EXECUTIVE SUMMARY

Shallow Water Lidar for Target Morphology: Impacts of Surface Roughness and Turbidity

SERDP Project MR18-1459

NOVEMBER 2019

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ACRONYMS AND ABBREVIATIONS

ASTRA	Atmospheric & Space Technology Research Associates LLC
ASTRALiTe	ASTRA Lidar Technologies
AUV	Automated Underwater Vehicle
DVL	Doppler Velocity Log
EMI	Electromagnetic Induction
GPS	Global Positioning System
JONSWAP	Joint North Sea Wave Project
lidar	Light Detection and Ranging
LLSS	Laser Line Scanning Sensors
LBL	Long Base Line
MCLST	Monte Carlo Lidar Simulation Tool
MR	Munitions Response
NTU	Nepholometer Turbidity Units
ROV	Remotely Operated Vehicle
RTK-GPS	Real Time Kinematic Global Positioning System
SEED	SERDP Exploratory Development
SERDP	Strategic Environmental Research and Development Program
SON	Statement of Need
USBL	Ultrashort Baseline
UXO	Underwater Unexploded Ordnance

ACKNOWLEDGEMENTS

The ASTRA Lidar Technologies (ASTRALiTe) team would like to thank the support from Dr. Herb Nelson in providing guidance and feedback on our project. Sarah Barlow has also been of great help. The project has also benefited from the support by the Atmospheric & Space Technology Research Associates LLC (ASTRA) team whose efforts and dedication made many of the flight opportunities possible. The Applied Research Lab at the University of Hawaii and the State of Colorado also provided support which benefited the results of this project.

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1.0 INTRODUCTION

As described in the Statement of Need (SON) in the Munitions Response (MR) program area, MRSEED-18-S1: Detection, Classification, and Remediation of Military Munitions Underwater, the problem to be addressed is to develop technologies to detect, classify, and remediate military munitions found in aquatic environments. A specific need is for technology to operate in depths less than 5 meters: where munitions of interest may be found in a wide variety of aquatic environments, such as ponds, lakes, rivers, estuaries, and coastal areas; where munitions are likely to be encountered by the public; and where mobility of munitions is expected to be an issue. Target morphometry (the ability to accurately determine the dimensions [length, width, and height] of targets identified compared to the known dimensions of these same targets) and target positioning (the ability to accurately determine the specific location of targets) are primary methods for reacquisition and remediation of underwater unexploded ordnances (UXOs).

Sensors considered previously for addressing this need include electromagnetic induction (EMI), magnetic, optical, sonar/acoustic, chemical sensors, and laser line scanning sensors (LLSS).

Platforms include autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), and towed arrays. Navigation and positioning technologies include long base line (LBL), ultrashort baseline (USBL), Doppler velocity log (DVL), real-time kinematic global positioning system (RTK-GPS), and inertial navigation technologies.

Many acoustic systems, such as high-frequency towed or hull-mounted side scan or multi-beam sonar systems, do not perform optimally in water depths shallower than 5 meters where issues associated with multipath, narrow beam widths, navigation and positioning with waves, and currents limit performance. In these shallow depths magnetic and EMI systems that crawl, or are towed across the bottom, are employed but their effectiveness is limited in resolution, noise contamination, and operations. Optical systems producing 2-D imagery have been demonstrated, as have LLSS. **However, these systems, along with the others, require submergence in water, and these shallow regimes create unique challenges in access, navigation, deployment, viewing, and sensor standoff distance. Furthermore, changing bottom topography or obstructions pose a risk to equipment and personnel in this dynamic shallow-water environment.** Thus, new technologies need to be explored to adequately address this challenging problem; the solution will likely need to operate out of the water.

An above-water lidar (Light Detection and Ranging) system is the proposed solution and this SEED (SERDP [Strategic Environmental Research and Development Program] Exploratory Development) project investigates the practicability of applying such a technique under conditions of wavy surfaces and turbid water.

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2.0 OBJECTIVES

The main objective of the SEED research effort is to investigate the effects of water surface roughness and turbidity on the performance of an above-water lidar technique in detecting and classifying underwater objects in shallow waters (< 5 meters). The technical objectives of the SEED grant are specified by the following tasks/criteria in the order they were carried out. These deviate slightly from the original task list to better organize activities and results in this report.

Task 1) Incorporate Water Surface Roughness into Lidar Models: This task required advancing lidar simulations to evaluate theoretically how surface waves will affect lidar performance.

Task 2) Incorporate Water Turbidity into Lidar Models: This task required advancing lidar simulations to evaluate theoretically how water turbidity will affect lidar performance.

Task 3) Measure Effect of Turbidity: This task required a controlled lidar experiment of depth measurements while introducing known properties of suspended particulates to evaluate optical propagation through particles of known size and concentration.

Task 4) Measure Effect of Waviness of Water Surface: This task required the construction of a small wave tank and lidar detection system to perform controlled indoor experiments that illuminate the effects of wave amplitude and frequency on the lidar's accuracy and precision in describing underwater objects.

Task 5) Outdoor Environmental Test: This task required the deployment of a prototype lidar system over water bodies of various conditions to demonstrate outdoor capabilities.

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3.0 TECHNICAL APPROACH

The technical approach used a variety of materials and methods involving simulation, controlled lab experimentation, instrument prototyping, and outdoor experiments. Simulations included a Monte Carlo scheme that followed photons as they propagated through turbid media and a ray trace scheme to map the effects of surface reflection, transmission, and refraction due to wavy surfaces. Indoor experiments were carried out using the lidar technique with a graduated cylinder and a water tank to determine turbidity and surface wave effects on lidar measurements. A prototype drone-based, scanning topographic/bathymetric lidar system was also used to demonstrate outdoor capabilities.

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4.0 RESULTS AND DISCUSSION

The results of the numerical and experimental activities are combined to explain the effects of surface waves and turbidity on lidar performance. Surface wave effects are summarized by findings related to the surface wave-lidar model and wave tank experiments. These findings are listed below using the identifier "W#" to indicate water-surface findings. Turbidity effects are summarized by findings related to Monte Carlo modeling and suspended-particle lab experiments. These findings use the identifier "T#". Outdoor experiments are presented that demonstrate the potential capability of this technology to detect underwater munitions in shallow waters (< 5 m). These measurements experienced both wavy and turbid conditions and provide empirical evidence for the technique's ability to operate in environments relevant to munitions response. These are identified using "O#".

4.1 SURFACE WAVE EFFECTS

Finding #1 (W1): A surface wave-lidar model was developed to assess the influence of waves on the lidar's ability to determine the dimensions of an underwater object. The model incorporates a realistic ocean surface-wave model with a lidar ray-trace scheme that simulates the lidar beam interaction with a wavy surface. The model has flexibility to produce a range of wavy surfaces and lidar parameters.

Finding #2 (W2): A wave tank was built and combined with a nadir-viewing lidar to observe the effects of wavy surfaces on the actual retrieval of range information from the backscattered lidar returns. The wave tank has flexibility to generate a range of wavelengths, from 0.12 to 0.7 meters, and amplitudes up to 4 centimeters. These waves can be simulated by the surface-wave model.

Finding #3 (W3): A lidar target morphometry test of a submerged brick using the wave tank at a specific wavelength and amplitude illustrated a spread in range values and cross-range values due to surface waves that blurred the edge, spread the top, and introduced a slight bias towards longer ranges – See Figure E1. These effects were replicated by the wave model and identified that refraction through the wave slope (ratio of wave amplitude to wavelength) was impacting the cross-range error the most, while the changing water path length due the crest and the valley of the wave caused the spread in range estimates. The range bias to longer range is attributed to refraction where a nadir-viewing lidar will always increase in range when experiencing a slope other than flat. These results will vary depending on the wave representation and particularly on the ratio of amplitude to wavelength.

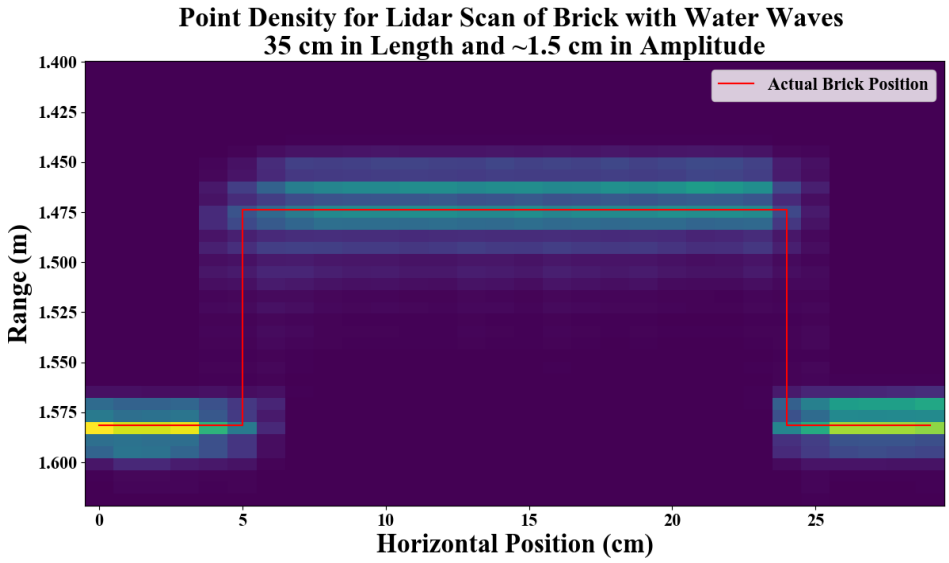

Figure E1. Lidar Scan of Submerged Brick in 26 Centimeters of Water.

The number of detections with range is displayed using a normalized color mapping. The actual brick shape is also shown for reference in red.

Finding #4 (W4): The absolute estimate of range errors for all wave conditions is highly dependent on the lidar parameters and the water surface wave properties. The effects of refraction due to changing wave slope and time delay due to wave amplitude changes are clearly the dominant factors in producing variability in range and cross range directions. The effects are observed in the data and captured by the wave-lidar model – see Figure E2. Specific conditions will need to be known to fully quantify the effects but a conservative uncertainty of several centimeters (< 5 cm) in shallow waters (< 5m) is the expected effect of surface waves on lidar target morphometry.

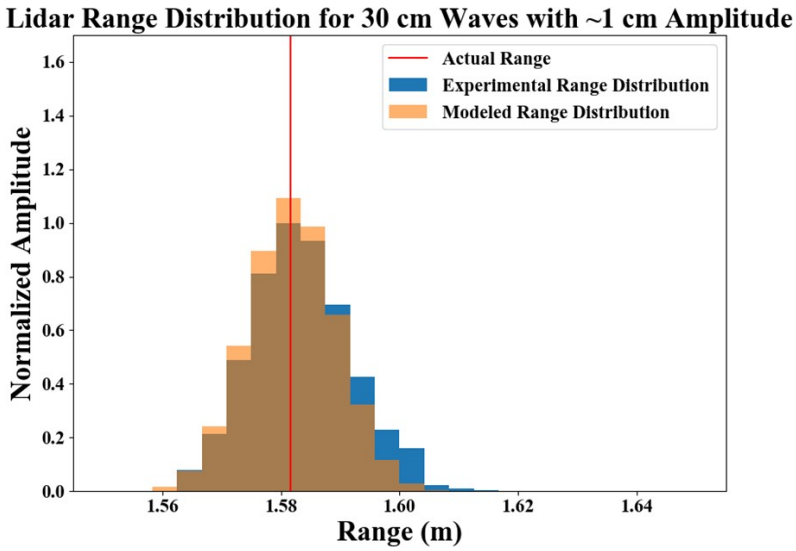

Figure E2. Comparison Between Modeled Lidar Range Distribution and Experimentally Measured Lidar Range Distribution for Lidar Aimed at Tank Bottom with 30 cm Waves at ~1 cm Amplitude.

Finding #5 (W5): Through a series of wave tank experiments with varied wavelengths and amplitudes (22 different tests), the surface wave-lidar model was validated and can serve as a useful tool to evaluate lidar performance and help optimally design lidar parameters given an actual ocean wave spectrum – see Figure E3.

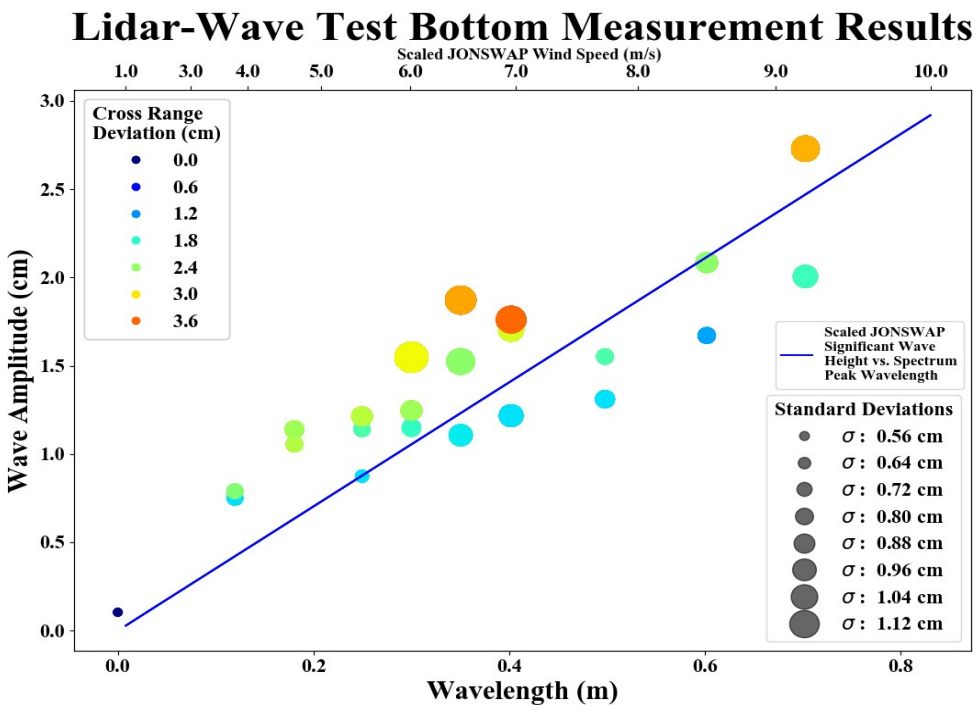

Figure E3. Graph Showing Many of the Results for 22 Different Wave Tests of Different Wavelength and Amplitude.

Each scatter plot point is its own wavelength and amplitude. The size of each point refers to its increase in standard deviation from a still water distribution. The color of each point represents the horizontal deviation caused by the waves. The Joint North Sea Wave Project (JONSWAP) significant wave height and peak spectral wavelength are also plotted with the scaling factor of 70 applied. The wind speed that corresponds to each JONSWAP peak wavelength is also shown at the top of the plot.

4.2 TURBIDITY EFFECTS

Finding #6 (T1): A 3-D Monte Carlo model, the ASTRALiTe Monte Carlo Lidar Simulation Tool (MCLST), was developed to simulate laser light propagation through turbid water. Various lidar (beam size, divergence, polarization state, wavelength) and environmental (particulate size, particle density, index of refraction, absorption) variables can be adjusted in the model to fully explore the trade space of lidar parameters and environmental conditions. In the simulations, photons from the lidar laser pulse are propagated through the water medium with uniformly distributed particulates of different particle size relative to the laser wavelength and each photon is tracked and counted to understand how the suspended particulate matter effects the laser light.

Finding #7 (T2): An experimental setup was built to validate the turbidity propagation model by mounting a stationary lidar system over a graduated cylinder and carefully controlling turbidity levels for specific particle sizes.

Finding #8 (T3): Experiments were conducted to match the model's conditions as closely as possible. A calibrated quantity of particles of uniform size and material are incrementally introduced into pure water and thoroughly mixed. Five different particle sizes were tested whose scattering regime ranged from Rayleigh-Mie-Geometric scattering. For verification, the water turbidity was measured by a Nephelometer and recorded in Nephelometer Turbidity Units (NTUs).

Finding #9 (T4): The model simulations illustrated the adverse effect of beam spreading caused by the presence of suspended particulates. Using the size parameter as a reference, the spreading of the beam was greater for particles with size parameters closer to one (i.e., small particles-weakly Mie scattering) than for size parameters closer to one hundred (i.e., larger particles-Geometric scattering). These particulate scattering aspects will affect the ability to detect and classify objects, as a spreading beam will make small objects more difficult to discern and, for a given lidar receiver field-of-view, the number of photons received for detection will be reduced as many photons are scattered out of the path before returning to the lidar.

Finding #10 (T5): Congruently, the depth penetration was found to be size-parameter dependent with larger particles allowing for greater depth penetration than the smaller particles. The model showed, through simulations of the scattering phase function, that the larger particles produced much more forward scattering, keeping the photons in line with the lidar receiver field of view – see Figure E4. This benefits detections to deeper waters than if the water column was populated with smaller particles of equal concentration.

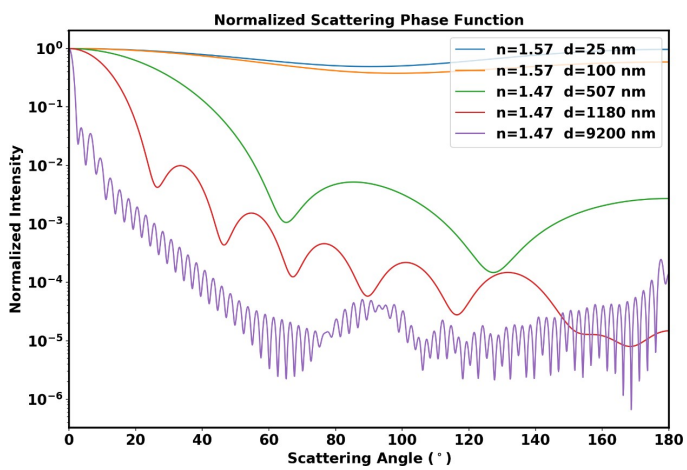

Figure E4. Lidar MCLST Simulation of the Normalized Scattering Phase Function at 0.532 Micron for Different Particle Sizes Used in the Lab Experiments.

Finding #11 (T6): Empirical results from the turbidity experimental setup confirmed the findings of the model with larger particles causing less light loss than the smaller particles for the same concentration. However, the outcomes can be less intuitive when the size parameter lies between weak and strong Mie scattering regimes. As simulated, the scattering efficiency and scattering phase function are important parameters for determining laser light propagation and these depend on size parameter, particle index of refraction, particle concentrations and related optical properties. These properties will play an important role when working with particles in between weak and strong Mie scattering regimes (essentially between 0.01 and 1 micron particles when illuminated by 0.532 micron light) – see Figure E5.

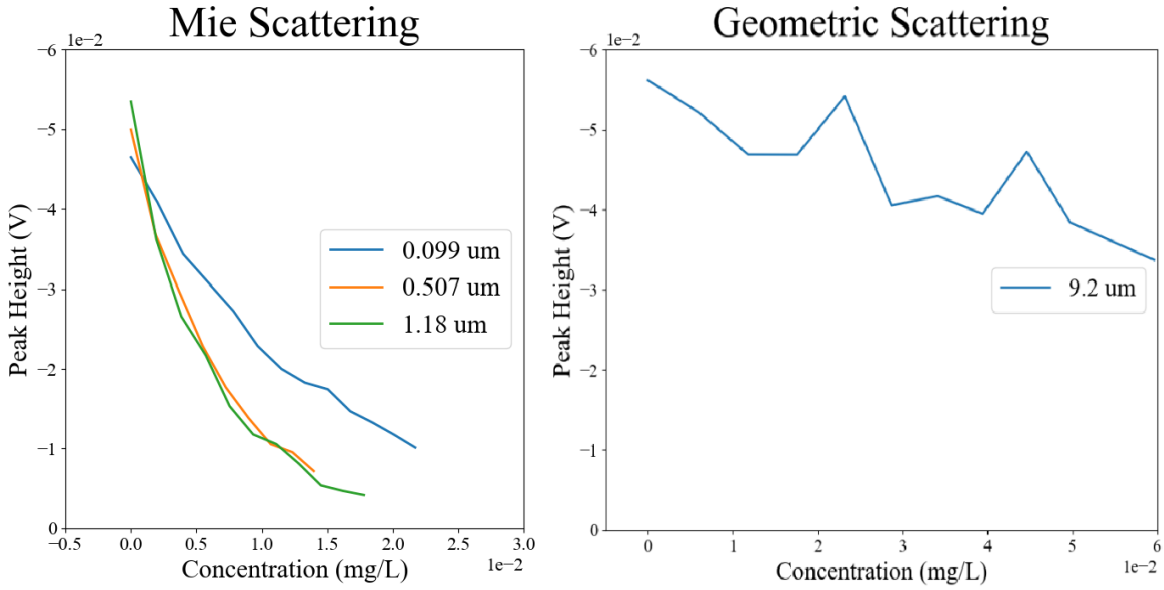

Figure E5. Bottom Return Signal Voltage as a Function of Particle Concentration for Four Discrete Particle Sizes.

Sizes demonstrate the scattering regimes of weak and strong Mie scattering models and Geometric scattering. Note the horizontal range of the concentration for Geometric Scattering is extended to 0.060 mg/L.

Finding #12 (T7): The lidar's optical detection of signals from underwater objects is favored by forward scattering of light caused by larger suspended particulates. These photons will remain in the lidar's field of view and contribute to the population of photons scattered back to the lidar receiver by the object. Thus, particle size and particle concentration matter when considering the lidar depth performance. A Nephelometer measures extinction at a given wavelength at a 90-degree scattering angle and thus does not capture all aspects of how lidar is influenced by turbidity. However, the straightforward Nephelometer measurement serves as a common reference by which to relate lidar depth performance in different water bodies (as will be demonstrated in the outdoor experiments).

4.3 OUTDOOR RESULTS WITH BOTH TURBIDITY AND WAVES

Outdoor experiments were carried out using a prototype drone-based, scanning lidar system in several different environments.

Finding #13 (O1): Outdoor experiments with a prototype drone-based, scanning topographic / bathymetric lidar were carried out for different water bodies under different surface wave and turbidity conditions. Calibration targets were placed in the water and mapped by the lidar – see Figure E6.

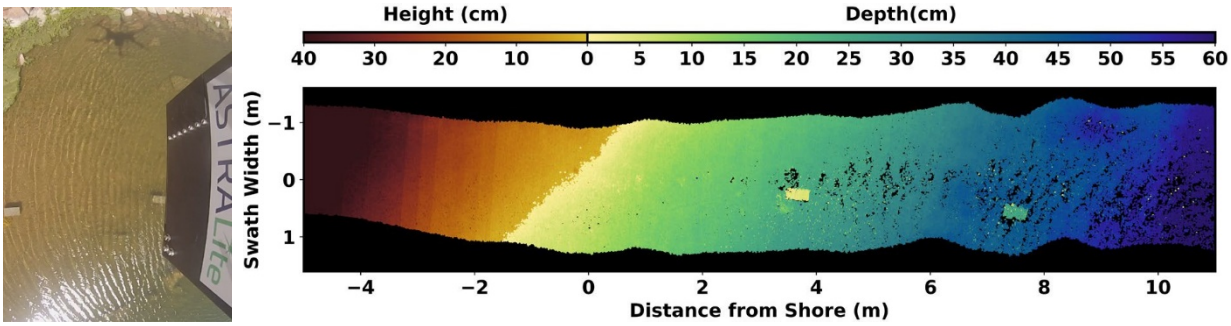

Figure E6. Drone-based, Scanning Topo/Bathy Lidar Measurements Over a Shoreline with Two Cinder Blocks Submerged in the Water.

Finding #14 (O2): The outdoor experiments identified known targets in shallow water (< 5 m) with centimeter-level precision illustrating in great detail natural features such as individual coral within the coral reef bed – see Figure E7.

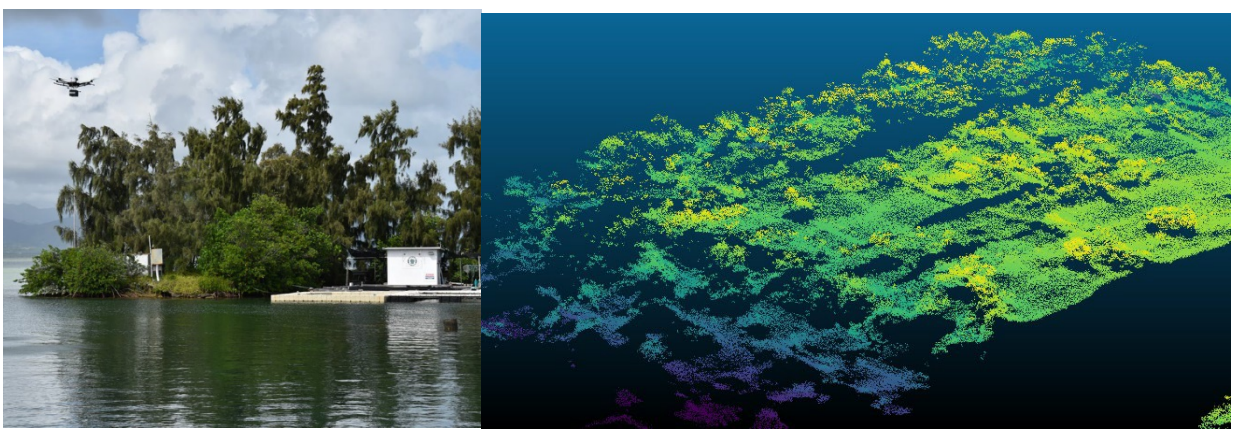

Figure E7. Drone-based Scanning Topo/Bathy Lidar Flying Over a Lagoon with a Coral Bed (left). The Resultant 3-D Point Cloud of the Coral Bed Displaying Great Detail with the Color Variation Indicating depth from Water surface (yellow is about 1-meter Depth and Dark Blue is About 4-meter Depth)

Finding #15 (O3): The outdoor experiments experienced a range of turbidity levels in different water bodies. These levels were recorded by the same Nephelometer and an empirical curve of lidar depth to turbidity level was determined – see Figure E8. As expected through modeling, the lidar depth performance followed a power law distribution with greater depth for decreasing NTU values.

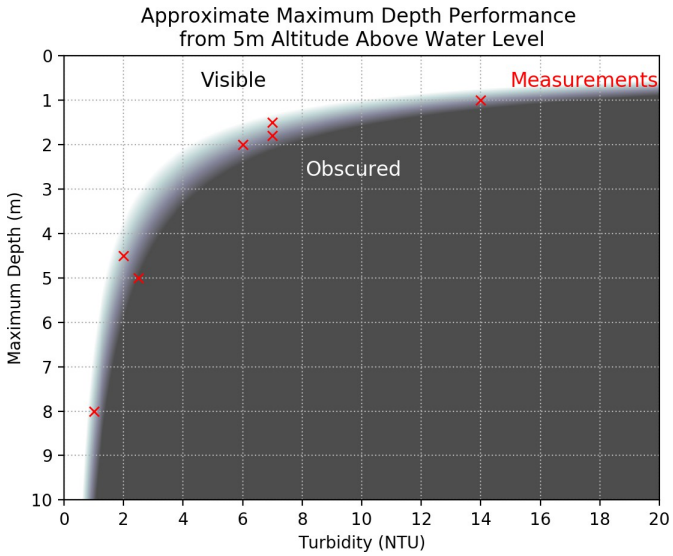

Figure E8. Lidar Maximum Depth Performance in Meters with Turbidity Levels in Nephelometer Turbidity Units (NTU).

The red X's indicate actual depth measurements with measured NTUs from outside experiments.

Finding #16 (O4): The outdoor experiments experienced a range of wave conditions. A sample data set off the coast of Oahu, HI consisted of breaking shore waves and wind-driven waves further from shore – see Figure E9. The lidar was able to map the sea floor in most of these wavy conditions and resolve detailed descriptions of 2-meter rocks in 4 meters of wavy surface water.

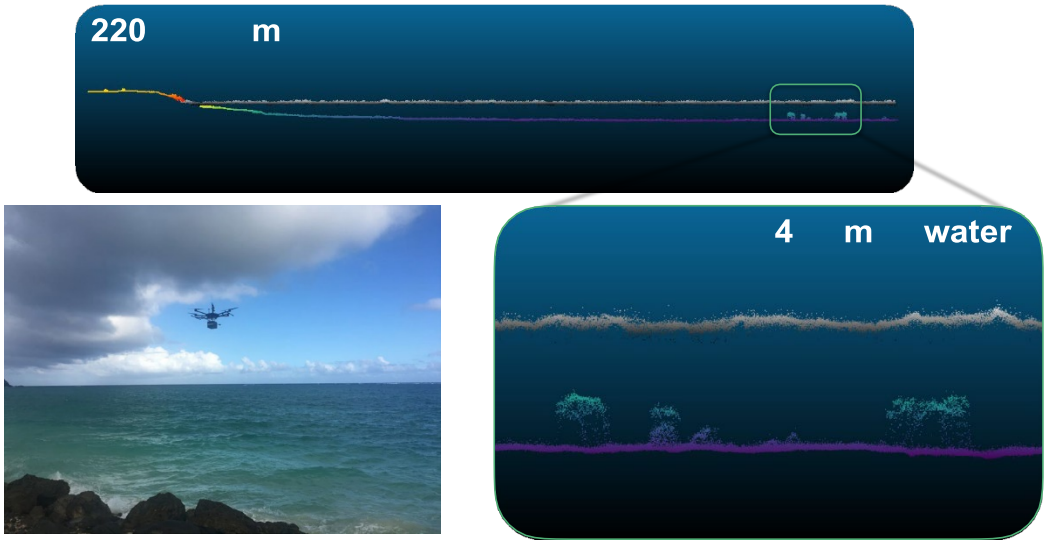

Figure E9. Outdoor Experiments Under Wavy Surface Conditions Off the Coast of Oahu.

The water surface conditions are shown in the lower left with the lidar mounted and flying on a drone above the surface. The top panel shows lidar measurements producing a 3-D mapping of land, the break wall, and the bay. The insert in the lower right provides detailed mapping of rocks submerged in about 4 meters of water depth.

The only limiting situation occurred when foam from breaking waves scattered laser light preventing bottom detections and increased turbidity caused by breaking wave action.

Finding #17 (O5): The prototype, drone-based scanning topo/bathy lidar has proven the technique can work in waters expected for munitions response and, through the improved understanding of performance in wavy and turbid waters, a system could be optimally designed for such applications.

5.0 IMPLICATIONS FOR FUTURE RESEARCH AND BENEFITS

The findings from our modeling, lab and outdoor experiments have established that our lidar technique is practicable for detecting and identifying munitions in waters less than 5 meters deep with a total uncertainty in both vertical and horizontal resolution of < 10 centimeters. This total error is a conservative empirical precision estimate based on the culmination of error introduced by the lidar (<1 cm), platform (<5 cm), and water conditions (~1-5 cm). We understand the impacts of surface conditions and suspended material within the column on the lidar performance to properly assess its ability under different environmental scenarios. We are confident that through future research we can transition these prototype findings to an operational, drone-based, topographic and bathymetric lidar system designed specifically for munitions response.

Future Research. The SEED grant has significantly advanced the lidar technique to a level of practical use for shallow water munitions response. However, there remains several areas of research needed to make the system operational and optimal. The research involves considering further environmental conditions and system design.

Although we have addressed the effects of surface waves and turbidity on the lidar performance, other environmental issues can impact lidar operations, such as sunlight and target reflectivity. Target reflectivity has a direct effect on lidar detectability by impacting the amount of light backscattered by the object. However, we employ polarization tactics in our lidar systems which also depend on the target's polarization scattering properties. This would be an area of research to explore and better understand how targets respond in different planes of polarization.

Sunlight degrades our system performance by lowering the signal to noise in detecting under water objects. Direct and diffuse sunlight scatter have different effects on the system and methods need to be pursued to diminish sunlight scatter from reaching the lidar detectors. This would require research in the sunlight scatter expected and methods to employ in the lidar system to reduce this effect.

Another potential research area is to correct for wavy surface refraction by using the lidar to map the water's surface and fit a grid by which to correct the bottom returns based on the empirically determined wave properties.

Future research is also needed in system design for operations in such conditions as rain, humidity, heat, spray, and wind. The prototype has demonstrated capability but flight time, flight altitude, scanning coverage, measurement capability, and related design-to specifications are needed to be researched and mapped to the munitions response program's requirements. For example, research into reducing size, weight, and power would lead to longer flight times.

Operating at higher altitudes would increase coverage but would require research into the design to improve performance as signal from bottom targets become weaker with greater distance from the water surface.

Integrating a camera system for data fusion between lidar and camera imagery would also be highly desirable and could enhance the measurement outcome.

Finally, machine learning techniques on the retrieved lidar point cloud should be researched to automatically identify features such as water surface, water column, and underwater terrain or objects in the data and to produce real-time maps.

Benefits. The lidar-wave model and the turbidity model have proven to be very helpful in understanding observed behavior in underwater target morphometry for wavy and turbid conditions. In fact, these models will be instrumental in optimizing the lidar instrument design. Airborne lidar bathymetry parameters could be varied and tuned such that optimal performance is achieved for a given expectation of ocean conditions and environment.

The findings from this SEED grant are highly relevant to SERDP munitions response program, Department of Defense, and science communities because this novel, above-water lidar technique could provide highly accurate ranging and mapping of submerged objects with centimeter-level precision, identify land-to-water transitions, provide accurate descriptions of bottom surface topography, object detection, object characterization, and precise water depth estimates, while eliminating risks associated with deploying traditional submerged sensors.

This lidar capability can be highly complementary to other SERDP techniques and can help provide a more complete description of the entire scene – particularly in shallow water. Like terrestrial lidar systems that determine indicators of prior munitions by detecting craters, aiming circles and other persistent surface features, the lidar technique could explore underwater bottom surface indicators of munitions activity. Providing such indicators may prove useful for quickly scanning large areas to identify likely munitions sites that will require further detailed investigation. Furthermore, mobility modeling of munitions is dependent on environmental parameters, such as water depth and bottom and top surface morphologies, which the lidar can provide as model input. The lidar measurements can also be used as a tool for designing, planning and executing surveys. An initial survey using the lidar technique can quickly provide data and insights for follow-on survey decision making, including reduction of risk to divers and other assets.

The results further address technology advancements by establishing a new technology with the ability to detect, range, and classify underwater objects with high vertical and horizontal resolution (< 10 cm) in shallow water (<5m) – without contacting the water. Relative to existing lidar systems, the resulting lidar provides unprecedented depth resolution and horizontal resolution for much improved hydrography, thus making survey results more useful. It also uses less expensive and less complex lidar components, which reduces the system cost and cost compared to other bathymetric lidar systems. The technology advancements have also led to reductions in size, weight, and power allowing for ASTRALiTe to develop the first drone-based, scanning topographic / bathymetric lidar.