Research Efforts for Detection and Recovery of Submerged Oils

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Abstract

For spills of submerged oil, current methods are inadequate to find and recover the oil. Many of the detection approaches are ad-hoc and the recovery techniques very labor intensive. The Coast Guard R&D Center has embarked on a multi-year project to develop a complete approach for spills of submerged oils. This paper describes the preliminary assessment of using sonar, laser fluorometry, real-time mass spectrometry and in-situ fluorometry to locate oil sitting on the bottom. Evaluation of proof-of-concept devices was conducted at Ohmsett between November 2007 and February 2008. Preliminary data and assessments are provided. Future tests are planned for early 2009 using sonar and laser fluorometry and additional work on recovery starting late in 2009.

1 Background

Even though heavy (sinking) oils have historically accounted for a small percentage of spills, environmental and economic consequences resulting from a spill can be high. Heavy oils can sink and destroy shellfish and other marine life populations in addition to causing closure of water intakes at industrial facilities and power plants. The underwater environment poses major problems including poor visibility, difficulty in tracking oil spill movement, colder temperatures, inadequate containment methods and technologies, and problems with the equipment's interaction with water.

In early papers, authors focused on what conditions are needed to be present (Michel and Galt, 1995) or what should not be done (Castle et al., 1995). Others addressed processes (Elliott, 2005 and Schnitz and Wolf, 2001). The International Maritime Organization (IMO) sponsored a forum in 2002. (Brown, et al., 2002, Parthiot 2002, Cabioc'h 2002). The US Coast Guard Research and Development Center (RDC) attempted to build on the efforts by Environment Canada (Brown et al, 2004 and 2006) by investigating an airborne laser fluorosensor to detect submerged oil (Fant and Hansen, 2005 and 2006). In parallel, efforts by international organizations (Parthiot, 2004) were also ongoing. A workshop, co-sponsored by RDC in December of 2006 also reemphasized research needs. (CRRC, 2007) A summary of past experiences especially with respect to the two latest spills (Michel, 2006) was funded by RDC.

As a result of the information submitted from a Request for Information (RFI) in the summer of 2006, it was decided to divide the effort into detection and then recovery. In April of 2007, RDC published a Broad Agency Announcement (BAA) that requested approaches for detection only due in June 2007.

2 Specifications for Techniques

The objective of the specification in the BAA was that the sensors should provide sufficient information so that decision-makers could determine if an amount of oil sufficient to merit recovering could be identified. Taken directly from the BAA:

For the successful proof of concept shall have the following capabilities:

1) Able to identify the presence of heavy oil on the sea floor with 80% certainty.
2) Able to detect oil on the bottom from at least 1 meter away.
3) Oil location shall be geo-referenced to one meter in accuracy.

4) Ideally, will provide real time data, but at a minimum shall produce results and data interpretation hourly.
5) Able to provide data for all sea floor conditions
6) Operate in fresh and sea water conditions equally well.
7) Operate in water depths of up to 33.3 meters (100 feet).
8) Have minimal maintenance requirements (easy to maintain and calibrate).
9) Easy to operate and involve minimal training.
10) Easily de-contaminated and durable.
11) Equipment operation not adversely affected by exposure to oil.

Once the proof of concept is demonstrated, the prototype device shall be able to operate in the following conditions:

1) Able to search a one square mile area in a 12 hour shift.
2) Operate in water current of up to 1.5 knots.
3) Operate in up to 5 foot seas.
4) Operable during the day and night.
5) Able to be set up within 6 hours of arriving on site.
6) Easily deployable and transportable. Capable of being deployed from a vessel of opportunity and a variety of other platforms (i.e., towed bodies, remotely operated vehicles, autonomous underwater vehicles (AUVs), and manned submersibles).

3 Proof-of-Concept Testing

3.1 Test Set Up

It was determined that the large Ohmsett tank could provide a somewhat realistic environment while providing the ability to create targets and provide sufficient area to address the multiple aspects of each type of approach. Because of the time of year of the testing (winter) and the nature of the sensors, the system from WHOI was tested in an inside tank and the configuration will be described below.

3.1.1 Oil Selection and Sinking Oil

The two oils selected were Sundex 8600, a standard Ohmsett oil and No. 6 fuel oil. The personnel at Ohmsett consulted with S.L. Ross Environmental Ltd to determine how to get the oil to sink and remain on the bottom. The solution used was adding barite to the oil at a rate of about 15% (Figure 1).

3.1.2 Test Trays

Two test trays were constructed that would serve to hold the oil at the bottom of the Ohmsett Tank. Each was fabricated from aluminum and were 2.4 meters by 2.4 meters (eight feet by eight feet). The trays were filled with water to saturate the sand and moved to the bottom of the Ohmsett main tank. (Figure 2)

3.2 RESON

3.2.1 RESON 7125 SeaBat System Overview

The SeaBat 7125 system is a multibeam sonar system that measures relative water depths over a wide swath perpendicular to the vehicle's track. The SeaBat 7125 ensonifies a 128° sector below the sonar head assembly and is suitable for mounting on a surface vessel, remotely operated vehicle (ROV), or for use on an autonomous underwater vehicle (AUV).

3.2.2 Test Results

The sonar was moved over the targets several times, with most runs performed at a frequency of 400 kHz. The varying thickness of the oil layers did not affect the detection. An empty depression in the sand was falsely detected as oil when using Sidescan-type imagery based on port and starboard signal magnitude versus time. Further analysis showed that a different method of imaging based on signal magnitude at the bottom location in each beam provided data that was less affected by bottom topology. (Figure 3) The SeaBat systems are able to extract both imagery types from the raw sonar data.

Using the magnitude of the signal extracted after bottom detection allows the system to avoid false alarm on the blank shapes by identifying them as depressions of various depths. In contrast, traditional sidescan imagery triggered a false alarm on these blank shapes. This benefit of the multibeam echo sounder is that the depressions are detected in the bathymetry and system will therefore not regard the depression as a target. The results presented in this paper were obtained during post-processing using a scientific package as the primary tool.

3.2.3 Next Steps

The next effort will be the development of an automated detection system that does not rely solely on the operator to visually detect the oil. The will include an advanced image processing solution and a model inversion solution. These will be based on measuring the backscattering strength as a function of multiple parameters including the physical characteristics of the seafloor.

3.3 SAIC Modified Laser Line Scan System

3.3.1 Overview

The SAIC SM-2000 Laser Line Scan System (LLSS) was originally developed as a seafloor imaging tool based on the reflectance of a solid-state Nd-YAG 532 nm (blue-green) laser. In order to elicit fluorescence in oil-based compounds, a shorter wavelength, higher energy laser light source approaching the UV-A band (405 nm) was incorporated in the LLSS. The LLSS operates with two, four-faceted rotating mirrors and a single synchronized receiver. Each rotation of the mirror assembly swept the laser beam through a 70° sector (Figure 4A). In order to isolate and record only the fluorescent response within the desired 476 to 488 nm range, an optical band pass filter was installed.

3.3.2 Results

During the OHMSETT tank testing, the LLSS was suspended in water by a four point harness system, beneath to the moving bridge. Due to the water depth within the tank, the LLSS was positioned to scan the test trays and oil targets at an angle (approximately 30°) to increase the focal distance between the LLSS and the tank bottom to 2.5 meters. During daylight conditions, the sunlight saturated the test area with the wavelength of light that the filtered PMT receiver was designed to capture. As a result, the modified LLSS provided accurate imagery data but failed to elicit and/or detect any fluorescent signal over the background light.

The LLSS imagery acquired over the test trays during the night runs was essentially a monochromatic image with dark areas indicating zero to weak fluorescent return (Figure 4B). The brighter areas in the imagery, representing relatively intense return within the preferred bandwidth, were indicative of a response to the excitation laser at the sufficient strength to pass through the filter. Due to the test configuration, there was insufficient overlap in coverage and timing between the excitation beam and the area the PMT receiver interrogates resulting in a signal that was out of sync. This resulted in one side of each test tray to appear dark (or no data) in the LLSS imagery. The intensity of the return signal suggests that the 10 nm band pass, 480nm filter was adequate to capture the light emitted by the weathered Sundex 8600 oil deposits that were embedded within the sediment matrix. In contrast, the fluorescent response of the Number 6 fuel oil and roofing tar deposits were present and detectable by the modified LLSS, but recorded at a much lower intensity.

3.3.3 Next Steps

The following is a list of key elements of any future modifications and testing of the LLSS as a submerged oil deposit detection and mapping system.

1) *Limit ambient light* –Future testing should be performed in an environment that better mimics conditions in a coastal harbor and/or port facility.
2) *Increase the power of the laser light source* – A higher intensity laser would increase the operational range of the LLSS.
3) *Filtering* –Alter the return light signal filtering scheme within the LLSS to allow the passage of a broader spectrum of visible light.
4) *Reduce System Size* - The minimum focal length and the sheer size and weight of the existing LLSS unit are limitations. A redesign of the LLSS bottle should make this system deployable on a broader array of tow vehicles.

3.4 EIC

3.4.1 Fluorescence Polarization Background

Fluorescence spectroscopy has been shown to be an effective tool for monitoring oil contaminants in water. But other fluorescing species in marine environments such as humic compounds and chlorophyll may interfere with direct measurements. One way to mitigate these problems and to enhance the selectivity of fluorescence is to incorporate polarization to the measurement technique. Fluorescence polarization (FP) can be considered as a competition between the molecular motion and the lifetime of fluorophors. If linear polarized light is used to excite an ensemble of fluorophors, only those fluorophors aligned with the plane of polarization will be excited. In particular, heavy oils, which are very viscous, will show significant fluorescence polarization when excited with polarized light.

In developing the Proof of Concept (POC) fluorescence polarization detection instrument was implemented. The main components (Figure 5A) are a miniature fiber optic fluorescence polarizer and a telescopic focusing/collection optic. The fiber optic fluorescence polarizer consists of three miniature optical trains arranged in a backscattering collection probe configuration. The probe telescope is a refractor telescope consisting of a 50 mm diameter, 100 mm focal length objective lens and a 9 mm diameter, 11 mm focal length eyepiece that can be moved manually.

A compact, continuous wave, green (532 nm, 100 mW output) diode-pumped solid-state laser is used for fluorescence excitation. Detection of the two fluorescence polarization components is done with two fiber optically coupled photomultiplier tube (PMT) modules, each incorporating a bandpass filter (40 nm bandwidth) centered at 585 nm. The data acquisition software records and displays both the raw fluorescence signals and also calculates and displays the polarization values. In addition, the software records the GPS signal.

3.4.2 Testing Results

The FP probe was slowly scanned (0.5 knot speed) through each of the oil targets while the FP signal was continuously recorded. In some oil targets, the probe was stopped for some time. Figure 5B shows the FP signal from the oil targets. It can be seen that several strong polarization signals (>0.25) were observed during the scan, and that these FP signals correspond to areas when the probe focus was on oil targets. In several of the targets, the oil samples were partially covered with sand. However, even with these samples, FP signal was still detected. FP grid scans of the test platforms were also successfully performed.

Testing results of the POC fluorescence polarization instrument at OHMSETT indicate that the FP probe is capable of accurately detecting heavy oil in real time. Oil targets in the test platforms showed significant fluorescence polarization signals and can easily be distinguished from ambient backgrounds such as sunlight or background fluorescence. All testing was done during daylight hours, and no interference from sunlight was observed.

3.4.3 Next Steps

The ultimate goal of this project is to develop an autonomous submersible fluorescence polarization detector for heavy oil that can be integrated with different types of deployment vehicles. To achieve this goal, the components of the POC fluorescence polarization instrument will be miniaturized and assembled into a compact instrument and encased in a sealed tubular housing. The FP instrument will incorporate an embedded computer to allow the system to operate autonomously and communicate with the host vehicle.

3.5 WHOI

3.5.1 Background

The WHOI detection system relies on two complementary modes of hydrocarbon sensing: a TETHYS underwater in-situ mass spectrometer in combination with an off-the-shelf UV fluorometer. Laboratory based sensitivity tests indicate that the mass spectrometer is well suited to detect trace levels of volatile short-chain hydrocarbons, while the UV fluorometer is able to detect water-soluble aromatic hydrocarbon components. Gas chromatographic (GC) analysis of hydrocarbon C1-C6 components from samples taken in parallel with TETHYS MS and UV fluorometer data suggest that even when undispersed Bunker C and Sundex 8600 both emit small but detectible amounts of these light hydrocarbons into the water column if no water flow is present. Furthermore, this sensitivity data suggests that because the flux rates are extremely low, plumes of these heavy oil tracers may persist at detectable levels in the calm water column for weeks to months. For localization, the sensor payload utilizes a 150kHz spread spectrum acoustic position system to provide precise estimates of heavy petroleum location. The system's compact size and real-time updates permit geo-referenced estimation of source location at spatial scales of less than 30 meters when surveying at speeds of 5 knots.

3.5.2 Testing and Results at Ohmsett

Tests were conducted within an indoor 7.6 m^3 portable tank (Fast Engineering Ltd., Antrim, N. Ireland) measuring approximately 3.2 meters diameter and filled 0.96 meters deep with fresh water. For all surveys the fixed navigation grid consisted of 3 acoustic elements and was located at the far end far end of the cylindrical tank. In each of these surveys a snorkel intake apparatus (Figure 6A) equipped with an acoustic transducer beacon was moved in a grid pattern through the water in pattern consisting of four parallel tracklines, spaced with approximately 0.5 meter separation and at an altitude of approximately 0.5 meter above the tank bottom. The first survey was conducted as a control, without any hydrocarbons, whereas the second survey was conducted with a hydrocarbon sample in the tank. Data from the second survey reveal a general increase in C1-C4 hydrocarbon levels throughout the tank, with the maximum occurring directly above the container of Bunker C (Figure 6B). Levels rapidly decrease as a function of distance from the container, with the gradient shape closely matching the outline of the oil-filled container. UV fluorometer data collected during the first and second surveys did not exhibit any meaningful change in aromatic hydrocarbon concentrations.

3.5.3 Next Steps

To improve the system, the TETHYS components could be optimized to improve the spectral resolution and sensitivity to the oil fractions identified in the fuel oil. Information regarding the behavior of other submerged oils whether through models or experimentation would be needed to further refine the system.

3.6 Conclusions for POC Phase

The testing objective as a proof-of-concept evaluation was successful. All four of these located oil under the conditions that were given; that is clear water with a limited amount of turbidity or sand covering the oil.

- The WHOI system can detect some oils in a calm water column. But it is not clear how much oil would be in the water column under more realistic circumstances, especially after several days or weeks or with current flow.
- The SAIC system has adapted from an existing system and appears to work in low light conditions. Any future tests should take place in a more realistic environment so that the light levels and focal length are in line with the system performance, conditions that cannot be met in a controlled tank environment.
- Although sonar systems have been used in the past to locate submerged oil, the issue of concern is the turn-around time of the interpretation and RESON appears to be addressing that issue. It is not clear how this system will perform in muddy bottoms where the difference in density between the oil and bottom is closer than the conditions documented in this test.
- The EIC equipment is a new approach and while it may have more risk, it also may have the most applicability. The small size of the equipment may lend its applications to multiple uses including mounting in small ROVs or autonomous vehicles. It also may be small enough to be mounted on a suction head for recovery operations.

The RESON sonar and EIC Fluorosensor were chosen for further evaluation.

4.0 Prototype Tests

A new test configuration was designed using ten 2.4 meters by 6.1 meters (8-feet by 20-feet) trays. These were filled with four types of bottom (stone chip/sand mix, river silt, pea gravel and #100 sand). (Figure 7) Rocks and seaweed were placed intermittently along with the two types of oil from the first test (No. 6 fuel and Sundex), pieces of asphalt and a new slurry oil with a high enough density so that no barite was needed to be added. During the tests, the water temperature was about -1°C with viscosities of the oil ranging from about 80,000cP for the slurry to over 500,000cP for the other two oils.

4.1 RESON Sonar

RESON returned with an algorithm that was embedded in a MATLAB software package. The data transfer and calculations were completed for the entire test section in less than one day for the 400 kHZ runs. Additional tests were done at 200 kHZ. A slow-ping run at 400 kHZ that used 1 ping/second at a tow speed of 0.5 knots was done that is equivalent to using 10 pings/second at 5 knots. These data are not yet available. A GPS input was not provided and the location of the sensor was tracked using the Ohmsett bridge location.

It appears that the software can learn what is most likely oil versus bottom and automatically outlines these areas (Figure 8). This includes complex geometries with oil near rocks and seaweed. While it is relatively easy to separate oil from the bottom, the probability of detection can be increased as more information is known about specific oils and their properties and entered into the model. The resolution of the results was not sufficient to map the exact shape of each of the targets. The evaluation of detection is based on the area of detection rather than the number due to the small number of targets. Overall the five passes over the test trays provided an average detection rate of about 87% with an average false alarm rate of 24 percent.

The actual coverage and resolution is dependent upon the distance between the sensor and the targets and the tow speed. Lowering the sonar closer to the bottom and moving slowly provide the best resolution but increase the time for covering a large area.

4.2 EIC

This company's compact unit (Figure 9A) had some difficulties with the bright sunlight which did not occur in the COP tests. Although some fluorescence was detected (Figure 9B), the input was saturated which did not happen during the previous tests, possibly because it may have been cloudier during the POC tests. The most promising method to compensate is to modulate the laser and look for the returned fluorescence that will also be modulated. A bench top system has been configured and was successful in detection in bright sunlight. The other problem encountered was the fluctuation of the Global Positioning System (GPS). While GPS is good for on the order of one meter, the sensor measurements were taken only 6 inches apart. Positions appeared to overlap each other and a smooth track line could not be displayed. Comparison of the detections to the actual location of the oil targets was done in an ad-hoc manner by matching the shape to the tray layout. A true detection probability could not be calculated.

4.3 Tests of Opportunity

Four vendors came to Ohmsett on their own funds in order to take advantage of the test setup before it was dismantled. None of these systems had their own GPS system so the position of the sensor was determined by tracking the location of the Ohmsett bridge.

4.3.1 Biosonics

This company bought a unit equipped with two single beam transducers (200 kHZ and 420 kHZ) that are usually used to classify substrate (sub-bottom) or submerged vegetation. (Figure 10A) It has a very narrow 6-degrees beam width and weighs about 20 pounds. The system was successful in classifying the oil as a different kind of material in real-time. It was also able to differentiate the 4 types of bottom material that was used. This differentiation is made possible by collecting sufficient data to develop a reference library so that the same bottom material can be recognized and designated as not of interest during a search for oil. (Figure 10B) Oil patches thicker that those tested (1-2 inches) would probably be easier to detect.

4.3.2 Codaoctopus

The EchoScope4D Imaging sonar, operating at 375 kHZ was used for these tests. This is the same system that the CG is evaluating for other uses. It generates 128 by 128 beams in a 50 by 50 degree cone. (Figure 11A). It is typically deployed with a navigation system so that position and orientation is known. Like the RESON system, this uses target strength to differentiate between rocks, bottom and oil. At almost all angles and frequencies, the contrast between oil and sand is about 15 dB and a sample result is shown in Figure 11B.

4.3.3 Megator Pumps

A Sala rollpump from Sweden was bought in to evaluate its usefulness in cleaning up the remaining oil. This has been shown to pump very viscous oils and can pass through stones up to 1½ inches across. A 3-inch pipe was supplied as a suction nozzle and a flange that can add water to create an annulus was also provided. (Figure 12A) The divers tried and pick up the oil in a couple of the areas. The oil was sticky enough to stay on the outside of the probe. Adding the heated water flange at the far end of the probe did not enhance pickup. When the probe was removed and the flange inserted directly into the oil, the pickup was better but was still clogged. (Figure 12B) The diver could collect the slurry oil with a little water but could not move the other oils without a large amount of water being collected.

4.3.4 SRI International/University of South Florida

This organization evaluated an in-situ mass spectrometer similar in operation to the one supplied by Woods Hole. It was larger and did not have a probe to extend the sampling closer to the oil. No oil in the water column was detected with this system although it was successful in a barrel in the indoor area where WHOI also tested the first time.

4.3.5 Overall Conclusions

The technologies represented here represent an improvement over the existing ad-hoc methods. Although these systems have not been tested in the difficult harsh environment of low visibility and the exact target configuration was not rigorously defined, they may be useful immediately in some situations which could reduce the amount of effort and increase reliability of oil detection on the bottom or in the water column.

The multibeam and imaging sonars appear the best sensors to conduct wide area detection. Some of the target strength issues which cause false positive detections for the low grazing angles of common side-scan sonar are reduced. Most systems should be able to automatically pick up large amounts (meters across). Before selecting a sonar system, spill responders should ensure that some type of automated detection is embedded to ensure timely processing. In addition, the sooner that a system is deployed before the oil breaks up, the better chance of detection will occur.

The laser systems and smaller beam sonars may be a better follow-up to the wide scan areas. These should provide better resolution and may be able to calculate general thickness which could provide some information about the amount of oil. The narrow areas covered could introduce resolution issues especially for widely scattered oil. Turbidity also has a large impact on this sensor.

The real-time mass spectrometry systems should be evaluated for neutrally buoyant oil detection in the water column. For some spills, especially those with rough waves or fast moving currents, these instruments may be useful in tracking subsurface plumes. Methods should be developed to deploy multiple sensors or have them placed/towed in critical locations that would permit tracking of the plume. This would be especially useful for municipalities and power plants that use the water for cooling.

Oil collection for thin oils in very cold environments is very problematic. While most viscous pumping capabilities assume that the entire input end of the system is immersed into the oil, more water and sand is collected as the oils cannot flow to the nozzle for thin areas. For any chance of success, the nozzle should be heated and flattened.

These types of systems should be integrated into recovery systems along with visual detection methods for clearer water. The CG RDC has begun a project to develop full recovery system and define specifications that should be completed by 2012.

5 Non-Attribution Policy

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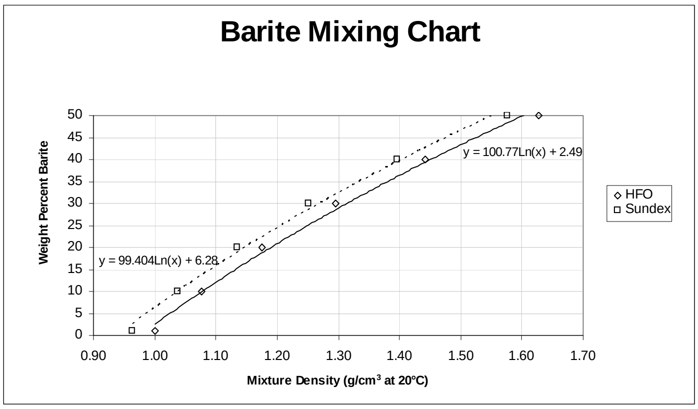

Figure 1. Chart for calculating oil/barite density

Figure 2. Test Trays Under Construction and on Bottom of Tank

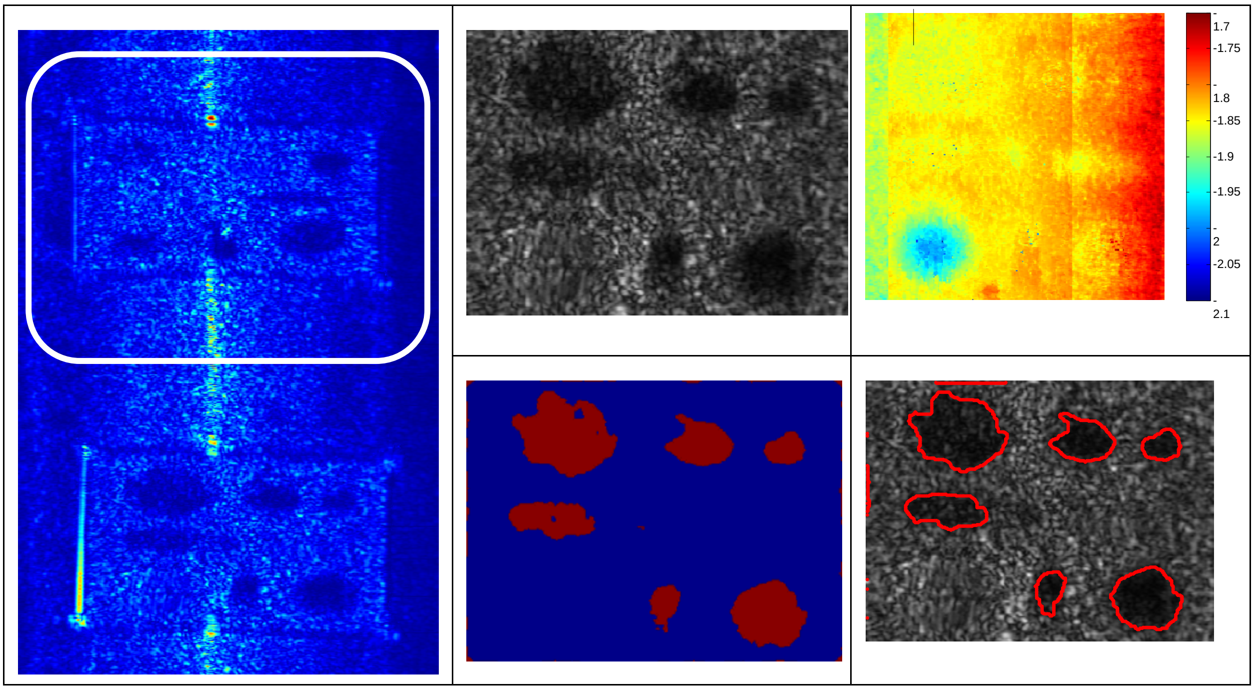

Figure 3. RESON Data with Sonar on Top of Tray (Left Figure: raw data, Top Center: zoomed raw data, Top Right: echo sounder data on same area, w data)

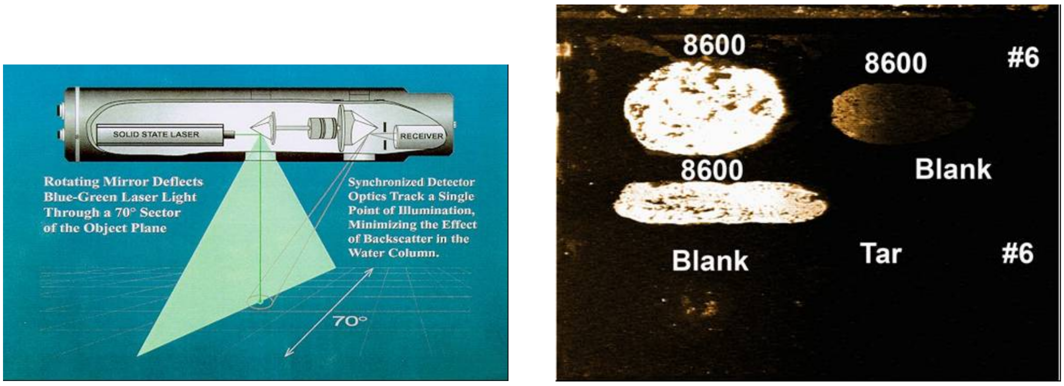

Figure 4. Diagram of the primary components and beam geometry of the SAIC LLSS;(A). Photograph of the LLSS electronics bottle being lowered over the side (B)

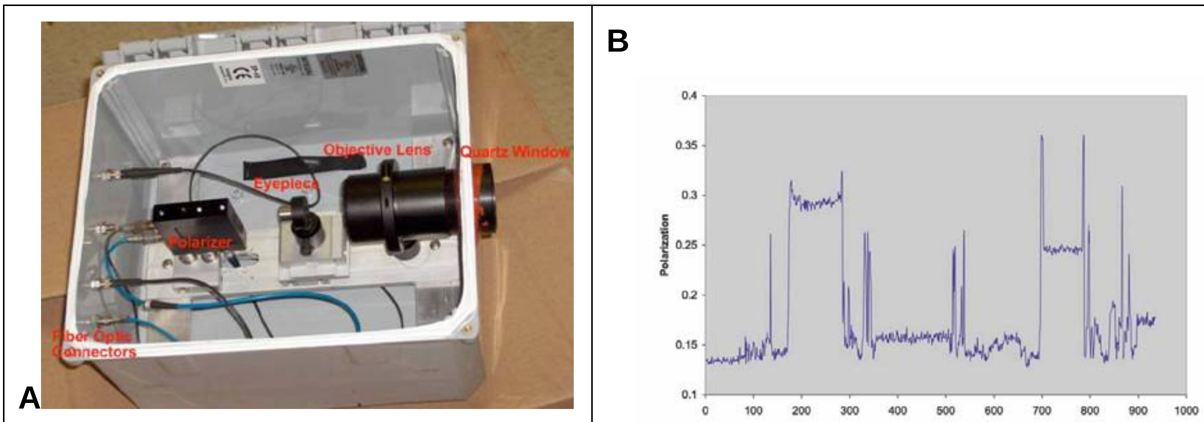

Figure 5. Photograph of the EIC POC fluorescence polarization detection instrument (A) and results indicating amount of polarization (B).

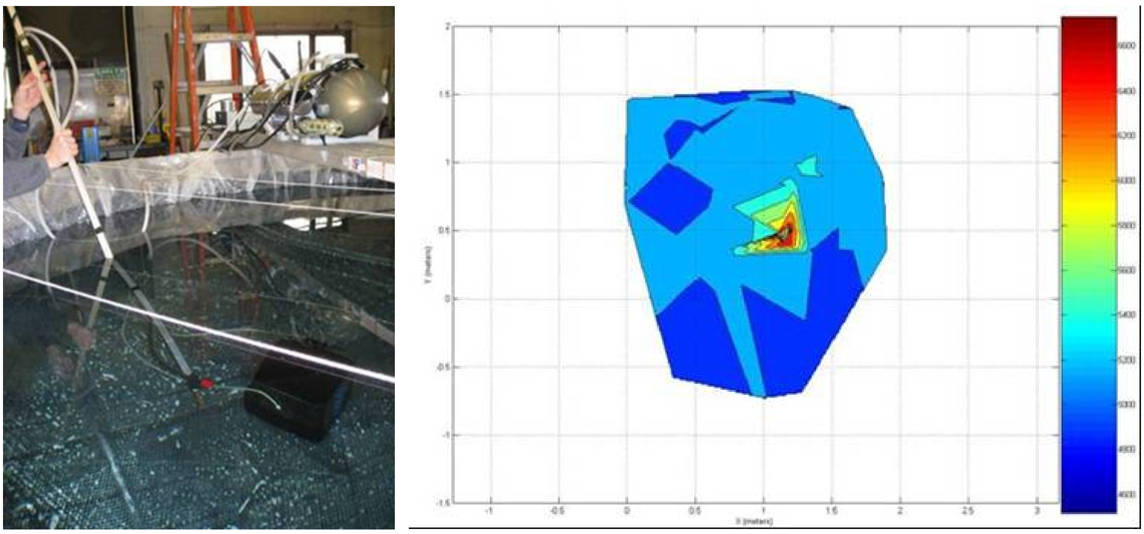

Figure 6: (A) Survey operations to and in Test Tank with Oil-Filled container on Bottom, (B) Results showing higher concentrations in red.

Figure 7. Configuration for Prototype Tests

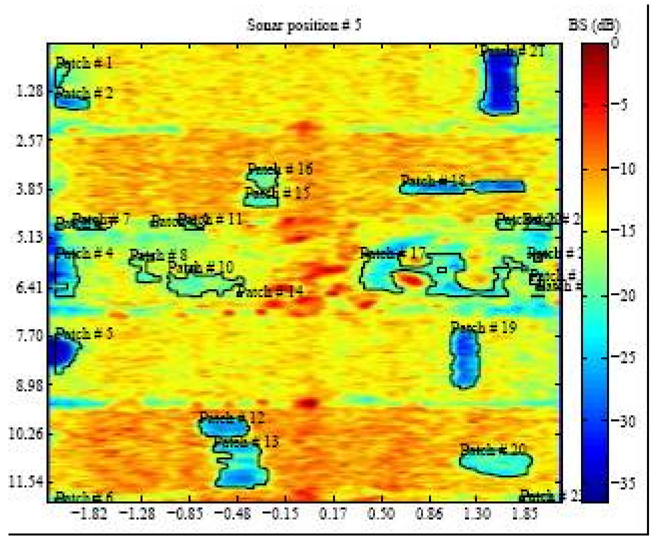

Figure 8. Sample 400 KHZ data for RESON Sonar

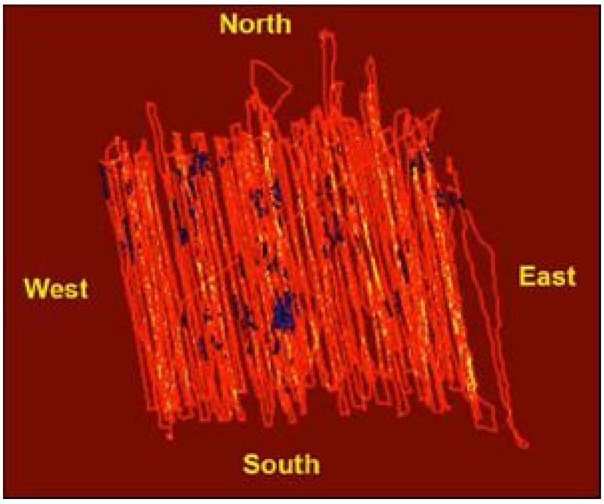

Figure 9. Sensor and Sample Data from EIC

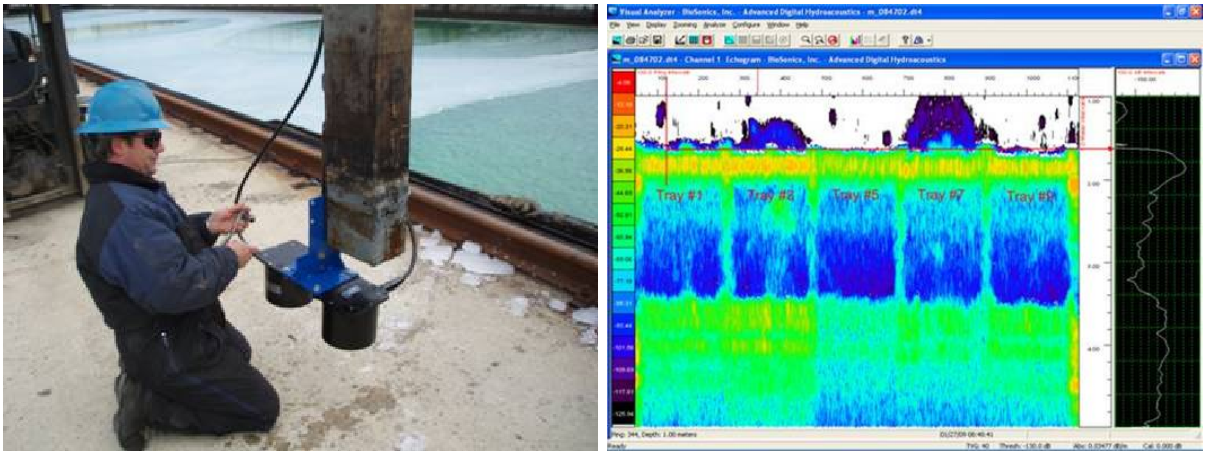

Figure 10. Sensor and Sample data from Biosonics

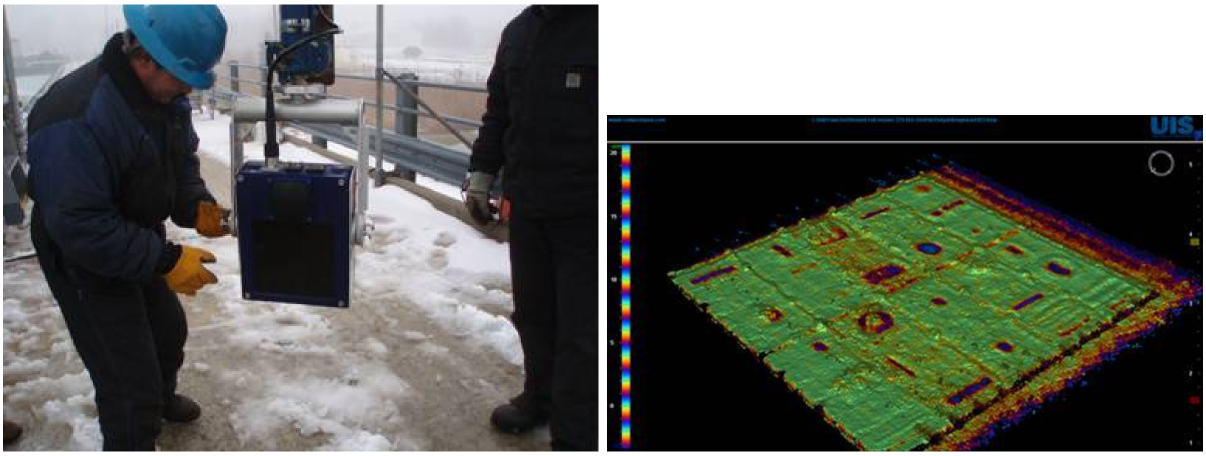

Figure 11. Sensor and Sample Data from Codaoctopus

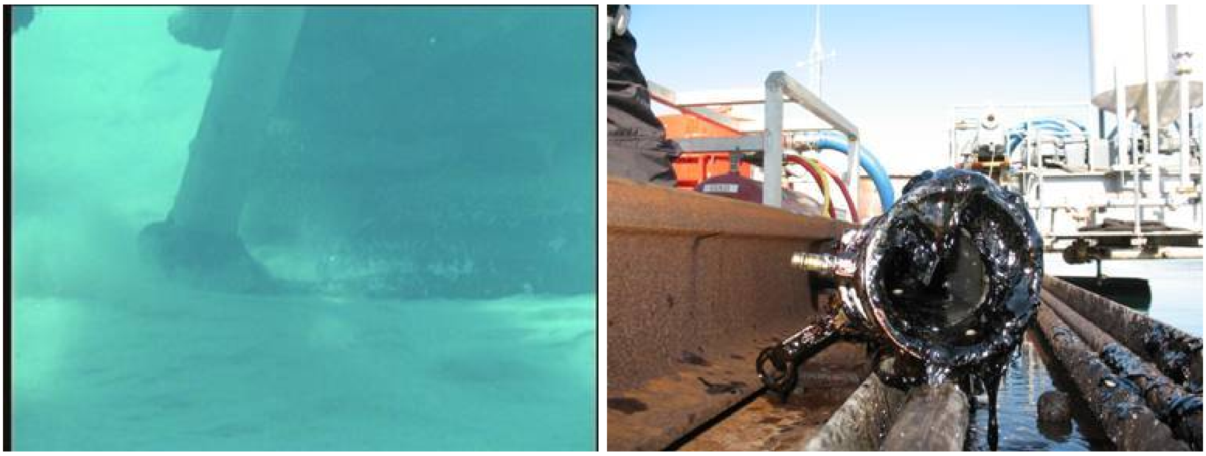
Figure 12. Probe and Hose during Pump Tests