Final Report

Acoustic Tool to Measure Oil Slick Thickness at Ohmsett

For

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DISCLAIMER

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EXECUTIVE SUMMARY

Detecting oil in and under ice is becoming more important as oil exploration expands in the arctic environment. The oil industry tries to ensure safe operations, but accidents and spills still occur. Concerns were heightened due to recent spills and desire for increased exploration in the arctic and throughout the world’s oceans. Typically, such spills are assessed and tracked by visual surveillance from planes and boats. However, it is difficult to measure oil thickness and other parameters from these platforms. Thus, it is desirable to have a remotely operated vehicle (ROV) or autonomous underwater vehicle (AUV) outfitted with sensors that travels under slicks to track location, measure thickness, etc. to enable the spill response community to focus their clean up on the thickest portion of the oil slick. Along the path to developing ROV and AUV platforms for use in the ocean to measure slick thickness, it is valuable to provide the slick thickness ability to Ohmsett to increase their capabilities as well as provide a test platform for future developments of other sensors and for field applications.

Acoustic methods are well suited for measuring the thickness of oil slicks because they have little difficulty traveling through thick oil, and can potentially be deployed from ROV or AUV platforms many meters below the oil slick. The objective of this project is to develop an acoustic ROV to measure the oil slick thickness in ice fields at Ohmsett. We accomplished this task by designing and fabricating a first-of-a-kind Acoustic Slick Thickness ROV for use in Ohmsett’s wave tank. It consists of remote control underwater tracks and several acoustic transducers for real-time measurements of the slick thickness and underwater cameras for real-time viewing and recording of the underwater environment.

We used the Acoustic Slick Thickness ROV to measure the thickness of various oil slicks including Arctic North Slope (ANS), Hibernia, Calsol, Hydrocal, and Diesel. In addition we were able to accurately measure the thickness of oil under ice and measure the thickness of a 2 mm slick on the surface in a sea state with waves that were 6 inches high.

The Acoustic Oil Slick Thickness ROV we developed during this project enhances Ohmsett’s ability to serve the community by enabling them to measure the thickness of an oil slick on the surface of the wave tank in various scenarios both in the presence of ice and during testing without ice. The ROV also provide a platform for delivering other sensors to part of the Ohmsett tank and stream and record live underwater videos of testing. The ROV can also be used for as a test platform for future developments for applications in the open ocean.
1. OBJECTIVE

The objective of this project is to develop an acoustic remotely operated vehicle (ROV) to measure the oil slick thickness in ice fields at Ohmsett.

2. OVERVIEW

Detecting oil in and under ice is becoming more important as oil exploration expands in the arctic environment. The oil industry tries to ensure safe operations, but accidents and spills still occur. Examples where oil was released are shown in Figure 1. Typically, such spills are assessed and tracked by visual surveillance from planes and boats. Measuring the slick thickness is important because the spill response community wants to focus their clean up on the thickest portion of the oil slick. However, it is difficult to measure oil thickness and other parameters from aerial or on water platforms. To help fill this gap we developed a remotely operated vehicle (ROV) to measure the slick thickness using acoustics. The focus of the project was to deliver the Acoustic Slick Thickness ROV to the Ohmsett test facility for their continued use. The ROV was designed around motorized tracks to allow the ROV to drive along the bottom of the wave tank at Ohmsett. The ROV can currently measure slick thicknesses smaller than ~0.5 mm to thicker than 100 mm. Precise ranges depend on the oil type and the operating acoustic frequency. Figure 2 shows the final configuration of the Acoustic Slick Thickness ROV and the associated slick thickness map for ANS oil in a surrogate ice field. The color scale represents the thickness of the slick in millimeters with red equal to 4 mm and light purple resenting the surrogate ice.

We tested the ROV in our labs and at Ohmsett under various conditions including oil-ice fields, with waves and during ASTM F 2709-08 skimmer testing. We performed measurements on Hibernia, Arctic North Slope Crude oil and several refined petroleum products including Calsol, Hydrocal, and Diesel. We also made initial measurements showing the ability to detect oil under ice. As part of this work we performed measurements simultaneously with Dr. Yan Svejkovsky from Ocean Imaging who is

Figure 1. Photograph of oil slick extending from ice shelf [1] (left) and in slush off the Canadian East Coast in 1986 (right)
developing optical and infrared imaging methods to measure slick thickness and Dr. Toomas Alik from Night Vision labs who is using multi-spectral imaging to measure slick thickness. The goal was to provide Ohmsett with comprehensive slick thickness measurements using the combined techniques to span the range from oil sheen to several centimeters of oil. While the main application for this ROV is for use at Ohmsett to measure oil slick thickness it can also be used to carry other sensors under water and serve as a testing platform for future developments of field applications. We integrated the operation of the ROV into one software platform including the driving, data acquisition, analysis and slick visualization.

![Figure 2. Acoustic Slick Thickness ROV and associated slick thickness map in surrogate ice field.](image)

### 3. DEVELOPMENT OF ACOUSTIC SLICK THICKNESS ROV

The main activities in the project were to design and fabricate an ROV to enable acoustic measurements of slick thickness at Ohmsett, test the ROV at Ohmsett under various conditions and deliver the ROV to Ohmsett staff. Subsequent sections will describe these activities.

#### 3.1 INITIAL DESIGN

The Acoustic Thickness ROV was built around waterproof motorized tracks manufactured by Inuktun. They are rated to depth of 100 feet (30 meters), have a maximum speed of 32 feet per minute (10 meters/minute) and can each pull up to 100 pounds (45 kilograms). A photograph of the tracks in our lab and at the William & Mary pool are shown in Figure 3. The tracks are controlled by numerous electronic components as show in Figure 4. The components in the green boxed region control the tracks and include a Galil motion controller, two Trust Automation linear amplifiers to power the tracks, and three power supplies to power the amplifiers and the motion controller. The Trust automation linear amplifiers are important because their low noise characteristics minimize electronic noise that could interfere with our acoustic
Figure 3. ROV in various configurations in our lab in the left photo and at the William & Mary pool in the two right photos.

measurements. Also in the instrument box is circuitry to measure the temperature, and the acoustic pulser-receiver manufactured by Peak NDT.

Using these components and InspectionWare programming platform from Utex Inspection we developed the software and graphical user interface (GUI) to control the motion of the ROV, collect the data, analyze the data and display the results all within one software platform. The ROV is tethered to the electronics by ~130 feet of cables and the controlling computer is connected to the Galil and the acoustic pulse-receiver through wireless Ethernet so that the ROV can be controlled wirelessly. We began testing the ROV in our labs and at a swimming pool at the College of William & Mary as described in the next section.

Figure 4. Motion control and acoustic components to control the ROV and measure oil slick thickness.
3.2 Initial Testing at the College of William & Mary Pool

We performed tests at the College of William & Mary pool on two separate occasions over three days. The ROV during the first test day is shown in Figure 5 scanning under a block of ice and 11 feet deep in the pool. The testing during the first day was to determine the maneuverability and water worthiness as well as the ability to scan under ice and determine the depth and location of the ice.

During the second occasion we tested over a two day period using 2 inch thick high density polyethylene (HDPE) sheets as surrogates for ice. Figure 6 shows the ROV scanning under the HDPE sheets to mimic floating ice. Two of the sheets were taped together with black electrical tape to mimic a 4 inch thick sheet of ice. These measurements were helpful to test the operation of the ROV and the maneuverability underwater, the slick thickness algorithms and to help prepare for Ohmsett.

![Figure 5. Photos of the acoustic slick thickness ROV at the William & Mary pool, scanning under ice and in the deep end in the right figure.](image1)

![Figure 6. Photos during the second session of testing at the College of William & Mary pool showing scans under plastic as a surrogate for ice. Each sheet is 2 inches thick. The left figure shows two sheets of ice taped together to achieve a thickness of 4 inches to simulate thicker ice.](image2)
3.3 Measurements of Oil Speed of Sound as a Function of Temperature

An important parameter needed to determine the slick thickness is the speed of sound of oils as a function of temperature and the strength of the reflection from the oil water interface. The next two sections describe our measurements in the lab and at Ohmsett to determine the speed of sound of various oils.

3.3.1 Lab Measurements

We performed a series of lab tests to measure the speed of sound using a set up shown in Figure 7. In this simple set up we placed an acoustic transducer at the bottom of a plastic tube and filled the tube with oil up to a known height. We first cooled the oil to ~10°C and measured the speed of sound at specific temperatures as the oil warmed to room temperature. A graph of the speed of sound as a function of temperature is show in Figure 8 from our data on Hibernia, Dorado, Rock and Canola oil along with a calculation of the speed of sound of water as function of temperature based on theoretical equations. Canola oil was also measured so that we understand how it compares to crude oils when it is used as a surrogate.

The ability to measure the slick thickness with acoustic measurements hinges on the ability to measure the reflection from the oil water interface. The strength of the reflection from the oil water interface is controlled by the difference of acoustic impedances of the water and the oil. The acoustic impedance is \( Z = \rho V \), where \( \rho \) is the density of the fluid and \( V \) is the speed of sound. The reflection coefficient is given by the following equation.

\[
R = \frac{Z_{water} - Z_{oil}}{Z_{water} + Z_{oil}}
\]

If the acoustic impedances of the water and oil are equal, then there will be no reflection from the water oil surface. The resultant reflection coefficients from our measurements are shown in Figure 9.

Using the equations from the linear fit of the speed of sound as a function temperature and densities from tables for high and low viscosity crudes we calculated the reflection coefficients as a function of temperature over the range of -15°C to 58°C. An important location is the point where the reflection coefficient equals zero. When the reflection coefficient equals zero there will not be a reflection from the oil water interface and thus measuring the slick thickness with acoustic measurements will not be possible. For the lighter crudes under the above assumptions the reflection coefficient does not cross zero until well below 0°C, while the more viscous Rock crude has a reflection coefficient of zero at ~18°C. Thus, for most crudes at temperatures at above 0°C, the reflection coefficient will be nonzero and should allow for measurements of the slick thickness.
Figure 7. Acoustic oil speed of sound measurement apparatus

Figure 8. Speed of sound in various types of oil and water as a function of temperature along with linear fits to the oil speed of sound.
Figure 9. The reflection coefficient at an oil-water interface for various types of oil based on our speed of sound measurements, the equation above and handbook values of density.

3.3.2 Speed of Sound in Oil at Ohmsett

For each oil the speed of sound was used as an input into the slick thickness calculation. In the field we improvised and set up the calibration measurement on the railing of the deck at Ohmsett for Calsol, Hydrocal and Diesel as shown in Figure 10.

Figure 10. Acoustic oil speed of sound measurement apparatus at Ohmsett.
For our measurements on the deck at Ohmsett we maintained a steady temperature for each oil by shielding the set up from the sun and collecting data as quickly as possible. These measurements at ambient temperature resulted in the sound speeds shown in Table 1.

Table 1. Sound speeds and relative viscosities for ANS, Hydrocal, Calsol, and Diesel.

<table>
<thead>
<tr>
<th></th>
<th>ANS (25.3°C)</th>
<th>Hydrocal (23.2°C)</th>
<th>Calsol (27.4°C)</th>
<th>Diesel (24.1°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound speed (cm/µs)</td>
<td>0.1384</td>
<td>0.1512</td>
<td>0.1502</td>
<td>0.1360</td>
</tr>
<tr>
<td>Grade/viscosity range</td>
<td>medium</td>
<td>medium</td>
<td>medium-high</td>
<td>low</td>
</tr>
</tbody>
</table>

### 3.4 Acoustic Transducer Beam Maps

The acoustic waves emitted from the transducers diverge as they propagate through the water. The equation below describes the beam diameter of an acoustic wave as it propagates water [2].

\[
\text{Beam Diameter} = w_0 \sqrt{\left(\frac{z (1 + b^2)}{F_0} - 1\right)^2 + b^2} \frac{1}{1 + b^2}
\]

\[
b = \frac{V_{H_2O}F_0}{\pi f w_0^2}
\]

Where \(w_0\) is the initial beam diameter, \(z\) is the distance traveled in water, \(F_0\) is the focal length of the transducer, \(V_{H_2O}\) is the speed of sound in water, \(f\) is the frequency of the acoustic wave. For the conditions at Ohmsett, the beam is expected to diverge from the 2.25 MHz, 0.5 inch diameter transducer and reach a diameter of ~ 7.4 inches at the surface of the water. Figure 8 shows the beam map results and theoretical predictions from the equation above. The predicted beam width at 2.25 MHz at the measurement distance of 30 cm was 2.8 cm and the measured beam width was 2.2 cm. The predicted beam width is likely larger because the model assumes the beam has a Gaussian shape without the side lobes observed in the experiential measurement is the right hand image in Figure 11. The left figure shows the experimental set up to map the beam of the transmitting transducer along with the theoretical prediction of the beam width from the equation above. The figure on the right shows the results of the experimental measurements at 2.25 MHz.
This diameter is important for two reasons. First, the diameter defines the region over which the signal will be spatially averaged. Secondly, the reflection from one transducer may overlap and interact with the reception from an adjacent transducer. To measure the beam size and overlap from adjacent transducers, we mapped the beam diameter in our small lab tank.

![Beam map at 2.25 MHz](image1)

**Figure 11.** The left figure shows the experimental set up to map the beam of the transmitting transducer along with the theoretical prediction of the beam width from the equation above. The figure on the right shows the results of the experimental measurements at 2.25 MHz.

3.5 **Initial Design Testing Oil and Ice at Ohmsett**

Our initial trip to Ohmsett occurred during the week of March 24 to March 28, 2014, when we tested the ROV at Ohmsett alongside Jan Svejkovsky from Ocean Imaging. Figure 12 shows photos of the ROV on the side of the deck and being deployed. Figure 13 shows the ROV under water and under an ice-oil mixture. We were able to drive the ROV along the bottom of the tank with a range of ~ 100 feet. We performed numerous runs over the week under ice and oil. During this time we also tested the deployment and retrieval of the ROV using the crane on the bridge.

![Experimental Results of Beam Width](image2)

We successfully measured the thickness of the oil slick in between the ice and were able to identify when the ROV was under open water, under oil and under ice. We also had indications that the ROV may be able to measure oil trapped under ice. Using the video from the upward looking camera on the ROV we stitched together several snapshots to obtain the composite view shown on the top of Figure 14. The two horizontal lines trace the path of the acoustic transducers as the ROV was scanned.
below the oil-ice region. The corresponding acoustic data from two channels at 2.25 MHz are shown in the bottom two panels of Figure 15. The vertical axis is the distance from the transducer, the horizontal axis is the distance along the oil-ice image and the color represents the strength of the acoustic reflection from either the oil, air, or ice surfaces with red being a large signal and blue a low amplitude signal. The measurement shows the ice varies from approximately 3 inches thick to approximately 4 inches thick. The presence of oil can be identified by the multiple reflections near the surface. One such region is indicated in purple in the lower acoustic image. The corresponding acoustic signals are shown in Figure 15 for two different regions. The slick thickness was calculated by measuring the time difference between the oil water interface and the oil air interface using the known speed of sound of the oil at the temperature when the measurements were performed.

Figure 12. Photos of the acoustic slick thickness ROV at Ohmsett.

Figure 13. Photos of the acoustic slick thickness ROV driving in open water at Ohmsett and under the oil ice field.
Figure 14. The top image is the result of stitching together multiple snapshots from the upward looking camera. The two lines indicate the scan lines of the acoustic transducers. The corresponding acoustic images are in the two lower figures.

Figure 15. Individual acoustic waveforms at two locations.
The resultant amplitude of the oil thickness along one line is shown in Figure 16 for the Hibernia oil. The slick thickness in the three regions measured was ~ 1 mm near 80 inches, between 4.5 mm and 6.8 mm near 110 inches and between 2 and 3 mm near 160 inches along the oil-ice field. The final determination of the thickness of the oil in the ice field is shown in Figure 17.

![Figure 16](image1)

**Figure 16.** The resultant oil thickness along one line of the acoustic san.

![Figure 17](image2)

**Figure 17.** The resultant thickness if the oil in the ice field and under the ice.
3.6 REDESIGN AND LAB MEASUREMENTS

3.6.1 ROV Redesign

During this period we redesigned the ROV with the acoustic transducers flush mounted to the surface of the ROV platform and the cameras were mounted close to the platform. A picture of the ROV is shown in Figure 18. We mounted two cameras, an upward looking high definition (HD) camera and an analog forward looking camera so the operator can see where they are going while driving. We also moved the retrieval rope to the center of the ROV so that it was balanced while being picked up by the crane. The retrieval rope was still attached to a long CB antenna to keep it out of the way of our measurement area. While we mounted 5 transducers on the ROV we only made measurements with 4 transducers since the area covered by each transducer overlapped at the surface.

Further modifications for the next trip to Ohmsett are shown in Figure 19 and Figure 20. The design was much more compact than previous designs with the transducers flush mounted to the ROV platform. We used various camera configurations including a design with two cameras—shown in Figure 19—with one pointed up and a second angled up to provide views in front and above the ROV. We also used a configuration with 3 cameras, orienting the third camera directly forward for situational awareness, shown in Figure 20.

Figure 18. The redesign of the ROV has decreased the height and has the transducers flush mounted and two cameras installed close to the platform.
All of the video feeds were recorded for post-processing purposes. An onboard temperature sensor recorded the temperature, allowing us to calculate an accurate value for the water’s sound speed. A metal antenna held the retrieval line ~1 foot below the surface so that the retrieval loop (hanging ~3 feet below) did not interact with the slick or ice. The line was easily grabbed with a boat hook and attached to the crane. Five transducers were flush-mounted along the ROV’s front edge (on the left in Figure 19). The middle transducer was not used as part of regular operation and was included only to test various configurations of the acoustic transducers.

The measurements presented in this report were made using the four equally-spaced transducers (omitting the center transducer). The four channels were received with an 8-channel pulser-receiver in a Dynamic Range Expansion mode. This Dynamic Range Expansion (DRE) noise reduction process combines the signals from the 2 analog-to-digital cards to improve the signal-to-noise ratio (SNR) of each channel [3]. The result of this noise reduction process improves our ability to measure small amplitude signals reflected from the surface of the slick which may be the result of a reduced reflection coefficient due to the oil properties or misalignment between the transducer beam and the slick surface which can occur in the presence of small surface waves or when the ROV tilts as it drives over debris.

Figure 19. Side and top views of the ROV with two cameras installed.
The redesign of the ROV went beyond the physical ROV and extended to the electronics and user controls. Figure 21 shows the electronics box with the Wi-Fi router installed so that the computer can be connected wirelessly to the electronics. This was a new feature added after discussion with the staff at Ohmsett. The wireless connection will now allow the user to be 100’s of feet away from the electronics and will allow them to operate in the bridge house or on the deck while the electronic can remain on the deck away from the moving parts of the bridge. The live video streams from the cameras also transmit through the wireless router. We were able to control the ROV, collect acoustic data and record live streams from outside of the Seawater Research lab. Also shown in Figure 21 is the new acoustic pulser receiver purchased specifically for this project. Up to this point we have been using a 2 channel system purchased on a different project funded by another government agency. This new pulser receiver has 8 channels and allows us to connect them to 4 transducers in a way that decreases the noise significantly. This reduction in noise is significant since the signal from the water oil interface can sometimes be only slightly higher than the electronic noise floor.
A photograph of the ROV work area is shown in Figure 22. Notably the ROV is now controllable using an industrial joystick. We added this feature based in discussions with the Ohmsett staff and our own desire to provide a user friendly interface for the users at Ohmsett. We stepped through 3 different joystick designs starting with a PlayStation controller and individual joysticks that make up the controller and concluded with the industrial joystick seen in Figure 22. Common to all the joysticks are potentiometers which change the electrical resistance and therefore the output voltage of the joystick in a given axis. The voltages from the joystick’s three axes (forward-backward, left-right, and twist for dime turn left-right) are continuously read by the motion control components to determine which direction the ROV should move. While the PlayStation controller and the individual joysticks were functional, they were not robust enough to withstand repeated handling and the Ohmsett environment. Furthermore, the joystick we finally chose is contactless and uses Hall effect sensors rather than metallic contacts further increasing the robustness and impact from the elements.
3.6.2 Lab Measurements

During the first task of this project we made measurements in the swimming pool at the College of William & Mary. To provide a more relevant and useful test environment we set up a large tank for additional experiments and testing. Figure 23 shows the tank and crane in the large high bay area of the Seawater Research Lab on the Virginia Institute of Marine Science (VIMS) campus were our office is co-located. The fiberglass tank measures 10 feet tall by 12 feet wide and holds 8460 gallons of water. We used the A-Frame crane to lift the ROV and plastic into and out of the water as shown in Figure 24. We segregated the tank into two regions with a commercial boom. One region was kept oil free while the other was used for oil and “ice” measurements. The boom and High Density Polyethylene (HDPE) we used to simulate ice is shown in Figure 25. We used rope and three eye bolts to lift the plastic in and out of the water. The ROV is seen at the bottom of the tank during a scan.
Figure 23. The large tank for data collection and testing in the Seawater Research Lab collocated with our office in Gloucester Point, VA.
Figure 24. We used the overhead A-Frame crane to lift the ROV and plastic in and out of the water.

Figure 25. The tank was segregated into two regions, one with clear water and the other with oil and plastic.

A snapshot from the upward looking camera is shown in Figure 26 in our large lab tank. The 4 pink circles represent the location and size of the acoustic beams at the surface of the water. Each circle is approximately 7 inches in diameter and each beam overlaps slightly with the beams from adjacent transducers. The plastic sheet that is fully visible at the bottom of the image measures 2 feet in the short direction by 3 feet along the long direction.
We performed several scans under the canola oil and plastic in our tank. We used canola oil so we would not generate large volumes of hazardous waste. Work by the team described in previous reports shows that canola oil can be a good surrogate for crude oil for slick thickness measurements as long as the speed of sound is known. The acoustic image and associated waveforms for a scan under plastic and an oil slick are shown in Figure 27. The top image shows a typical "sonar-like" image with the vertical axis representing the distance from the transducer and the horizontal axis the distance traveled. In this case the surface of the water was at ~7.4 feet and the bottom of the plastic was at ~7.2 feet from the transducers and the color is the amplitude of the signal with light blue being low and red being high. Signals from the bottom of the plastic arrived closer to the transducer while the slick was much further away. The slick is visible by the presence of the signal just before the surface along with a reverberation...
showing up “further away”. This image is for one of the channels on the two channel system we used for data collection prior to going to Ohmsett. The acoustic waveforms at specific locations are shown in the bottom graphs from the “ice” region on the left and the oil slick region on the right. Each graph is plotted over the same distance on the vertical axis from 7.0 feet to 7.5 feet from the transducers. The signal from the ice and the presence of the slick are evident and were used to calculate the thickness. The graph in the middle shows the signal when the transducer was just under the edge of the plastic and thus received signals from both the plastic and the slick due to the size of the acoustic beam at the surface (~7 inches). The results of this ambiguity will manifest itself as a jump between ice and oil near the edges of the plastic.

Figure 28 shows the thickness calculated for these two channels along the scan on the top and bottom as well as a composite color image in the middle graph. The ambiguity around the edges of the plastic can be seen in the bottom graph where the slick looks present and then drops out for a brief distance. The data is quite good and clearly shows the ability to measure the oil slick thickness and identify ice and measure its thickness with little input from the user. In this case the oil was quite thick over the scanned region of ~ 7 mm.
Results from a scan over a region with a thinner slick are shown in Figure 29 and Figure 30. In that case the slick was ~2 mm to 3 mm thick except where the plastic was present. In this scan there were also a few points with missing data. The data was missed for various reasons including the speed of the computer, the bandwidth of the router, the speed of the scan, and the frequency of the data collection. We worked on isolating these effects and optimized the acquisition to minimize missing data for the final delivery.
Figure 29. The sonar-like image (top) from a scan under a slick ~ 2 mm along with the acoustic waveforms in the bottom three graphs as specific locations.
In addition to working on scanning various scenarios in preparation for Ohmsett we have also integrated the joystick into the GUI and created controls to allow accurate turning and intuitive control of the ROV using the joystick. Two videos streams are converted from analog to Ethernet-based IP video feeds through converter boxes and are displayed using the VLC viewer 3rd party software.

Figure 30. The resultant slick thickness for the scan above along with the slick thickness map.
4. TESTING MULTIPLE OILS AT OHMSETT

This section describes the results from this trip including the redesigned ROV and testing with the various oils and refined products including ANS, Hydrocal, Calsol, and Diesel.

4.1 TANK SET UP

The oil-ice fields were set up along the west side of the tank as shown in Figure 31.

Figure 31. Overhead view from the crow’s nest of the boomed off field of ANS oil and plastic. A fire hose and fire monitor were used to contain the field within the boomed off region. The calibration squares were anchored northeast of the boom.

We used high density polyethylene (HDPE) as a surrogate for ice with the sizes shown in Table 2. Northeast of the boomed area we anchored two 4-foot squares of PVC pipe that were filled with various thicknesses of oil for calibration.
Table 2. Sizes of plastic sheets used in ANS slick.

<table>
<thead>
<tr>
<th>1” thick</th>
<th>2” thick</th>
<th>3” thick</th>
<th>4” thick</th>
</tr>
</thead>
<tbody>
<tr>
<td>2’ x 4’</td>
<td>2’ x 4’</td>
<td>2’ x 3’</td>
<td>1’ x 1’</td>
</tr>
<tr>
<td>4’ x 4’</td>
<td>4’ x 4’</td>
<td>4’ x 4’</td>
<td>1’ x 2’</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1’ x 4’</td>
</tr>
</tbody>
</table>

4.2 CALIBRATION MEASUREMENTS

We filled the squares with the calculated amounts of oil needed to produce slicks that were 1mm and 5mm thick so that we could drive the ROV under the squares to calibrate our thickness measurement. When conditions were calm and the oil was low viscosity, like ANS, this method proved reasonably accurate. However, when the oil was very viscous and had a large interfacial tension, like Calsol, the oil did not spread evenly across the entire square causing this method to not be so accurate for calibration. Furthermore, in windy conditions the oil often escaped from the squares, as can be seen above toward the bottom of Figure 32.

![Figure 32. Two images from upward-looking camera of the thinner Calsol square. The oil’s high interfacial tension prevented it from spreading evenly across the whole square.](image)

Even with these complications, we were able to use our measurements of the speed of sound in oil to calibrate the thickness of the ANS slicks as shown in Figure 33. The three images are aligned along the x-axis for ease of comparison. At the top of Figure 33 are images from the upward-looking camera showing the two calibration squares. The plot in the middle of Figure 33 shows consecutive pings (vertical slices) as a function of distance (in feet) the ROV traveled. Red depicts high scattering amplitude and blue is lower amplitude. This image is a standard view that would be seen in a commercial sonar instrument. The vertical axes in these plots correspond to the targets’ relative proximities to the transducers, with smaller times of flight being closer and longer times of flight being farther away. The times of flight are the round trip travel
time from the transducer to the surface and again back to the transducer. The surface can be seen in these plots as the reddish lines near 3115 microseconds (us) and the PVC structures are the crescent shapes near 3050 us. These times correspond approximately 7 feet 7 inches and 7 feet 5 inches from the transducer respectively. The bottom plot shows the acoustic calculation of the slick thicknesses. The square with the thin slick was measured to be close to 1 mm, the thick slick was closer to 3.7 mm, instead of 5 mm.

Figure 33. Two images from the upward-looking camera stitched together to show both calibration squares is at the top of the figure. The thin slick is on the left and the thicker slick is on the right. The stacked pings of the thin slick and part of the thicker slick are shown in the middle, and the acoustic calculation of the slick thicknesses is at the bottom. All three images are aligned along the x-axis for direct comparison. The vertical axis is in the middle figure is the round trip time of flight between the transducer and the reflector.
When the squares were filled with low viscosity diesel, the wind and waves caused the thickness to vary significantly across the square. This issue was not seen when larger volumes of oil were poured in the large boomed off area. We worked with Ohmsett staff to determine an optimum calibration method for the thick oils like Calsol and thin oils like Diesel and provided a lab calibration set up for the final delivery where the thickness can be varied in a controlled manner in a controlled environment. Figure 34 shows a scan under the squares when they were filled with Diesel with a target thickness of ~ 1 mm and 5 mm. The top image is two snapshots from the upward-looking video camera with four yellow lines overlaid to show the transducer locations.

![Image of calibration squares with yellow lines](image1)

![Image of 2D Slick Map](image2)

![Image of Slick thickness in diesel squares](image3)

Figure 34. At the top are two images from the upward-looking camera stitched together to show both calibration squares with yellow lines overlaid to show the paths where the four transducers measure the surface slick thickness. The thick slick is on the left and the thin slick is on the right. An acoustic image of the slick thicknesses is shown in the middle of the figure with a colorbar to show the color that corresponds to the thicknesses in millimeters. At the bottom is the acoustic calculation of the slick thicknesses for channel 3. All three images are aligned along the x-axis for direct comparison.
The middle color figure is a 2-D slick map produced by combining the ROV’s four channels—each channel corresponds to a horizontal band of pixels with the color corresponding to the thickness, in millimeters as given by the scale at the bottom of the map. The picture of the square with the thin slick (on the right) appears to show the slick congregated on the left side of the square, which is validated by the slick map and the line scan of channel 3 at the bottom of the figure. While the borders of the squares are not visible in the slick map, the right square looks noticeably smaller, and the slick thickness decreases towards 0 mm toward the right. The line scan along channel 3 at the bottom shows that the slicks in each square were not uniformly thick and ranged from ~3mm to 6 mm in the left square and ~ 1 to 2 mm in the right square. The gradual drop off in thickness is also evident after 10 feet in the scan direction.

4.3 ALASKAN NORTH SLOPE (ANS)

A picture of the ANS slick is shown in Figure 35 and a scan under the ANS slick is shown in Figure 36. The top image is several snapshots from the video recorded by the upward-looking camera stitched into a panorama. The transducer paths are overlaid on this image to illustrate where the acoustic data was collected. The x-axes on all plots are aligned with the image for ease of comparison. The plot labeled “Channel 3” shows consecutive pings (vertical slices) as a function of distance (in feet) the ROV traveled. Red depicts high scattering amplitude and blue is lower amplitude. This view is a standard view that would be seen in a commercial sonar instrument. The vertical axes in these plots correspond to the targets’ relative proximities to the transducers, with lower being closer and higher being farther. The surface can be seen in these plots as the reddish lines in the upper half of the plots, and since the plastic blocks sit below the surface, they can be seen as the bluish lines in the lower half of the plots. From the surface reflections the slick thickness was calculated by measuring the difference in the time between the echo from the oil-water interface and the oil-air interface, as described in previous reports. The locations where the slick thicknesses go to zero correspond with the points where the transducer is below ice. The bottom plot shows the slick thickness calculation from all four transducers, with color representing the thickness. The legend at the bottom shows the thicknesses in millimeters that correspond to the colors other than lavender. Lavender indicates that the data acquisition system dropped data, no surface was detected, or the ROV is under plastic. This ambiguity is something that has been cleared up with improved algorithms and software upgrades and has been implemented in the final version of the ROV. These ANS thickness measurement calculations were calibrated using the speed of sound as a function of temperature that was measured in our lab.
Figure 35. View from the crow’s nest of the ANS oil and plastic field in the boomed region along the west side of the tank.

Figure 36. At the top are several images from the upward-looking camera showing the ANS oil and plastic field. The yellow lines show the paths where the four transducers measured the slick thickness. Pings from channel 3 are shown below the photos. Below this is the acoustic calculation of the slick thicknesses from channel 3. The slick thicknesses map is shown in the bottom of the figure. The scale shows the color which corresponds to the slick thicknesses in millimeters.
4.4 Calsol

A picture of the slick of Calsol is shown in Figure 37, and a representative data set is shown in Figure 38. The black oil on top of the plastic is residual ANS from the previous measurement.

Figure 37. Overview photograph of the Calsol oil and plastic field.
Figure 38. At the top are several photos from the upward-looking camera. The yellow lines show the paths where the four transducers measured the surface slick thickness. Pings from the four channels are shown below the photos on the left. Oil under ice can be seen in channel 1 between 12 feet and 14 feet along the scan direction. The slick thicknesses map is shown on the right of the figure with the color corresponding to the thicknesses in millimeters.
The top panorama in Figure 38 is several snapshots of the Calsol and plastic field from video recorded by the upward-looking camera, with the transducer paths overlaid in yellow lines. Similar to ANS, the measurements on Calsol provided a slick thickness map shown on the right of Figure 38. On the left, the stacked pings from all four channels are shown for comparison purposes. The received signals from the four channels are shown in the four color figures on the left of Figure 38 where the vertical axis is the round trip travel time which represents the distance from the transducer and the horizontal axis is the distance the ROV traveled during the scan. The range on the vertical axis is approximately 7 feet 2 inches to 7 feet 5 inches and the horizontal axis range is 0 to 15 feet. The start of the scan (at the left) was under a block of plastic that was two inches thick and the second block was 1 inch thick. The double line in the bottom right of the bottom plot (channel 1) indicates that oil under ice was detected. More data on oil under ice will be discussed later in this report. The different arrival times of the leftmost ice blocks also indicate the differences in their thicknesses, with the first block being twice as thick as the second.

4.5 HYDROCAL

We also performed test on Hydrocal which produced a mostly translucent slick shown in Figure 39. The underwater panorama, transducer paths, and acoustic data are shown in Figure 40.

Figure 39. Overview photograph of the Hydrocal oil and plastic field.
Figure 40 At the top are several images from the upward-looking camera stitched together to show the Hydrocal oil and plastic field with yellow lines overlaid to show the paths where the four transducers measure the surface slick thickness. The stacked pings from channel 1 are shown below the images, and the acoustic image of the slick thicknesses is shown at the bottom of the figure with a colorbar to show the color that corresponds to the thicknesses in millimeters. All images are aligned along the x-axis for direct comparison.
Similar to ANS and Calsol, this scan of Hydrocal produced the plots of the stacked pings, with the lavender bands showing the dropped pings caused by the data acquisition system. The map of the slick thickness is noisy after about 22 feet because after the ROV drove beyond the end of the Hydrocal and plastic field into open water, the open water had more wind-generated surface waves than usual.

4.6 Diesel

The off-road Diesel produced the reddish slick shown in Figure 41. The slick was very thick in the center, as can be seen as an orange color in the slick thickness map with a thickness of ~9 mm. The stacked pings also depict this increased thickness by the surface reflection (around 3090 us) gradually splitting up into three distinct reflections. These reflections are the water-oil interface, oil-air interface, and multiple reflection signals in the slick that have been discussed in previous reports for this project.

Figure 41. Overview photograph of the diesel oil and plastic field.
Similar to the previous oils, the underwater panorama, transducer paths, and acoustic data are shown in Figure 42.

Figure 42. At the top are several images from the upward-looking camera stitched together to show the Diesel oil and plastic field with yellow lines overlaid to show the paths where the four transducers measure the surface slick thickness. The stacked pings from channel 1 are shown below the images, and the acoustic image of the slick thicknesses is shown at the bottom of the figure with a colorbar to show the color that corresponds to the thicknesses in millimeters. All images are aligned along the x-axis for direct comparison.
4.7 OIL UNDER ICE

Indications that we can measure the oil under the ice are shown in Figure 43 where the reflection from the water oil interface occurs before the oil-ice interface. Also visible are signals from the interior of the ice to a depth of approximately 5 mm.

![Figure 43. Acoustic waveform of oil under ice with the interfaces identified as well as the oil thickness under the ice](image)

In order to simulate oil getting trapped in pockets beneath ice in a more controlled fashion and to allow us to test during warm weather conditions, pockets were machined under one of the plastic blocks, shown in Figure 44.

![Figure 44. Photograph of the pockets cut out beneath a block of plastic to trap oil.](image)
Figure 45. Photograph of oil trapped under a block of plastic taken by the upward-looking camera with the transducer scan paths overlaid (top). The stacked pings from channel 4 are shown in middle of the figure, with the double line between -4.5 and -1 feet in the scan direction representing the water-oil and oil-plastic interfaces. The thickness calculation for this slick of oil beneath the plastic is shown at the bottom. The thickness ranged between 3 and 5 millimeters.

Scanning under this block produced the data shown in Figure 45. The best data for oil under ice for this particular scan was collected on channel 4. In the middle image, the lower surface of the plastic shows up as a greenish line at 2990 microsecond or 89.7 inches, above a green and blue line at 980 microseconds or 89.4 inches, which represents the water-oil interface. From these two reflections, the slick thickness was calculated for the pocket of oil trapped beneath the plastic. This thickness of the oil slick under the plastic as a function of distance across the plastic block is shown in the bottom plot.
4.8 Wave Effects on Slick Thickness Measurement

For the data shown in Figure 46 the ROV was held stationary while the waves moved along the surface. The data in the lower two figures show the thickest part of the slick moved overhead between 15 and 30 seconds, with a thinner slick remaining afterward. It was somewhat remarkable that the algorithms and ROV could measure the thickness of a slick that varied from ~2mm to ~3mm on the surface ~7 feet away that had waves with a peak to trough of 6 inches.

Figure 46. At the top are stacked pings during large waves, showing how the surface height changes with time. In the middle is the slick thickness calculation, which shows that the slick thinned by about a millimeter after 50 seconds. At the bottom is the slick map that shows all channels measuring a thinner slick after 50 seconds.
Zooming in between 50 and 80 seconds and narrowing the color pallet, the data show the thickness of the slick changing over the period of the waves. See Figure 47 and Figure 48.

**Figure 47.** Zoomed in slick map that shows the slick thickness in all channels varying as large waves pass by.

**Figure 48.** Zoomed in slick thickness calculation that shows how the slick thickness and surface height are changing as large waves pass by.

In addition to providing a slick thickness during the large amplitude waves, the ROV was able to track the changes in the slick thickness ~100 microns during the waves. The figures above show that the slick thickens slightly at the peak of the wave and thins at the wave’s trough.
5. SKIMMER NAMEPLATE TESTING (ASTM F 2709-08)

During November of 2014 we performed additional test at Ohmsett on ANS in a surrogate ice field along with Dr. Toomas Alik from Night Vision labs and during ASTM F 2709-08 skimmer name plate testing. Figure 49 and Figure 50 show the tank set up for the ANS and skimmer testing respectively from the crow’s nest above the main bridge.

Figure 49. Tank setup for testing ANS. The PVC squares have oil at a specific depth for calibrating the acoustic measurements as well as the multi-spectral imaging.

Figure 50. Tank set up for ASTM F 2709-08 Skimmer Nameplate Testing for Hydrocal during Test 4 for the Helix skimmer.
An image of the skimmer during operation from the underwater camera on the ROV which points at an angle upwards is shown in Figure 51. This image was recorded during our data collection during the skimmer test.

Figure 51. A screen shot from the underwater video on the ROV of for Hydrocal during Test 4 for the Helix skimmer.

The associated acoustic measurement of the slick thickness is shown in Figure 52 as the skimmer removes oil from the pool from a thickness of 3 inches to 2 inches as prescribed in the ASTM standard. The Acoustic Oil Slick Thickness ROV software provides both real time measurements of the thickness as well as post processing as shown in the screen shot shown in Figure 52. The top image is a sonar-like image of the amplitude of the signal from the top and bottom of the slick as a function of time with time along the horizontal axis. The brighter red lines are the top and bottom of the pool of oil. The corresponding thickness of the pool during the test is shown in the bottom figure. This detailed level of data is unprecedented and allows the operators to dynamically measure the rate of oil uptake as well as determine the endpoint of the test. Prior to our acoustic ROV they relied on physical measurements of the pool by dipping a container into the pool from the side of the tank. The software we developed records the date and time of the test as well as the oil type and temperature and allows for additional notes from the operator. Further customization can be implemented based on feedback from the Ohmsett users to help improve the functionality and user friendliness of the software.
We continued to collect data after Test 4 was complete while they filled the pool back up to 3 inches deep as can be seen in Figure 53. We also measured the pool thickness while they were emptying the boomed off area as shown in Figure 54 where the thickness decreased from ~2.25" to ~ 1.25". This slick thickness measurement capability provides them active measurements of the pool thickness and will allow them to actively measure the thickness in real-time.
Figure 53. The real-time measurement of oil slick thickness during filling the pool of oil for the next skimmer test.

Figure 54. The real-time measurement of oil slick thickness during while emptying the skimmer test area.
Figure 55 shows the Ohmsett staff operating the Acoustic Slick Thickness ROV both inside and outside the bridge building using the joystick to maneuver around the tank. Based on their feedback we modified the GUI and software algorithms to improve operation.

Figure 55. Ohmsett staff operating the Acoustic Slick Thickness ROV using the joystick while watching the live video feed from the on board cameras on the left and looking directly at the ROV moving along the floor of the tank on the right image.

6. FINAL DESIGN AND DELIVERY

The final configuration of the Acoustic Slick Thickness ROV is shown in Figure 56. The electronics to move the ROV and power the acoustic sensors is enclosed in the pelican box as shown in the top photograph. Each cable has a unique function and thus a unique connector or color as is the case for the acoustic transducers. The computer can be connected wirelessly to the router or wired directly. The ROV shown in the bottom photograph operates on the two underwater tracks and uses two analog cameras to provide views straight up and forward. The four transducers to measure the slick thickness are located at the front of the ROV and are color coded (1) blue, (2) green, (3) yellow, and (4) red. The corresponding cables and connections on the electronics panel are also color coded and numbered for easy connecting. The angle of the forward looking camera can be adjusted a few degrees by loosening the bolt shown in the bottom figure.
Figure 56. The final configuration of the electronics box (top) and ROV (bottom).
The cable assembly shown in Figure 57 which connects the ROV to the electronics is approximately 130 feet long. It is robust, but should be treated with care. The entire assembly is encased in rugged water hose and sealed at several splice points and at each end to make it watertight. The gray end is the topside and the black end connects to the ROV. Inside the hose are 5 cables. One large cable containing the wires to the ROV tracks, the cameras and the temperature sensor. Separate from the large cable are the 4 acoustic transducer cables.

![The cable assembly with 5 cables enclosed in a water tight hose to survive the rugged conditions at Ohmsett.](image)

We also provided the ability to measure the speed of sound in new oils as a function of temperature outside of the large tank in the Ohmsett lab or other location. The lab measurement apparatus is shown in Figure 58. The software measured the speed of sound and allows the user to enter the measured speed as a function of temperature into the ROV software for use during measurements in the tank. The cable is color coded blue to plug into channel 1 on the electronic panel and the software automatically recognizes the transducer.
During final delivery and training the Ohmsett staff received direct instructions on the setup and operation of the ROV. The ROV includes the ability to manually drive the ROV using either an industrial joystick or a standard mouse. It can measure the slick thickness at a single location using 4 acoustic transducers and can be manually or automatically scanned underneath an oil slick. The ROV can also measure the slick thickness during skimmer testing and displays the thickness as a function of time in real time for determining the time to completion of the test as well as the rate of oil removal.

Several PVC squares were placed in the tank with different oil thicknesses to perform the final set up of the system and train the staff. The squares are shown in Figure 59 with the thicknesses of 1 cm in the closest square, 0.5 cm in the middle square and approximately 1 mm in the furthest square. We also inserted a plastic block to simulate ice so that they could be trained on measuring the oil slick thickness in an ice field as we had done on previous trips to Ohmsett.
The training went smoothly even though the water was very murky from testing during the previous week. Figure 60 shows the buoy floating from the ROV about 1 foot under the surface of the water. Even with visibility limited to about 1 to 2 feet the ROV was able to accurately measure the slick thickness of the oil and the staff were able to navigate around the tank. The ability to measure the slick thickness in murky conditions is a strength of the acoustic technology used for measuring the oil slick thickness.
7. SUMMARY AND CONCLUSIONS

We developed a first-of-a-kind Acoustic Slick Thickness ROV for use at Ohmsett. The ROV was used to measure the thickness of oil slicks in ice fields as well as during the ASTM F 2709-08 Skimmer Nameplate testing. We performed measurements on numerous crude oils and refined petroleum products including ANS, Hibernia, Hydrocal, Calsol, and Diesel we showed the ability to measure the thickness of oil slicks from below 0.5 mm to above ~ 8 cm. The ROV was able to measure the thickness of pools of oil under ice and could measure the thickness of oil slicks in wavy sea states. As part of this work we also measure the speed of sound of several oils as a function of temperature for several oils. This capability to measure speed of sound as a function of temperature has also been transferred to Ohmsett as part of the deliverable. The ROV provides a previously unobtainable capability to Ohmsett and the oil spill response community to directly measure the oil slick thickness and to record underwater videos. The ROV can also be used as a platform to deliver other sensors to various test sites in the pool as well as provide a platform to test other instruments for use at Ohmsett and in the field.

8. RECOMMENDATIONS AND FUTURE WORK

The Acoustic Slick Thickness ROV has been shown to be effective at measuring the oil slick thickness for various scenarios. There are several improvements that could be made as well as ideas for future work to enable slick thickness measurements to be performed in the open ocean for spill response. After extended use at Ohmsett we anticipate receiving suggestions on specific changes that could be made to improve the functionality, user friendliness, and versatility of the ROV. We will solicit feedback from the Ohmsett staff to guide us to further actions. During this project we identified several improvements that could be made including integrating the video camera operation into the ROV software for more seamless operation. It would also be useful to provide additional frequency options and locations/orientations of the transducers for use in other experiments. Providing a data base of the acoustic properties of oil to include the speed of sound, attenuation and reflection coefficient as a function of temperature will also be an important future activity. It would also be useful to add in the ability to enter oil type, viscosity, and temperature into the ROV software for future oils. An especially nice feature would be to develop the ability to visualize the location of the ROV on an image of the tank as the ROV moves in a way that is similar to mapping the location of a car on mapping software while driving.

It will also be important to study the effects of sea state on the slick thickness measurement to enable measurements for various wave heights and wind conditions. Long term it is important to migrate these types of high fidelity acoustic measurements to autonomous underwater vehicle (AUV) and tethered ROV platforms that operate in the ocean to enable these thickness measurements and other measurement opportunities to improve spill response.
9. REFERENCES