area.

GPS Iridium is a mission conducted after a search/survey is completed to determine the accuracy of the INS, as compared to the GPS, and correct for any drift of the INS.

Each mission can produce a series of data files which are distinguishable from each other via different filename extensions. Magnetics data is defined by a ***.dat** extension while positioning data is defined by a ***.sts** extension. The common parameter among all data files which ties them together is the LSG counter which is streamed within each of the data file types.

Data Processing Workflow

The general approach to detecting and classifying a ferrous object with magnetic data using the MAGMA workflow is (also see Figure 23):

1. Import the missions / survey data
 - a. Magnetics data [MAG] (i.e., Laser Scalar Gradiometer [LSG]),
 - b. Inertial Navigation System [INS]) positioning data and
 - c. Global Positioning System [GPS] data
2. Quality control the three datasets.
3. Filter and merge the magnetic and positioning data.
4. Compensate the magnetic data for the motion of the AUV.
5. Identify targets and determine source (dipole) locations.
6. Refine the source list to identify duplicate targets.

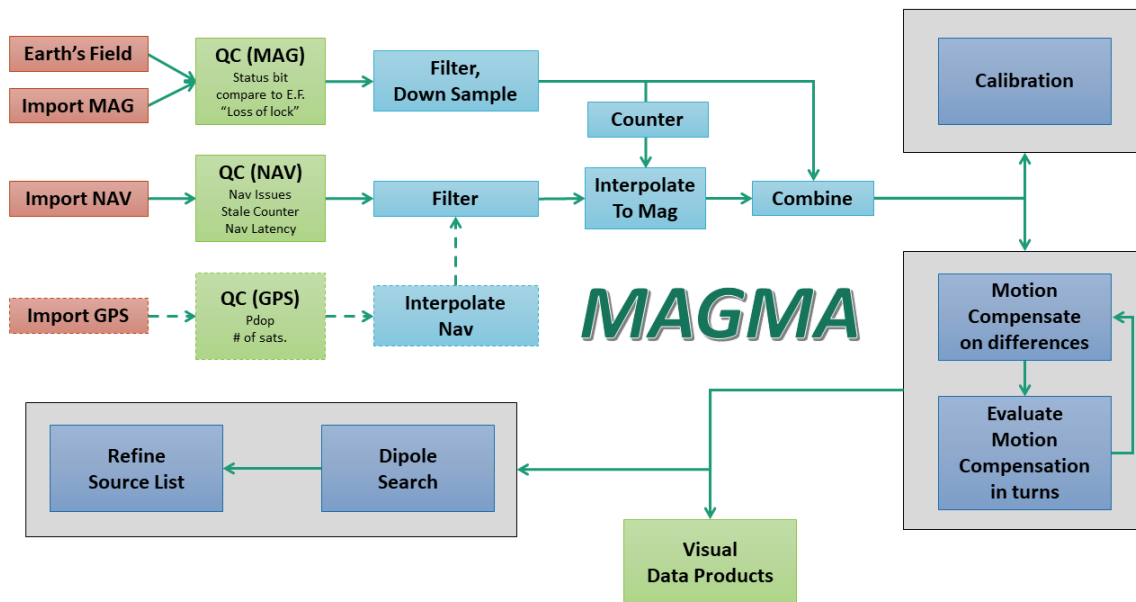


Figure 23 – The MAGMA data workflow.

Glossary of Variables

Glossary of the databases and channels of the MAGMA data processing workflow.

Magnetic Data

Database name *DatabasePrefix_MAG.gdb*

This database contains the information from the magnetic sensors. The lines are named with the mission/survey name.

Table 9 – List of channels in MAG database.

LSG Count	Pulse counter from LSG unit
MAG_A	Magnetic reading from sensor A (furthest from aft engine), nanotesla
MAG_B	Magnetic reading from sensor B, nanotesla
MAG_C	Magnetic reading from sensor C, nanotesla
MAG_D	Magnetic reading from sensor D (closest to aft engine), nanotesla
X	Approximate position, UTM/WGS84, metres
Y	Approximate position, UTM/WGS84, metres
MASK_SampleRate	Quality control mask for sample rate Good data 1 Failing data * (dummy)
MASK_StaleCounter	Quality control mask for stale or repeating counter Good data 1 Failing data * (dummy)
MASK_LossofLock	Quality control mask for loss of signal lock Good data 1 Failing data * (dummy)
MASK_Spike	Quality control mask for magnetic spikes Good data 1 Failing data * (dummy)

Inertial Navigation Data

Database name *DatabasePrefix_INS.gdb*

This database contains the information from the inertial navigation sensor. The lines are named with the mission/survey name.

Table 10 – List of channels in INS database.

Depth	Distance below the water surface, metres
Roll	Rotation from the horizontal about an axis running from nose to tail, degrees
Pitch	Rotation from the horizontal about an axis running left to right, degrees
Yaw	Rotation from a vertical axis, degrees
Altitude	Distance above the ocean floor, metres
Roll_Rate	Rate of change of the Roll, degrees/minute
Pitch_Rate	Rate of change of the Pitch, degrees/minute
Yaw_Rate	Rate of change of the Yaw, degrees/minute
Time	Time in seconds
LSG_Count	Pulse counter from LSG unit
Latitude	Position, Geographic/WGS84, degrees
Longitude	Position, Geographic/WGS84, degrees
X	Position, UTM/WGS84, metres
Y	Position, UTM/WGS84, metres
MASK_Backward_TimeCounter	Quality control mask for time and the counter Good data 1 Failing data * (dummy)
MASK_SampleRate	Quality control mask for sample rate Good data 1 Failing data * (dummy)
MASK_StaleCounter	Quality control mask for stale or repeating counter Good data 1 Failing data * (dummy)

Global Position System Data

Database name *DatabasePrefix_GPS.gdb*

This database contains the information from the Global Positioning sensor. The lines are named with the mission/survey name.

Table 11 – List of channels in GPS database.

Depth	Distance below the water surface, metres
Roll	Rotation from the horizontal about an axis running from nose to tail, degrees
Pitch	Rotation from the horizontal about an axis running left to right, degrees
Yaw	Rotation from an vertical axis, degrees
Altitude	Distance above the ocean floor, metres
Roll_Rate	Rate of change of the Roll, degrees/minute
Pitch_Rate	Rate of change of the Pitch, degrees/minute
Yaw_Rate	Rate of change of the Yaw, degrees/minute
Time	Time in seconds since midnight January 1 1970
LSG_Count	Pulse counter from LSG unit
Latitude	Position, Geographic/WGS84, degrees
Longitude	Position, Geographic/WGS84, degrees
X	Position, UTM/WGS84, metres
Y	Position, UTM/WGS84, metres
INS_line	Name of matching INS mission/survey line
INS_FID	Fiducial (row number) of matching point in the INS mission/survey line, based on the counter
INS_dist	Distance offset between the GPS and INS positions, metres

Merged Data

Database name *DatabasePrefix_MERGED.gdb*

This database contains the magnetic and the location or position data merged together into a single file. The lines are named with the mission/survey name.

Table 12 – List of channels in MERGED database.

LSG_count	Pulse counter from LSG unit
Mag_A	Magnetic reading from sensor A (closest from aft engine), nT
Mag_B	Magnetic reading from sensor B, nT
Mag_C	Magnetic reading from sensor C, nT
Mag_D	Magnetic reading from sensor D (furthest to aft engine), nT
Mag_B_Minus_A	Difference between the magnetic readings of sensors B and A
Mag_A_Minus_D	Difference between the magnetic readings of sensors A and D
Mag_C_Minus_D	Difference between the magnetic readings of sensors C and D
Depth	Distance below the water surface, metres
Roll	Rotation from the horizontal about an axis running from nose to tail, degrees
Pitch	Rotation from the horizontal about an axis running left to right, degrees
Yaw	Rotation from a vertical axis, degrees
Altitude	Distance above the ocean floor, metres
Roll_Rate	Rate of change of the Roll, degrees/minute
Pitch_Rate	Rate of change of the Pitch, degrees/minute
Yaw_Rate	Rate of change of the Yaw, degrees/minute
Time	Time, seconds
Latitude	Position, Geographic/WGS84, degrees
Longitude	Position, Geographic/WGS84, degrees
X	Position, UTM/WGS84, metres
Y	Position, UTM/WGS84, metres
Mag_A_Corrected	Magnetic sensor A readings corrected for motion compensation, nT
Mag_B_Corrected	Magnetic sensor B readings corrected for motion compensation, nT
Mag_C_Corrected	Magnetic sensor C readings corrected for motion compensation, nT
Mag_D_Corrected	Magnetic sensor D readings corrected for motion compensation, nT
Roll_Corrected	Roll, interpreted to time of magnetic measurement, degrees
Pitch_Corrected	Pitch, interpreted to time of magnetic measurement, degrees
Yaw_Corrected	Yaw, interpreted to time of magnetic measurement, degrees
Time_Corrected	Time, relative to magnetic measurement, seconds

Source Data

Database name *DatabasePrefix_SOURCES.gdb*

This database contains the information for the magnetic (dipole) sources. The lines are named with the mission/survey name.

Table 13 – List of channels in SOURCES database.

Size	Approximate size of the source based on the magnetic moment: Small <1 Am ² Medium 1 to 10Am ² Large 10 to 100Am ² Huge >100Am ²
Latitude	Position, Geographic/WGS84, degrees
Longitude	Position, Geographic/WGS84, degrees
Depth	Distance below the surface, metres
Moment_mag	Magnetic moment, Ampere·metres ²
Moment_Unit_North	Magnetic moment unit vector northward, Ampere·metres ²
Moment_Unit_East	Magnetic moment unit vector eastward, Ampere·metres ²
Moment_Unit_Down	Magnetic moment unit vector downward, Ampere·metres ²
Range	Distance from sensor to target, metres
Lateral_Offset	Horizontal distance to the target, metres
Vertical_Offset	Vertical distance to the target, metres
Bottom_Offset	Vertical distance below the seabed to the target (dipole), metres. Calculated by the difference between vertical offset for the equivalent dipole and sensor altitude above sea floor.
Peak	Time of peak magnetic signal within each data window
Angular_Rate_sum	Sum of magnitudes of platform roll, pitch and yaw rates, degree/second
Yaw	Heading of the platform, degree
Location_Segment	Estimated target location (CPA) within window. Typically, range is 0.25 to 0.75, where the start and end of the window are 0 and 1 respectively.
Time_CPA	Time of closest point of approach (CPA), hours
Time_Elapsed	Time elapsed from the beginning of the mission (merged) magnetic data to the time of closest point of approach (CPA), seconds. Used to help find the anomaly(waveform) associated with estimated source location.
SNR	Signal to Noise Ratio
Confidence	The confidence number, an indication of how well the anomaly fits a dipole model: > 9 high, 8 to 9 medium, < 8 low. Negative values indicate, the source is a secondary or additional source for another source (at the same location) with a higher confidence.
Target_number	Target number
Target_Id	Unique target identifier, that is composed of mission (line) identifier and Target number.

Menu Item – Import AUV Data

Use this *Import AUV Data* option to import the mission or survey data, this includes magnetic, inertial navigation/vehicle status and optionally GPS data.

Import AUV Data dialog options

Mag/Ins	
Mission data folder	Specify the folder that contains mission data files. <i>Script Parameter: NSWC.MISSION_FOLDER</i>
Available missions	Lists of the missions found in <i>Mission data folder</i> . For a mission to appear in the list, it has to include both <i>.DAT</i> and <i>.STS</i> files, where <i>.DAT</i> contains the magnetic and <i>.STS</i> the navigation data.
Missions to import	Use Add or Add All , Remove , and Remove All buttons to select the missions to be imported from the available missions. <i>Script Parameter: NSWC.MISSIONS_TO_IMPORT</i>
Database prefix	Specify the databases prefix, used to name each of the databases. <i>Script Parameter: NSWC.DB_PREFIX</i>
Flight number	Specify the optional flight number. Default value is 1. <i>Script Parameter: NSWC.FLIGHT_NUMBER</i>
GPS	
GPS data folder	Specify the folder that contains GPS data files. <i>Script Parameter: NSWC.GPS_FOLDER</i>
Available fixes	This is filled with the GPS data found in <i>GPS data folder</i> . For a GPS data to appear in the list, it has to include both <i>.DAT</i> and <i>.STS</i> files, where <i>.DAT</i> contains the magnetic and <i>.STS</i> the navigation data. <i>•.DAT files are not imported for GPS data.</i>
Fixes to import	Use Add or Add All , Remove , and Remove All buttons to select the GPS data to be imported from the available files. <i>Script Parameter: NSWC.FIXES_TO_IMPORT</i>

Application Notes

Each of the data types are imported into separate databases:

Magnetic data (DAT)	DatabasePrefix_MAG
Inertial navigation Data (STS)	DatabasePrefix_INS
Global Positioning Data (STS)	DatabasePrefix_GPS

Currently only LSG format files are supported. The import process is logged in **import_auv.log**, which includes any errors during the import.

From the magnetic data files, the Vector, Accelerometer and Analog channels are not imported. During the import approximate positions are calculated for the magnetic data, using the LSG Counter to lookup INS positions, and interpolate. The survey date is derived INS data and set in each of the line headers. For details of the database fields see Glossary of Database Channels.

Menu Item – QC Position Data

Use this *QC Position Data* option to perform a quality control check of the INS and GPS (if available) positioning data.

QC Position Data dialog options

Database prefix	Select the database prefix. <i>Script Parameter: NSWC.DB_PREFIX</i>
Lines to process	Select the lines to process. <i>Script Parameter: NSWC.QC_LINES_TO_PROCESS</i>
Report file name	Specify the output report file name. A summary of the process will be saved into the output text file report. <i>Script Parameter: NSWC.QC_POS_REPORT</i>
Minimum gap to interpolate (m)	Specify the minimum allowable distance between INS and GPS data. Default 1 metre <i>Script Parameter: NSWC.QC_MIN_GAP</i>
Maximum time difference to interpolate (sec)	Specify the maximum allowable time between INS and GPS data. Default 10 seconds. <i>Script Parameter: NSWC.QC_MAX_TIME</i>

Application Notes

For the INS data, the *QC Position Data* option tests for:

- consistency of the sample rate and
- stale (not incrementing) counters.

Mask channel are added to the INS database, where the test fails, and a summary text file is created. If the GPS data is available, a polar plot is generated showing the INS-GPS offsets.

The sample rate is checked for consistency, where changes in the rate are found they are marked in a mask channel, *Mask_SampleRate*. The pulse counter should continually increase with each reading, readings where the counter is found to not change are marked in a mask channel *Mask_Stale_Counter*. The mask channels indicate (have a value of 1) where the test passes, readings that fail have a dummy (*) value.

For the GPS data, a polar plot is created in the project folder (*database prefix_QC_Position.png*) showing the offsets between the INS position and the GPS position. If the distance offset between the INS and GPS position is greater than the Minimum gap to interpolate, and the time offset is less than Maximum time difference to interpolate; the INS positions will be corrected by equally distributing the difference between the INS and GPS position.

A summary text file report named, "*INS database prefix*"_QC_Position.txt, is created in the project folder. It includes a Checking INS lines(s) section detailing the sample rate and the number of stale counters expressed as a percentage of the total number of readings, for each line. If GPS data is available, also included, is the *Checking GPS line(s)* section, which details the GPS distance offset from the INS data and the names of the INS lines corrected by GPS.

Menu Item – QC Magnetic Data

Use this *QC Magnetic Data* option to perform quality control check of the magnetic data.

QC Magnetic Data dialog options

Database prefix	Select the database prefix. <i>Script Parameter: NSWC.DB_PREFIX</i>
Lines to process	Select the lines to process. •Note: Since [IGRF] button calculates the total field based on the INS database, it is important to have the same lines selected in MAG and INS databases when you process with Selected lines . <i>Script Parameter: NSWC.LINES_TO_PROCESS</i>
Total field (nT)	Specify the total field value, or use [IGRF] button to calculate it. •Note: [IGRF] calculation of the total field is based on the location from INS database, see Lines to Process. <i>Script Parameter: NSWC.TOTAL_FIELD</i>
Report file name	Specify the output report file name. A summary of the process will be saved into the output report. Default file name is [Database prefix]_QC_Mag.txt. <i>Script Parameter: NSWC.QC_MAG_REPORT</i>

Application Notes

For the magnetic data, this tool will test:

- the consistency of the sample rate; does the rate change,
- the number of stale counters; does the counter continually increase with each reading,
- the number of dropouts (loss of lock); for the line calculate the average, excluding readings that are outside of Total Field value $\pm 5000\text{nT}$. For each reading, where the difference between the average and the reading is outside $\pm 5000\text{nT}$, a loss of lock occurred.
- data spikes; to identify spikes, a moving window of 7 readings is selected, centred on the current reading. The average for the window is calculated, then removed from each reading within the window. Of the resultant, if the sum of squares is greater than 10^{99} , the current reading is a spike. For each spike the current reading is identified in the mask channel along with previous and subsequent readings.

For each test, a mask channel is created in the MAG database (*Mask_SampleRate*, *Mask_Stale_Counter*, *Mask_LossOfLock*, and *Mask_Spike*), reading that pass are indicated with a 1 and those that fail are dummy (*).

A summary text file (database prefix_QC_Mag.txt) is create in the project folder. For each survey line the following metrics are calculated:

- Total Field, Minimum and Maximum
- Number of point or readings
- Average of reading from each sensor
- Root Mean Square (RMS) error for each sensor
- Number and percentage of readings in the line where there is a change in the Sample rate
- Number and percentage of readings in the line with a Loss of Lock
- Number and percentage of readings in the line with Spikes for each sensor and the sensor differences

Menu Item – Plot QC Symbols

Use this *Plot QC Symbols* option to plot symbols on a map to visualize the results of quality control checks (*QC Position Data* and *QC Magnetic Data*).

Plot QC Symbols dialog options

Database prefix	Select the database prefix. <i>Script Parameter: NSW.C.DB_PREFIX</i>
Lines to process	Select the lines to process. <i>Script Parameter: NSW.C.LINES_TO_PROCESS</i>
Map name	Specify the existing map name. <i>Script Parameter: NSW.C.MAP</i>
Plot QC symbols for	Select any combination of the following options to plot QC symbols: GPS data INS data Magnetic data <i>Script Parameter:</i> NSWC.PLOT_GPS NSWC.PLOT_INS NSWC.PLOT_MAG
Symbol size (mm)	Specify the output report file name. <i>Script Parameter: NSW.C.SYMBOL_SIZE</i>

Application Notes

On an existing map, this tool will create a group(layer) for each of the data type (MAG, INS and GPS) and a legend.

The map includes:

- Line path of the AUV, based the INS data
- Symbol plot for the GPS locations
- Symbol plots for readings that fail the QC tests:
- Inertial Navigation data (INS)
 - a "stale" counters (where they did not increment correctly)
 - a sample interval changes

- Magnetic data (MAG)
 - a "stale" counters (where they did not increment correctly)
 - a sample interval changes
 - a data "spike"
 - a loss of lock

Tip: On your map, you can deselect groups (layers), if your map is too cluttered or slow to display if there are many points.

Menu Item – Merge Magnetic and Location Data

Use this *Merge Magnetic and Location Data* option to merge the magnetic (MAG) and location or position (INS) data.

Merge Magnetic and Location Data dialog options

Database prefix	Select the database prefix. <i>Script Parameter: NSW.C.DB_PREFIX</i>
Lines to process	Select the lines to process. <i>•When Selected lines is picked, the assumption is that the same lines are selected in both MAG and INS databases. If the line selections are different, only the ones selected in both databases will be processed and saved into the merged database.</i> <i>Script Parameter: NSW.LINES_TO_PROCESS</i>

Application Notes

Prior to merging the magnetic data is processed to:

- a) remove measurements where there was a loss of lock, and
- b) filter out the spikes, linearly interpolating to fill the gaps.

The magnetic and the position data are resampled to 10Hz, and then merged together using the counter readings.

The merge process is logged in **Merge Magnetic and Location Data.log**, which includes any errors during the merge.

Menu Item – Calculate Calibration Coefficients

Use *Calculate Calibration Coefficients* menu option to calculate calibration coefficients for motion compensation of the magnetic data.

Calculate Calibration Coefficients dialog options

Database prefix	Select the database prefix. <i>Script Parameter: NSWC.DB_PREFIX</i>
Line to process	Select the line or mission to process. <i>Script Parameter: NSWC.MISSION_TO_PROCESS</i>
Declination (deg)	Specify the magnetic declination, in degrees. <i>Script Parameter: NSWC.DECLINATION</i>
Inclination (deg)	Specify the magnetic inclination, in degrees. <i>Script Parameter: NSWC.INCLINATION</i>
Total field (nT)	Specify the magnetic total field, in nanoTelsa. <i>Script Parameter: NSWC.TOTAL_FIELD</i>
[IGRF]	When clicked, the magnetic field components will be calculated based on the latitude and longitude and time of the merged data.
Output calibration coefficient file	Specify the output calibration coefficient file. This file contains the information required to run Apply Motion Compensation GX. <i>Script Parameter: NSWC.CALIB_COEFF_FILE</i>

Application Notes

The calibration mission data is collected in deep water, with at least 15 meters of water below the sensor (see Survey Method). The initial processing of the calibration data is the same as regular survey data (i.e. import, QC, and merge). This tool is then used to calculate the calibration coefficients, that are used to compensate the magnetic data for motion-generated noise.

Tolles and Lawson first proposed a method to compensate for impacted of motion generated noise in airborne magnetic data in the 1940's and 50's. A modified version of the Tolles-Lawson noise reduction model has been developed to apply to multi-channel gradiometers (Bickel, 1979). The model was developed for airborne systems and uses auxiliary fluxgate measurements to estimate signal due to platform permanent and induced moments rotating in Earth's field. For the LSG, the fluxgate measurements are synthesized from nominal value of background field (IGRF) and INS measurements. In the case of the LSG, this improves the calibration, resulting in less noise in the data due the effect of the AUV subsystems and avoids the complexity of removing the impact of near targets from fluxgate measurements.

Coefficients are calculated for each magnet sensor independently. Underwater systems have a limited range of motions as compared to airborne systems, resulting in some of the Tolles-Lawson coefficients being linearly dependent. If a coefficient can not be calculated from the available data, it is set to zero.

The coefficients are output in a text file (default file name Cal_Coefficients.txt) for use with the *Apply Motion Compensation* tool. The calibration coefficients file contains the calibration coefficients. There are 4 blocks (one for each magnetic sensor), each with 16 components of the magnetic signal due to motion in background field.

The components are proportional to:

1	$B_x,$
2	$B_y,$
3	$B_z,$
4	$B_x*B_x,$
5	$B_x*B_y,$
6	$B_x*B_z,$
7	$B_y*B_y,$
8	$B_y*B_z,$

9	$B_x*(dB_x/dt),$
10	$B_x*(dB_y/dt),$
11	$B_x*(dB_z/dt),$
12	$B_y*(dB_x/dt),$
13	$B_y*(dB_y/dt),$
14	$B_y*(dB_z/dt),$
15	$B_z*(dB_x/dt),$
16	$B_z*(dB_y/dt)$

Menu Item – Apply Motion Compensation

Use *Apply Motion Compensation* menu option to apply motion compensation on merged magnetic data.

Apply Motion Compensation dialog options

Database prefix	Select the database prefix. <i>Script Parameter: NSWC.DB_PREFIX</i>
Lines to process	Select the lines to process. <i>Script Parameter: NSWC.LINES_TO_PROCESS</i>
Declination (deg)	Specify the magnetic declination, in degrees. <i>Script Parameter: NSWC.DECLINATION</i>
Inclination (deg)	Specify the magnetic inclination, in degrees. <i>Script Parameter: NSWC.INCLINATION</i>
Total field (nT)	Specify the magnetic total field, in nanoteslas. <i>Script Parameter: NSWC.TOTAL_FIELD</i>
[IGRF]	When clicked, the magnetic field components will be calculated based on the latitude and longitude and time of the merged data.
Input calibration coefficient file	Specify the input calibration coefficient file. <i>Script Parameter: NSWC.CALIB_COEFF_FILE</i>
Output RMS signal file	Specify the output RMS signal file. <i>Script Parameter: NSWC.RMS_SIGNAL_FILE</i>

Application Notes

This tool is used to reduce the noise from the motion of magnetometers in the earth magnetic field, using a modified Tolles-Lawson model (Bickel, 1979).

Prior to collection the search or survey data, a calibration mission is collected to calculate the calibration coefficients for the survey area, using a clover-leaf shaped maneuver that minimize non-motion dependent noise (see Calculate Calibration Coefficients). In addition, if the survey area is relatively free of magnetic anomalies, the calibration coefficients are refined using the

survey data. This refinement is calculated for each mission, starting with coefficients from a calibration test and looping through the calibration calculations to reduce the root-mean-square (RMS) misfit.

A text file is created called DatabasePrefix_MoComp_Residual.txt that contain the root-mean-square (RMS) misfit results. The RMS file has the following fields:

MissionName: RMS of MagC, RMS of Mag_B_Minus_A, RMS of Mag_A_Minus_D, RMS of Mag_A_Minus_D

L123223_Search:13.23833,8.591635,7.613436,8.946251

The resulting magnetic data compensated for the motion of the AUV are stored in the new database channels, with the suffix "corrected". Note roll, pitch and yaw data are interpreted to time of magnetic measurement.

Menu Item – Find Sources (Dipoles)

Use this *Find Sources (Dipoles)* option to locate dipole sources from the (merged) magnetic data.

Find Sources (Dipoles) dialog options

Database prefix	Select the database prefix. <i>Script Parameter: NSWC.DB_PREFIX</i>
Lines to process	Select the lines to process. Selected lines or All lines. <i>Script Parameter: NSWC.LINES_TO_PROCESS</i>
RMS signal file	Specify the input RMS signal file. Created by the Motion Compensation. <i>Script Parameter: NSWC.RMS_SIGNAL_FILE</i>
Declination (deg)	Specify the magnetic declination, in degrees. <i>Script Parameter: NSWC.DECLINATION</i>
Inclination (deg)	Specify the magnetic inclination, in degrees. <i>Script Parameter: NSWC.INCLINATION</i>
Total field (nT)	Specify the magnetic total field, in nanoteslas. <i>Script Parameter: NSWC.TOTAL_FIELD</i>
[IGRF]	When clicked, the magnetic field components will be calculated based on the latitude and longitude and time of the merged data.

Application Notes

To locate dipole sources from the LSG magnetic data, there are two steps:

1. Dipole Search
2. Refine Source List

The Dipole Search uses a series of moving windows to examine the data for each mission and identify potential dipole sources. Three window sizes are used: 10 seconds, 30 seconds, and 60 seconds in length. As the data is examined using a given window size, each subsequent window

overlaps the previous window by 50%. The data in the window is searched for an anomaly waveform indicative of either a single dipole or two dipoles. Typically, the dipoles are identified in the middle half of the search window, this is measured by Location Segment channel, with a typically, range is 0.25 to 0.75, where the start and end of the window are 0 and 1 respectively.

Refine Source List, once the Dipole Search is complete it necessary to refine the list, as the search produces many potential sources. To refine the list:

1. Exclude sources with a high (> 5 deg/sec) Angular_Rate_Sum. The excluded sources are likely due to noise due rapid movement of the AUV.
2. Examine the sources that are close together in the data, that is found within 2 seconds each other. Retain source from the window that the highest confidence number. The confidence number is a measure of the well the observed data fit a dipole model, 0 is no fit and 10 a perfect fit.
3. Automatically remove sources with low (< 8) confidence numbers, and low (< 8) signal to noise ratio's (SNR), as these are not likely to be targets of interest. Sources with a high confidence number or a high SNR, should be further examined and investigated.

When multiple passes (i.e. two legs of a mission), identify sources at the approximately the same location, the source with the high confidence number is the primary source. The secondary or additional sources are indicated with a negative confidence number.

Note: The LSG has a limited ability to separate dipoles with similar magnitude and CPA time (< 2 sec). For example, if there are two items on either side of the track with similar responses.

Configuration File

A configuration file, nswc.config, which is located in "C:\Program Files\Geosoft\Desktop Applications 9\etc" folder. This file contains parameters for several tools:

- Plot QC Symbols
- Calculate Calibration Coefficients
- Apply Motion Compensation
- Find Source Dipoles

Application Notes

Plot QC Symbols

Parameters to control how the line path and quality control symbols are plotted on the map.

- `<qcPlot>`
- `<symbols>`
- `<symbol dataType="GPS" test="" type="circle" colour="R0G0B0" fillColour="none" weight="light" />`
- `<symbol dataType="INS" test="staleCounter" type="octagon" colour="R0G255B255" fillColour="none" weight="light" />`
- `<symbol dataType="INS" test="sampleRate" type="triangle" colour="R0G255B255" fillColour="none" weight="light" />`

- `<symbol dataType="MAG" test="staleCounter" type="octagon" colour="R255G0B255" fillColour="none" weight="light" />`
- `<symbol dataType="MAG" test="sampleRate" type="triangle" colour="R255G0B255" fillColour="none" weight="light" />`
- `<symbol dataType="MAG" test="lossOfLock" type="square" colour="R255G0B255" fillColour="none" weight="light" />`
- `<symbol dataType="MAG" test="spike" type="cross" colour="R255G0B255" fillColour="none" weight="light" />`
- `</symbols>`
- `<line style="solid" colour="R192G192B192" width="0.15" labelLocation="none" labelSize="2.5" addCompassDirection="+X is East" breakOnGaps="2" />`
- `<calibration>`

Calculate Calibration Coefficients

Parameters to help with debugging NSWC algorithm. When `SaveIntermediateFiles` is set to true, a folder called *Calibration* is created in the project folder. This folder will contain files for each mission/survey line. The files are:

- Mission_DatabasePrefix_LSGLegsout.txt
 - Mission_DatabasePrefix_LSGCalout.txt
 - Mission_DatabasePrefix.ls1
 - Mission_DatabasePrefix.ls2
- `<calibration>`
 - `<saveIntermediateFiles value="false" />`
 - `<legFileName value="LSGLegsout.txt" />`
 - `<logFileName value="LSGCalout.txt" />`
 - `</calibration>`

Apply Motion Compensation

Parameters to help with debugging NSWC algorithm. When `SaveIntermediateFiles` is set to true, a folder called *MotionCompensation* is created in the project folder. This folder will contain files for each mission/survey line. The files are:

- Mission_DatabasePrefix_LSGMCCout.txt
 - Mission_DatabasePrefix.csv
 - Mission_DatabasePrefix.ls2
 - Mission_DatabasePrefix.ls5
- `<motionCompensation>`
 - `<saveIntermediateFiles value="false" />`
 - `<logFileName value="LSGMCCout.txt" />`
 - `</motionCompensation>`

Find Source Dipoles

Parameters to help with debugging NSWC algorithm. When `SaveIntermediateFiles` is set to true, a folder called *Localization* is created in the project folder. This folder will contain files for each mission/survey line. The files are:

- Mission_DatabasePrefix_LSGAtrgout.txt

- Mission_DatabasePrefix_LSGLOCout.txt
- Mission_DatabasePrefix.csv
- Mission_DatabasePrefix
- Mission_DatabasePrefix.trg
- <targetLocalization>
- <saveIntermediateFiles value="false" />
- <atrgFileName value="LSGAtrgout.txt" />
- <logFileName value="LSGLOCout.txt" />
- </targetLocalization>

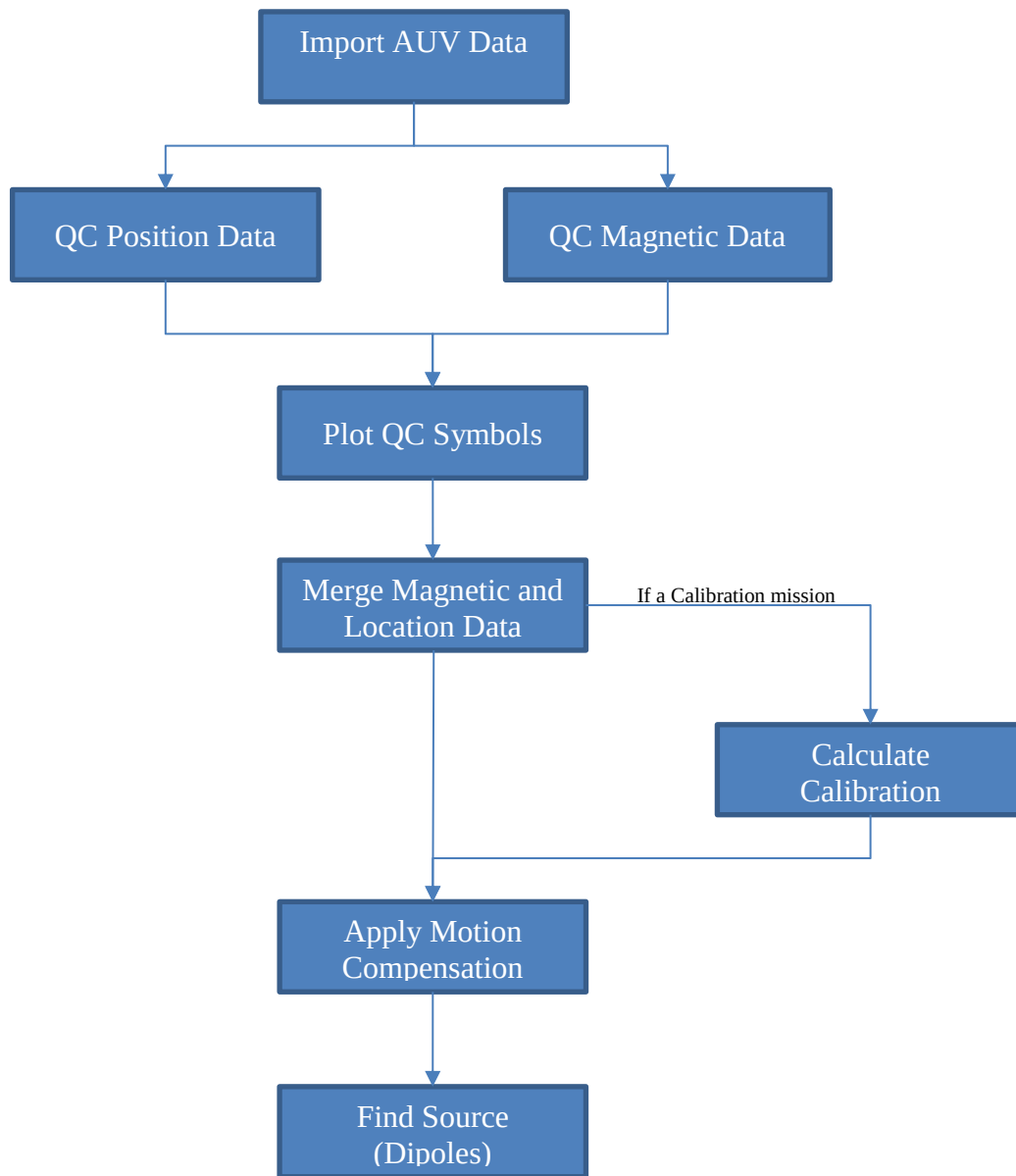


Figure 24 – MAGMA Oasis montaj tools and a typical processing workflow.