FINAL REPORT

Bistatic Target Localization and Classification using low-cost ASVs and AUVs in Shallow Water

SERDP Project MR18-1443

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14. ABSTRACT

The objective of this research was to investigate acoustic characterization techniques for seabed targets that are scalable to multiple low-cost autonomous vehicles fitted with simple hydrophone arrays and sources in response to the “detection, classification, and remediation of military munitions underwater” statement of need. Specifically, this research investigated the use of bistatic and multistatic scattering from seabed targets for target localization and characterization using unmanned marine vehicles.

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Abstract

Introduction and Objectives:
The objective of this research was to investigate acoustic characterization techniques for seabed targets that are scalable to multiple low-cost autonomous vehicles fitted with simple hydrophone arrays and sources in response to the "detection, classification, and remediation of military munitions underwater" statement of need. Specifically, this research investigated the use of bistatic and multistatic scattering from seabed targets for target localization and characterization using unmanned marine vehicles.

Technical Approach: In the bistatic approach a region of interest is insonified by a single omnidirectional source while multiple low-cost, low-power receiver vehicles record echo data from the surrounding area. This multistatic receiver network is then used to detect and classify seafloor objects. Typical sonar systems use a monostatic approach, where the source and receiver are collocated and the echo data is primarily backscattering. If the receiver and source are not collocated, the recorded echoes are *bistatic*; the bistatic scattering strength from a target will depend on both the source and receiver positions, as well as frequency, target composition, target position/orientation, environment, and other factors. In our approach, an acoustic data collection payload including a hydrophone array was located on an autonomous surface vehicle (ASV) and a time-synchronized acoustic source was mounted on a separate surface platform. As the receiver vehicle progressed through the environment, the bistatic acoustic reflections from the scene (and associated seabed targets) were captured on the receiving array. Two techniques were considered in this work (Fig. 1): the case where the source position is fixed will be considered the bistatic configuration, while in the multistatic configuration the source platform is also mobile. In both cases, the intent was to feed the resulting source/receiver position dependent scattering data into signal processing algorithms for initial mapping of targets, and then into machine learning algorithms to attempt classification.

Results: We encountered significant limitations to low-cost bistatic and multistatic target detection/classification in this project. Previous work was conducted on tightly-integrated autonomous underwater vehicle systems with custom hydrophone arrays, high-quality sound sources, and well-controlled target fields: this project attempted to replicate those results using low-cost sources, receivers, and a less well-defined target field. Simulation work also attempted to extend previous work by looking at the possibility of detecting and classifying targets using multiple vehicles driving in straight lines through a target field, intersecting the scattering radiation pattern but not fully circling the target. Both of these techniques were found to be ineffective due to different limitations: for multistatic scattering, intersecting without fully sampling the aspect-dependent radiation pattern did not provide enough information for classification. The project was re-focused on bistatic imaging and/or classification using low-cost vehicles, arrays, and sources in a concentrated field study in June 2019. Analysis of that data found that the uncertainty introduced by system noise, navigation error, and mechanical vibration on the low-cost system meant that the target detection and classification was not possible within the data set.

Impact: The hope was that this technique would be found to be an effective option for low-cost UXO detection/classification. Our conclusion is that, at this time, the low-cost off-the-shelf systems do not provide high enough quality data to make bistatic or multistatic sensing viable for low-cost UXO detection/classification. In addition, there are fundamental challenges to the bistatic/multistatic configurations that may preclude these techniques from ever being effective as compared to the more familiar single platform monostatic configuration.

Introduction

This work addressed the "detection, classification, and remediation of military munitions underwater" statement of need by looking at possible classification features in bistatic and multistatic acoustic scattering from seabed targets in the 1-20 kHz range. The advantage of bistatic or multistatic systems is that source and receiver are on separate vehicles: that means that a single acoustic source may be used with multiple low-cost, low-power sensing platforms, with the potential for localizing and classifying targets at higher area coverage rates than possible using monostatic systems.

Objectives

Bistatic imaging and multistatic radiation pattern recognition were explored as ways of using scattering data available in multi-vehicle systems for seabed target classification. This initial work focused on exploring data processing algorithms and identification of features within processed acoustic data that would be useful in classifying seabed targets based on geometry and composition in order to narrow down the objectives for field trials. Simulation work looked at spheres and cylinders, and field experiments included cylinder, plate, and "clutter" objects. The objective of this SERDP SEED was to determine if bistatic imaging and/or multistatic radiation pattern recognition are feasible methods for target discrimination in the field using low-cost unmanned vehicles with simple omnidirectional sources and line hydrophone arrays. The methods were investigated together because the same simulation algorithms, targets, sources and receivers were required for collecting acoustic data sets with only a difference in vehicle behavior and experiment geometry.

Technical Approach

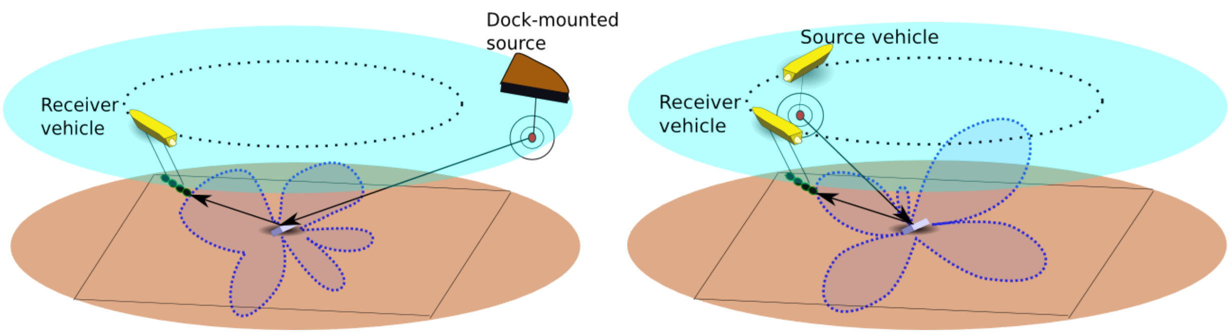


Fig 1. (Left) Bistatic configuration: fixed-source, mobile receiver. (Right) multistatic configuration: mobile-source, mobile-receiver.

A growing application for unmanned vehicle technology is the localization, classification and mitigation of underwater hazards such as munitions in shallow harbor environments. Because visual inspection of targets can be difficult or impossible in murky harbors and requires precise target localization, acoustic sensors are used more extensively for munition detection/classification missions. The use of acoustic imagery for target detection and categorization is currently an area of active research using both incoherent (e.g. side-scan sonar) and coherent (e.g. synthetic aperture sonar, SAS) techniques; these imaging modalities typically use pseudo-monostatic systems where the relative source-receiver geometry is fixed (Ferguson and Wyber, 2005).

While these techniques can provide rich images of targets and the environment, the sensors themselves are too expensive to be practical in multi-vehicle operations. Our objective was to investigate the practicality of low-cost acoustic target localization and classification technology for distributed, multi-vehicle systems by using features of target bistatic (fixed-source, mobile receiver) and multistatic (mobile-source, mobile-receiver) scattering fields that can be sensed using a simple hydrophone array. Field studies were conducted using Woods Hole Oceanographic Institution (WHOI) JetYaks (P. Kimball et al. 2014), gasoline-powered autonomous surface vehicles (ASVs). The advantage of low-cost multi-vehicle systems would be broader coverage than with, for example, a high-power monostatic imaging system.

When an object is insonified by an acoustic source, it re-radiates that acoustic signal. Re-radiation consists of interfering time-delayed echoes, resulting in a 3D radiation pattern containing minima and maxima. The exact features of that 3D radiation pattern, or scattered field, are determined by factors such as frequency, target geometry, target composition, and environment. The radiation pattern changes for non-symmetric targets, such as cylinders or UXOs, with aspect angle, which is determined by the acoustic source direction relative to the target's major axis.

We investigated two potential methods of extracting target information from this kind of acoustic data collected on a low-cost hydrophone array on an unmanned marine vehicle: bistatic imaging and multistatic radiation pattern characterization.

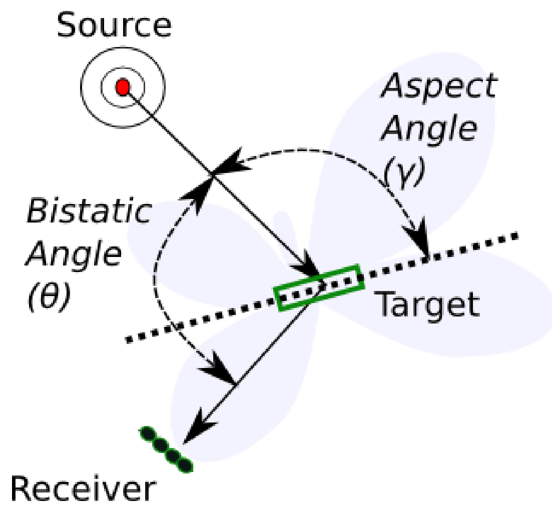


Fig 2. Bistatic and aspect angles relative to source, target, receiver in bistatic/multistatic scattering reference frame.

The bistatic scattering part of this work focused first on the objective of assessing whether detection/classification of targets using low-cost ASV-mounted array systems was feasible. For bistatic imaging we were interested in what happens when SAS-type processing was run with a fixed source and mobile receiver. The experimental/numerical geometry suggested here is most similar to circular SAS (CSAS), and this work used existing CSAS imaging methods as a starting point. Some laboratory work had been previously done in (Plotnick 2015) and on bistatic imaging (Plotnick et al. 2016), where bistatic CSAS images were successfully created; however, that work was limited to the specific case of evanescent insonification, while this project explored generalized cases using less-well-constrained field measurements.

We also investigated target classification by looking at the relationship of bistatic angle, aspect angle, and scattering amplitude. This expands on previous AUV-based bistatic scattering research: experiments were run as a part of BayEx'14, and in Massachusetts Bay. The data from those experiments was successfully used to demonstrate target shape and orientation discrimination using the relationship of scattering amplitude to bistatic angle, as described in Fischell and Schmidt 2015. Preliminary investigations into the mobile-source, mobile-receiver (multistatic) case have been conducted in simulation to begin to understand autonomy requirements and the relationships between multistatic radiation patterns and target characteristics (Fischell and Schmidt 2017).

The advantage of using radiation pattern analysis is that it is less sensitive to vehicle navigation error than phase-based techniques such as SAS (errors on the order of 5-10 m are acceptable), and processing can be conducted on autonomous vehicles. This makes the technique suitable for low-cost AUVs in addition to ASVs. Radiation patterns are calculated as the contact amplitude for a known-location target versus bistatic and aspect angle relative to that target.

We attempted to use the relationship of radiation pattern, bistatic and aspect angles in the 1-20 kHz range to estimate target characteristics. Bistatic angle is the angle between the source and receiver relative to the target, and aspect angle is the angle between the target major axis and the forward-scatter source direction. **Our effort under SERDP focused on understanding the application of preliminary multistatic "circling" type features to different types of targets, the efficacy of the multistatic features for classification in field transect behaviors, and its translation into the field using AUVs and ASVs for data collection.**

Tasks

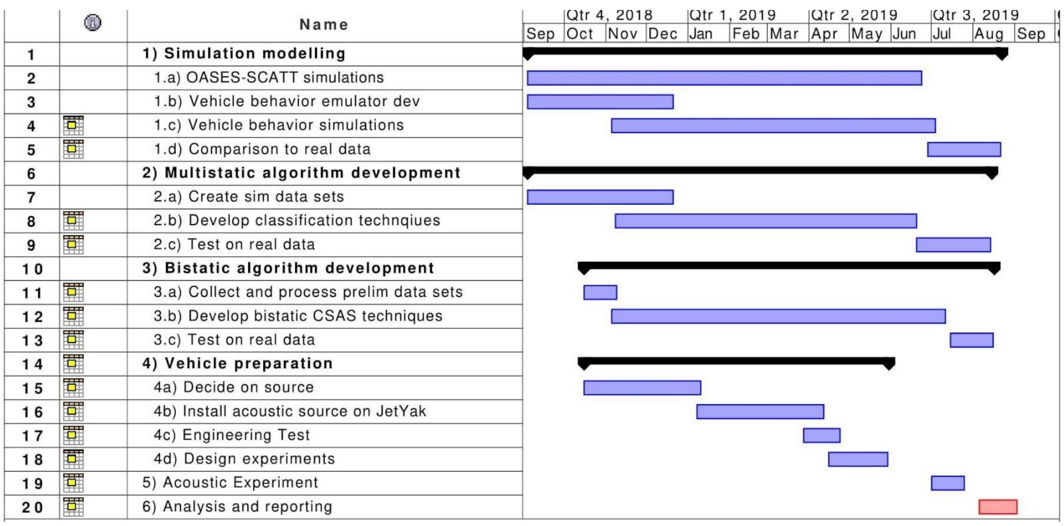


Fig 3. Gantt chart showing original tasks and timeline for the project

In this project, we explored techniques for bistatic and multistatic UXO detection and classification. We conducted simulation and real-world experiments, with the goal of developing target characterization techniques that work in the multi-vehicle context on low-cost platforms. The main tasks associated with this proposal were:

1. Simulation modeling: Conduct simulation experiments, vehicle behavior experiments using OASES-SCATT on different target types and environments.
2. Vehicle preparation: Prepare JetYak ASV for field experiments and conduct engineering testing.
3. Acoustic field experiment: Conduct field experiments using targets and autonomous vehicles fitted with sources and receivers in Ashumet Pond in Falmouth, MA near Woods Hole Oceanographic Institution.
4. Bistatic imaging algorithm development: Develop bistatic processing techniques based on existing CSAS in simulation and assess using experimental data.

5. Multistatic algorithm development: Develop multistatic radiation pattern classification techniques in simulation.
6. Final data analysis and reporting.

All of these tasks were completed, though there were delays in the final data analysis and reporting due to Plotnick's move from APL-UW to ARL-PSU.

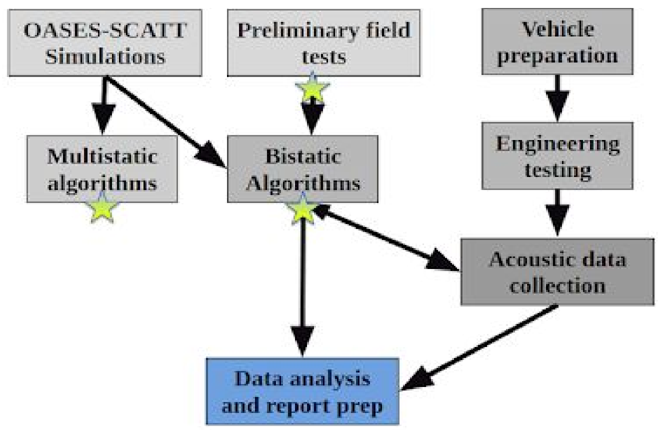


Fig 4. Task decision space, with key decision points marked as stars. Multistatic was found to be less likely to work than bistatic based on simulation studies and preliminary field tests, so bistatic was selected as the focus of the field experiments.

Simulation studies

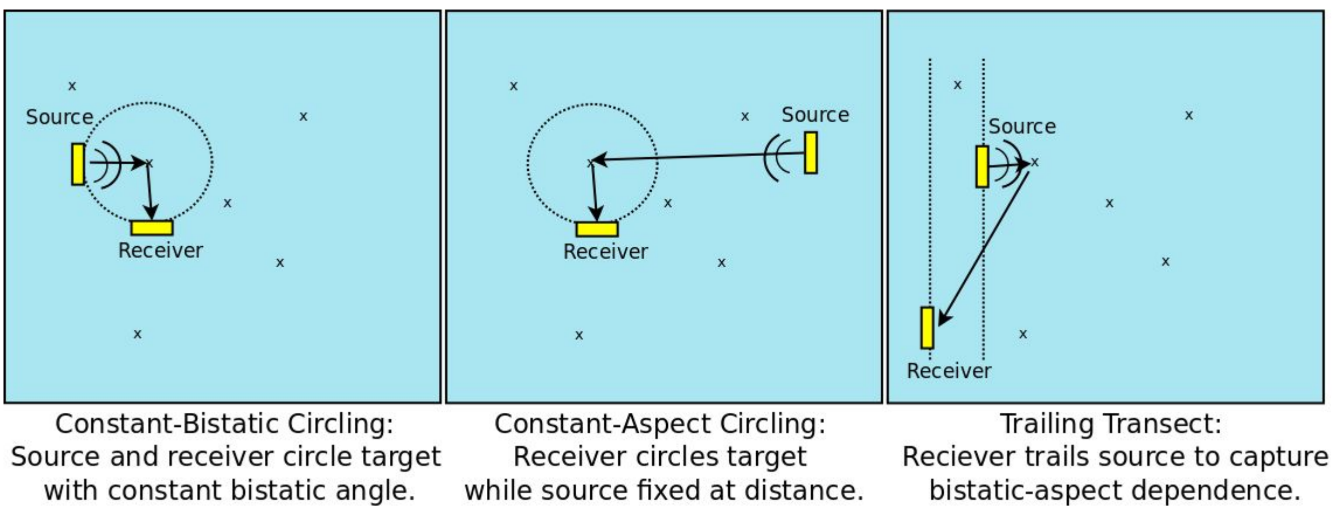


Fig 5. Bistatic imaging geometries

OASES-SCATT simulation studies were carried out to identify critical features for bistatic imaging and multistatic sampling using autonomous vehicles for spherical and cylindrical targets. There are three behavior options for bistatic/multistatic data collection: constant-bistatic circling, constant-aspect circling, and trailing transect. The constant-aspect circling was examined in prior work in simulation (Fischell et al. 2015, JASA) (Fischell et al. 2016, IEEE ICRA). Constant-bistatic circling was also examined in prior work (Fischell et al. 2017, JASA), so the additional simulation effort was focused on the trailing transect method. Code was written to create examples for machine learning training, testing, and validation emulating a source vehicle intersecting a 100 m circle around a target at an arbitrary angle, with a receiver vehicle following at a set range.

Field Trials

3 days of field testing of the system were conducted in Ashumet pond, in Falmouth, MA in June of 2019. 3 targets, originally deployed in summer 2017 and now buried, were used: an aluminum cylinder, a steel cylinder, and a steel plate. A JetYak ASV was equipped with a time-synchronized data acquisition system that collected time-synchronized acoustic data at a sample rate of 50 kHz across an 8-element hydrophone array. A sound source was deployed from a floating platform at a 50 m distance to the targets. A wireless network was established between the receiver vehicle and a shore based computer, allowing for live data viewing and on-site analysis/troubleshooting.

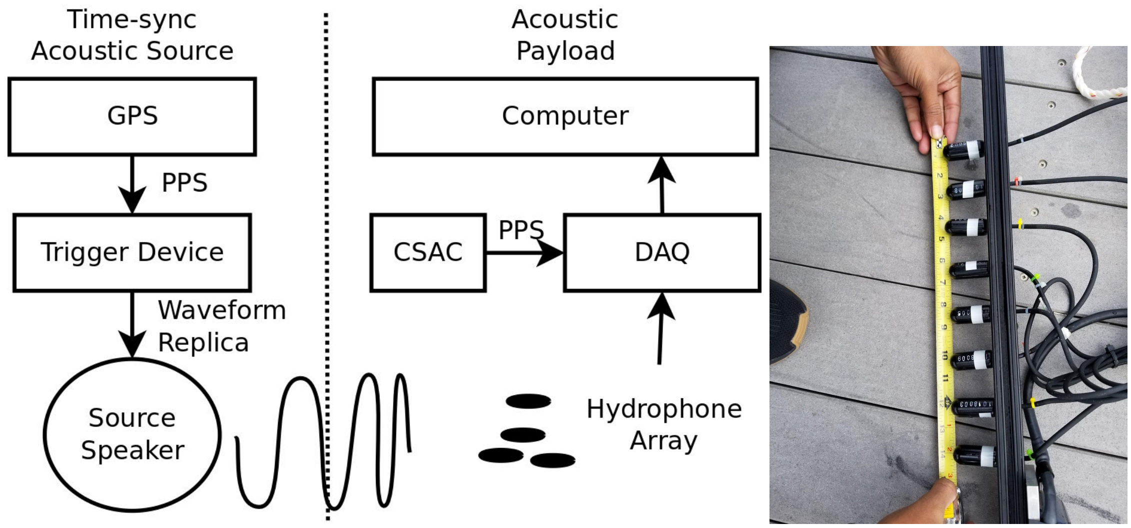
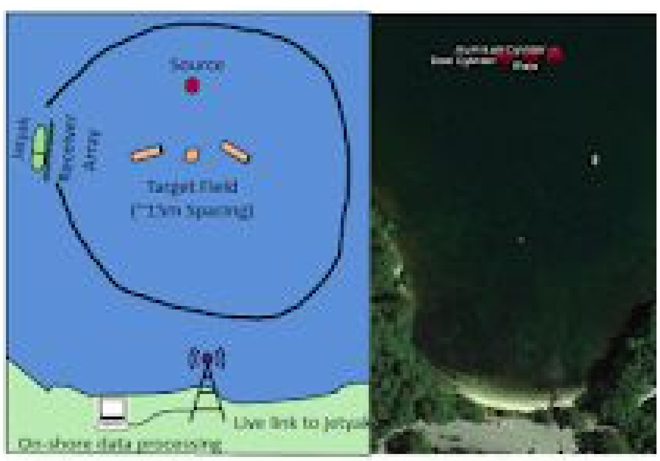


Fig 6. Payload block diagram and photograph of hydrophone array for initial prototype. Hydrophone system records pulse-per-second synchronized acoustic data, capturing time delay due to direct path from sound source and any scattering from the environment.



Target field is 200 m from boat launch, 100m from nearest shoreline.

Fig 7. Experiment site, Ashumet Pond, field experiment team with JetYak ASV equipped with hydrophone array.

Results and Discussion

Simulation studies

The new simulation work conducted under the SERDP SEED involves virtual experiments emulating 2-vehicles capturing multistatic scattering using a trailing transect-type behavior. In these simulations, the target was "visible" with amplitude estimated from 150 m distance, and there was no a priori or behavior change based on target position. This is a change from the prior work, where it was assumed that targets are first detected and then circled to capture information on target characteristics. This simulation was conducted using sphere versus cylinder target.

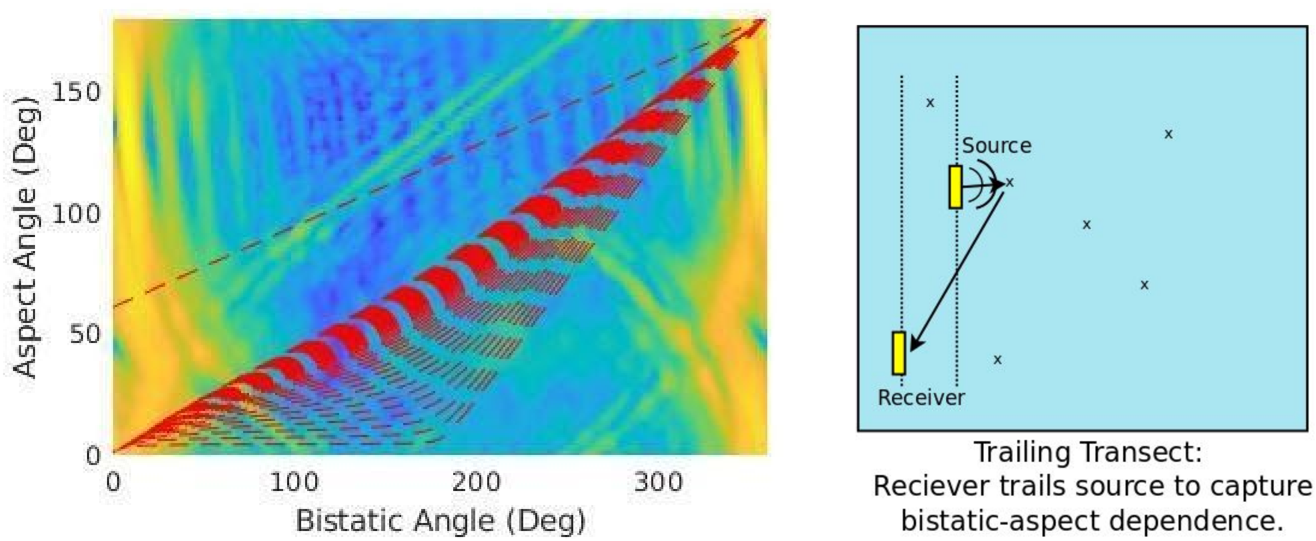


Fig 8. Paths captured over the space represented by bistatic versus aspect scattering of a cylinder target by trailing transect with a fixed source-receiver range of 20 m. Variability is caused by different angles of intersection with the 150 m circle surrounding the target,

The finding from the trailing transect simulation experiments was that this is not an effective way to classify targets, even in simulation: the approach simply does not capture enough information from a single-frequency scattering amplitude pattern over intersection with the radiation pattern to provide even a classification of aspect-dependence. While in the bistatic and fixed-aspect circling behavior high accuracy (approaching 100 %) in machine learning classification was achieved for simulation studies, greater than 60 % accuracy in simple sphere versus cylinder was not observed in any of the transect distances tested. While multiple receiving vehicles at different transect distances might mean this information could be used for classification, looking at the bistatic angle versus aspect angle plot, and what is captured by fixed-bistatic and fixed-aspect versus trailing transect behaviors, the difference between amplitude patterns in sphere versus cylinder are apparent in the bistatic and fixed-bistatic-angle circling classes, but not in the trailing transect.

Field Trials

The project was re-focused on attempting to get bistatic scattering using the low-cost systems originally proposed: an 8-element configurable hydrophone array mounted on a JetYak ASV, and a Lubell underwater speaker as a sound source. During the experiment, source and receiver positions were measured using GPS, and the recorded data post-processed via pulse compression and beamforming. In the below figure, vehicle position is shown in dark-blue to cyan, and source position is shown in green to yellow. Vehicle heading is shown as the red lines starting from each vehicle position. Estimated target locations of the plate, steel cylinder and aluminum cylinder are shown as the top-to-bottom black crosses respectively.

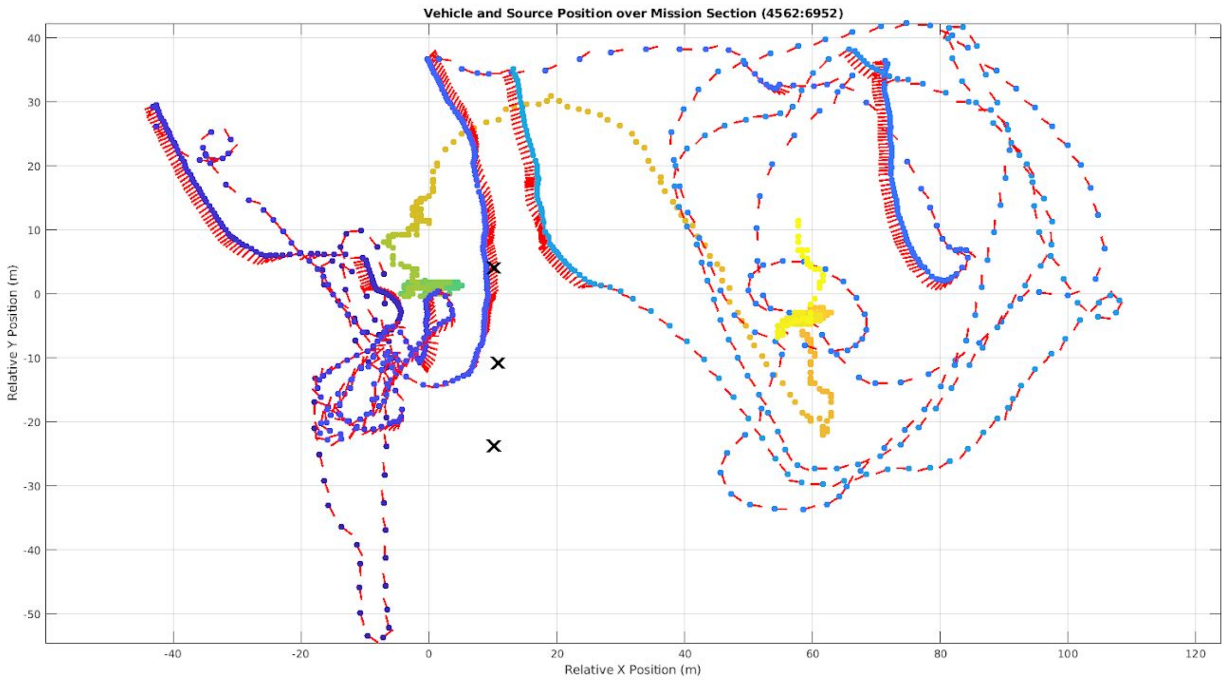
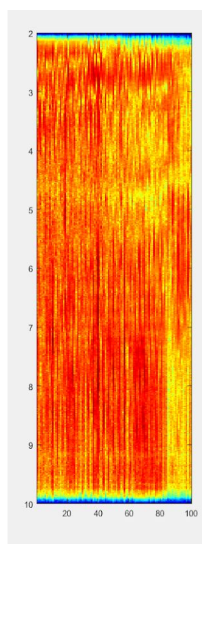


Fig 9. Positions of the vehicle and the source over time during the most relevant part of the mission.

Lessons Learned: Lubell Speaker as a sound source



In engineering testing, it was found that the waveform was not accurately transmitted by the low-cost source, so a near-field recording was used to create a replica to be used in matched filtering steps. The Lubell 3400 used in this experiment is a 12 V diver recall system, and the amplifier in the system did not provide high fidelity replication of desired waveforms. The system was also limited in power and omnidirectional, but has the advantage of being low-cost. The source spectrum contained a considerable amount of structure, which may have reduced some of the quality of the results. Acoustically, the wide bandwidth *should* have resolution advantages, but the main source band of the Lubell also overlapped with the self-noise of the receiver platform. Also of likely greater negative impact on the results was the uncertainty in the exact position of the source, addressed below.

Lessons learned: JetYak as an acoustic measurement platform

There were a number of challenges encountered over the course of this program in using the JetYak ASV as a platform for bistatic acoustics. Prior work used a tightly-integrated AUV system with built-in array: for this project, an array was mounted to the side of the JetYak; this resulted in mounting uncertainties for the receive array including position and orientation relative to the AHRS sensor on the ASV. As noted for the source, this compounded the bistatic system position uncertainties. In general, many of the complications experienced during this work stem from the JetYak being designed as a highly configurable, low-cost general use system; navigation uncertainties in particular would require a more tightly integrated and more costly adaptation of the JetYak or other platform.

Fig 10. Array system mounted on JetYak ASV, JetYak ASV being remote-controlled during field trials.

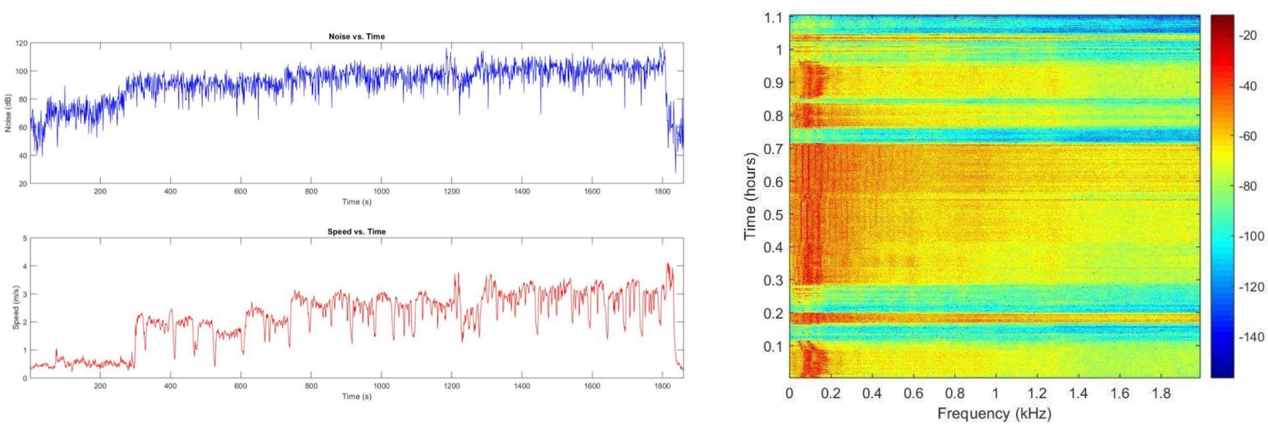


Fig 11. (Left) JetYak Speed versus noise level during Spring 2019 engineering testing. (Right) spectrogram of JetYak noise. The bright bands are periods where the JetYak throttle was too high, and engine noise dominated the received data.

While the original intent of this experiment was to operate the JetYak in an autonomous mode, allowing for better positional control, noise generated by the gasoline engine proved to be an insurmountable hurdle when the vehicle was traveling at its operational speed (even after extensive signal processing). As the JetYak could not be run autonomously, the platform was operated in two other modes: in the first, the engine was shut off completely and the platform was manually towed by another kayak (which had its own drawbacks). In the second it was radio-controlled, with the driver manually steering and keeping the throttle low enough as to enable data collection. The disadvantage of both of these techniques is that they make it extremely difficult to perform the circling behaviors needed to get unambiguous bistatic scattering profiles of targets.

Lessons Learned: GPS Navigation

As shall be discussed below, an accurate navigation solution is important for understandable signal processing. While the bistatic configuration precludes many of the techniques used for data-driven navigation in SAS for underwater platforms, the goal was to leverage GPS (which is unavailable to AUVs) to reduce the uncertainty. Unfortunately, several problems with the low-cost GPS solution (rather than an INS) presented themselves after the experiment. First, while the source platform was anchored, it did drift and turn with the wind, meaning that a single location was insufficient, and the onboard GPS needed to be used. Second, there were lever arm and relative rotational/positional uncertainties between the GPS and source/receiver array on both platforms. Third, there appeared to be an unknown bias in the recorded GPS positions. Fourth, and most problematic, the GPS units appeared to have internal filters that smooth the GPS solution: when the receiver platform would accelerate, the GPS position would appear to lag the likely true position for a considerable time. Had automated, mow-the-lawn transects been possible, the positional data may have been recoverable; however, with the manually driven JetYak the positional uncertainty was too high.

The consequences of this uncertainty may be seen in Fig. 12, where the acoustic direct blast (source-to-receiver) is visible as the earliest (topmost) bright return on each ping. The range-to-source is marked out in red; once sound speed and clock synchronization issues are taken into effect, this should correspond to the arrival time of the direct blast. In other words, with a proper position fix for the source and receiver, the direct blast signal and range-to-source plot should perfectly overlap. Instead, there are times where the predicted and observed arrival times match, but the predicted time sometimes leads and sometimes lags the observed. Considerable effort was made to try to remedy this apparent GPS error, but in the end there were too many unknowns associated with having two separate GPS systems, each of which has their own errors, biases, and internal filters.

Lessons Learned: Beamforming, mapping, and delay estimation

As was mentioned above, Fig. 12 shows the expected arrival times of reflections from the three targets as well as the direct blast. While there are suggestions that we are observing bistatic scattering from the target field, the positional (and thus arrival time) uncertainty makes this difficult to verify. An additional complication arises from what appears to be multipath from the direct blast, and bistatic scattering from a shallow environmental feature from the Southwest of the target field. Additional attempts to localize the targets included directional beamforming; looking for strong echoes from directions other than in the source direction, which would indicate bistatic scattering from the environment and targets. The results can be seen in Fig. 13, where the expected angle-of-arrival relative to the array is plotted for various targets vs. received directionality (polar beamformed data summed across ranges). The direct blast has decent correlation with the predicted angle of arrival (red plot), indicating that the heading estimate for the platform behaved reasonably well, but there are also no clear signals from the targets. There are indications of bistatic scattering from other directions, again likely the environmental feature.

Finally, we tried generating an incoherent map of the region in a manner similar to time-delay synthetic aperture sonar. This data product (Fig. 14) shows the bright region to the Southwest, but again no clear indications of scattering from the targets. It should be noted that this data product in particular suffers from navigation error.

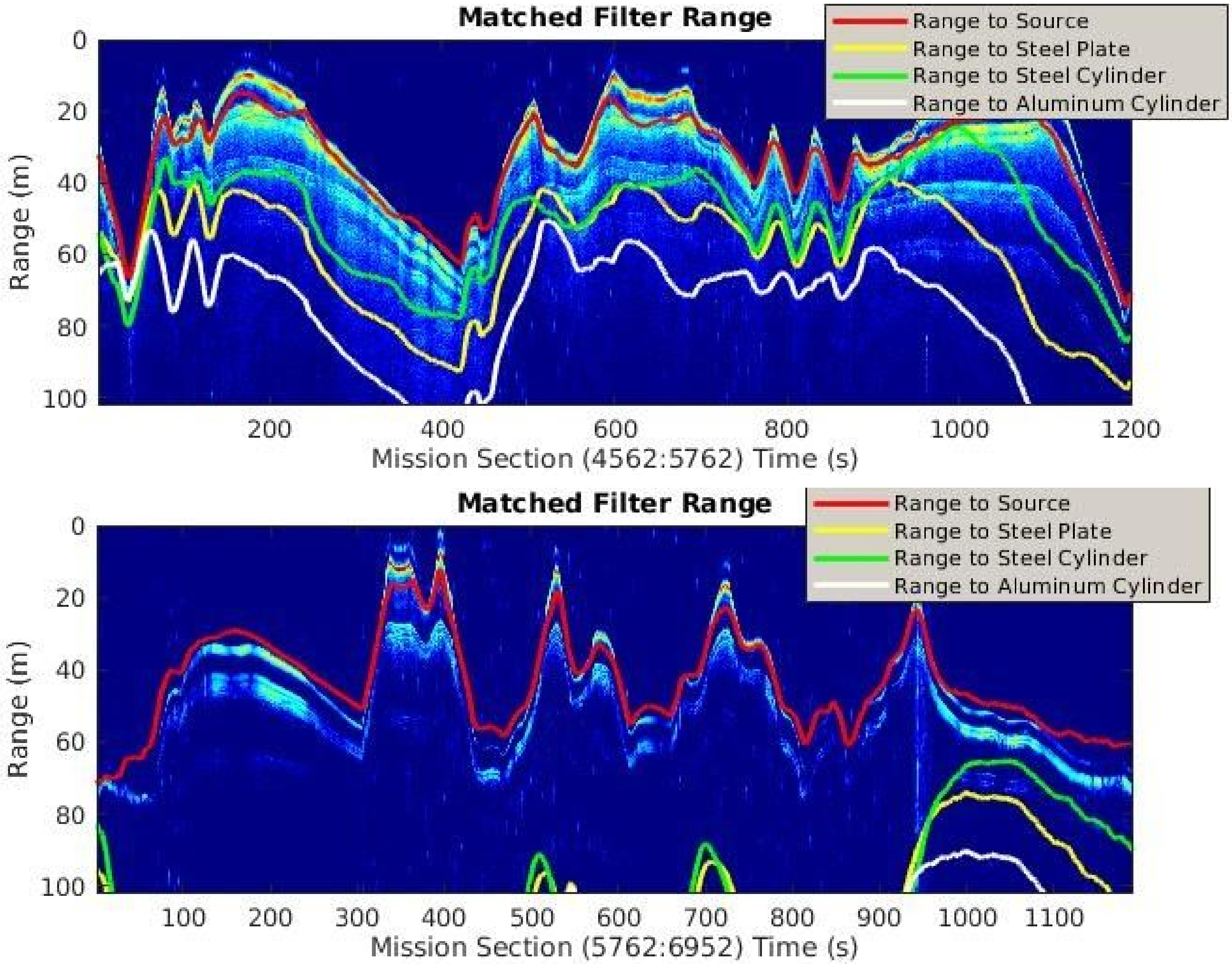


Fig 12. Pulse compressed echo data for two missions. The predicted range to various targets is shown.

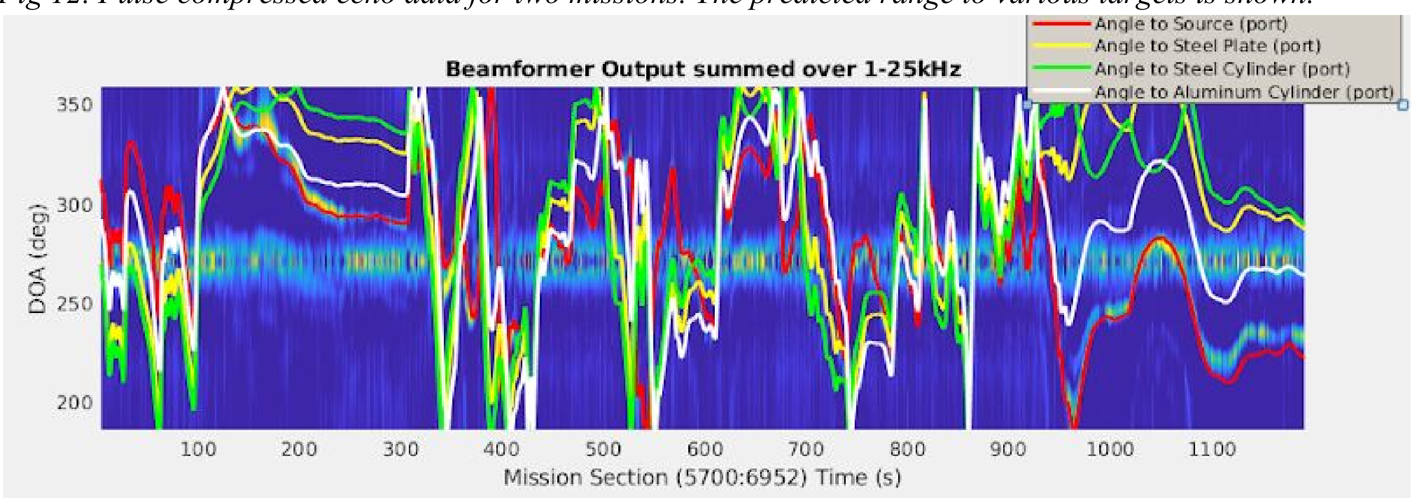


Fig 13. Normalized directional map of beamformer output (colorbar) summed across all ranges. Expected angle to various targets is shown. Note that there is a 180 mirror due to starboard-port ambiguity with a linear, unbaffled receiver array. The direction of the direct blast matches fairly well, but no other targets are clearly visible. The spike at 270 deg is likely engine noise picked up by the array at end-fire.

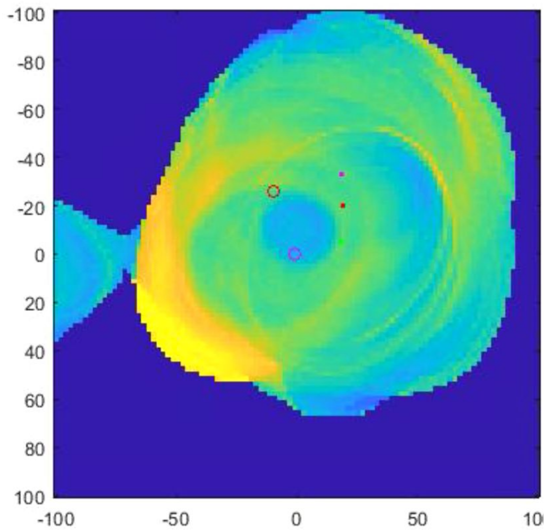


Fig 14. Results of backprojecting incoherent data to a low-resolution grid, units are in meters Northing and Easting. The red and purple rings are the receiver and source, respectively. The three points represent the locations of the targets. The direct blast has been timegated out, and the scattering intensity is normalized by the area coverage to remove the effect of overlapping scans. There is no strong indication of the targets, but there is considerable scattering from the Southwest; this is likely the source of most of the bistatic echoes seen in the other data.

Summary of Results

In the end, we found no conclusive evidence of bistatic scattering from the target field experiment. The failure to localize these targets likely resulted from a combination of (1) a relatively low-power omnidirectional source paired with a noisy receiver platform (2) a lack of tight integration between the acoustic systems, the platforms, and the GPS navigation systems, and (3) major navigation uncertainties related to the low-cost GPS systems used. While these issues may be mitigated with further engineering, there are several additional caveats about using bistatic scattering for target localization. In the simulation study, the accuracy of classification in the relatively simple "trailing transect" multistatic study was poor compared to the fixed-source-bistatic and monostatic cases. While physically separating the source and receiver may have some advantages, the mechanical, electrical, operational, and acoustic processing complexities introduced by bistatic and multistatic systems call into question whether there is actual added value at this time. Finally, the navigational uncertainties introduced by having multiple platforms is further compounded by the fact that the decoupled platforms lose many of the data-driven navigation techniques necessary to proper image formation in monostatic systems (notably redundant phase centers). However, better controlled experiments with better-integrated systems would go a long way to addressing the questions of the efficacy of mid-frequency bistatics: and bistatic features observed in this work (e.g. crossover from backscatter to forwardscatter) might be targeted in future experiments on UXO detection and classification. Our conclusion is that while the low-cost off-the-shelf systems did not provide high enough quality data to demonstrate bistatic sensing using the loosely integrated surface platform in this SEED project, there may be potential in the method with additional engineering and integration.

Implications for Future Research and Benefits

The hope was that this technique would be found to be an effective option for low-cost UXO detection/classification. Our key findings for carrying forward are that better integration, navigation, sound source selection, and a quieter low-cost platform would be required to make this technique feasible. The JetYak with gasoline engine is loud, coupling both acoustic noise and mechanical vibration into the array not see in the earlier array data. The attempt to transect the radiation pattern for classification was not effective for multistatic classification: moving around target to capture scattering pattern was more effective. The most interesting feature observed in the data is the presence of forward versus backscatter visible in data to find targets: when the receiver is in the backscatter direction of the source-target path, the target scatter is easier to pick out from multipath. To be an effective real-world tool, the engineering issues uncovered in this work would need to be addressed: vehicle noise, source replica quality, navigation quality, tightly integrated acoustic sensors, and behaviors that highlight and exploit the forward-backscatter features.

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