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Detection of Oil within the Water Column

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ABSTRACT 299483:

Current technology makes it difficult to detect and locate oil in the water column and make timely decisions to prevent significant ecological and economic damages. There is a very short timeframe between the start of an oil spill and for the responders to make decisions to protect the environment, numerous water-intakes and commercial facilities located along the shorelines or rivers. Therefore, data needs to be gathered from subsurface detection systems in an accurate and timely manner. However, challenges in detecting oil within the water column include poor visibility in deeper waters, difficulty in tracking oil movements in fast-moving currents and current technological limitations to finding trace amount of oil or dispersed oil at any depth.

This paper captures the planning process, technological descriptions and prototype tests performed at Ohmsett. In November 2011, the Coast Guard Research and Development Center started a multi-year effort to come up with a detection and mitigation system for oil in the water column. The first phase was the design concept for a detection system with 18 goals to be met, including acquiring data in real time (less than one hour), calibrating easily for different types of oil and dispersed oil and working in currents or tow speeds up to 5 knots. Technologies include a multi-beam sonar, a flow-through multichannel fluorometer and a wide-angle scattering that measures the refractive indexes of particles. The second phase is currently underway and focuses on the development and testing of prototype systems. The multi-beam sonar and wide-angle scattering prototypes were tested at Ohmsett in December 2013 but quantitative test results are not yet included as they are still being analyzed at the Research and Development Center. Future plans include design concepts and prototype developments of mitigation systems.

INTRODUCTION:

The Deepwater Horizon oil spill in the Gulf of Mexico was a case that revealed several glaring technological gaps in responding to oil spill disasters. One of the issues was determining the size and location of subsurface plumes and making timely decisions to prevent significant ecological damages. While some advances were made during the Deepwater Horizon incident for tracking underwater plumes, a robust, quick, and efficient technology for scanning and sampling the water column to determine the extent of an oil plume and characterize the oil in the plume (oil type, concentration, droplet size, and physical properties) is needed. The technology would need to provide data in real-time and be presented in an easily comprehensible format to enable a more efficient monitoring of the submerged plume and possible initiation of countermeasures and recovery.

Most spills occur over a shorter period of time and closer to shore than the Deepwater Horizon oil spill. Often there is a very short timeframe for decision making to protect the environment and critical infrastructure. Challenges in detecting oil within the water column include poor visibility, difficulty in tracking oil movements in fast-moving currents, and not being able to discover very low levels of oil or dispersed oil at all depths. Current subsurface oil sensing technologies are tailored for detecting oil at a single location and must be moved along numerous transects over a period of time to accurately map contamination horizontally and vertically.

Objective

To address this technology gap, the USCG Research and Development Center (RDC) is undertaking a Research and Development (R&D) effort to identify and/or develop a system that can detect and characterize oil that is entrained and dispersed in the water column. This report summarizes the results of Phase I (Concept Design) of the effort in which remote sensing technology developers were solicited through a Broad Agency Announcement (BAA) to configure and describe systems that were at least at the proof-of-concept stage of development that could potentially address the remote sensing of oil in the water column. Two vendors responded describing and proposing three systems for further development in three separate reports. The next phase (Phase II – Development and Testing) involves further development, refinement and integration of the technology components in a field-deployable configuration, and testing prototypes in a simulated oil spill environment at the Ohmsett facility (now called The National Oil Spill Response Test Facility).

Design Criteria

The RDC had 18 requirements that were to be addressed in the proposals for the Concept Design phase. Table 1 on page 11 describes how each criteria were addressed by each of the three proposed technologies. The criteria in Table 1 are listed in the order of importance.

PROPOSED DESIGN CONCEPTS:

NORBIT Wide Band Multibeam Acoustic Camera

NORBIT's Wide Band Multibeam Sonar (WBMS) platform is based on modern components and extensively uses Field-Programmable Gate Array (FPGA), as well as Digital Signal Processor (DSP) technology to maximize the flexibility of the system. This creates a very flexible platform as most aspects of the sonar can be changed in firmware and does not require extensive redesign. The WBMS is an acoustic sensor that can provide 3D topology of the oil plume. The WBMS sonar (Figure 1) is specifically designed as an ultra wide band (160 kilohertz (kHz) band width) very compact unit, with low power consumption. It operates at a nominal frequency of 400 kHz. Also, the sonar has integrated processing capabilities so that processing of water column scatters can be generated in the sonar head itself.

Figure 1. WBMS sonar.

Some tests were conducted prior to the Phase II testing. This was done primarily to reduce the risk of non-performance for the tests in Phase II and to improve on the setup scenarios. One test was performed using dispersed oil in water (oil treated with dispersant) at Ohmsett in August 2012. Two WBMS sonars (see Figure 1) were used in the setup. Sonar configurations were both in the normal forward-looking sonar (FLS) mode and in a vertical mode "scanning" the tank. Both sonars were mounted at mid-water in the column oriented horizontally across the longitudinal axis of the tank throughout the experiment. The images produced acoustic anomalies that were associated with the dispersed oil plume entering the water column (Balsley et al., 2013). See Figure 2 for the sonar image of the dispersed oil plume in the water column.

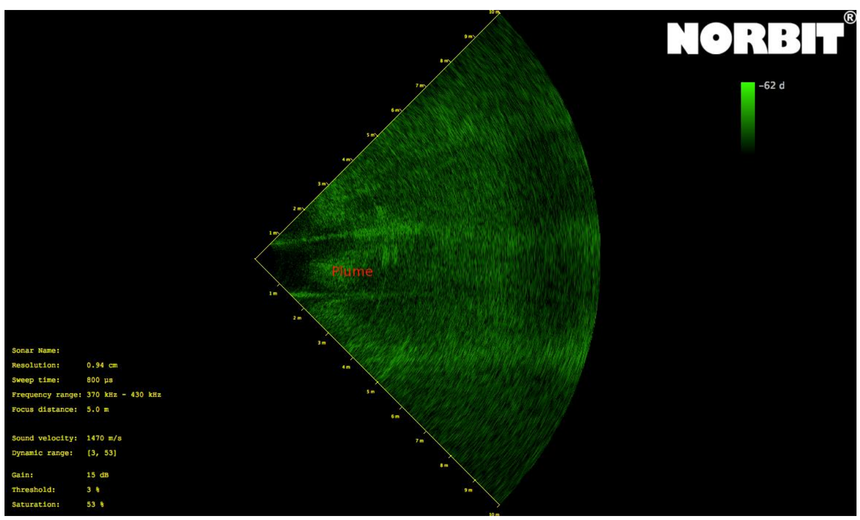

Figure 2. Sonar image of a dispersed oil plume deeper in the water.

The system can survey a wide area of the water column, easily meeting the 3 feet by 3 feet areal coverage target cited in the BAA. The system was already deployed and tested in the Ohmsett tank prior to Phase II testing, albeit only for a short time.

The primary disadvantage of the system is the inability to conclusively discriminate petroleum hydrocarbons from other materials which may have a similar acoustic signature. Identification of the acoustic anomaly/material encountered often requires a complimentary sensing technology. The system may be able to detect oil in the water column, but positive identification and characterization may be difficult, especially if the oil disperses as individual droplets. There is no certainty that acoustic imagery will be able to determine oil concentration or physical properties. The physical size of the Ohmsett test tank limits the ranges that can be tested where detection of oil is possible. Also, the reflections from the tank walls appear to have interfered with the detection of oil during Phase II testing. However, it is possible to establish a detection threshold from shorter range data not subject to the interference from the tank reflections, which can be scaled to longer ranges to assess detection effectiveness. In addition, acoustic profiling at multiple frequencies generates a large amount of data which must be stored and processed. This may limit real-time availability of data and imagery to support rapid decision-making. Finally, computer-automated interpretation and mapping of acoustic imagery is challenging, and real-time interpretation currently requires subjective analysis by a trained operator.

WET Labs WINDOW

The WET Labs WINDOW design is a compact, multi-angle scattering instrument with an automated inversion algorithm and intuitive smart phone display that will quantify the size distribution and abundance of emulsified oil droplets in water and determine the refractive index of the oil to readily derive density and viscosity.

The technique of wide angle scattering relies on the dependency of light refraction and reflection on the sizes and refractive indexes of the particles. For oil emulsions, the latter (refractive index) is a close analog to density and viscosity (Vargas & Chapman, 2010). Particles that are most readily detected and quantified with this technique are those that are nearly spherical, namely bubbles and oil droplets, because such particles produce spherical lensing effects characterized by distinct and unique constructive and deconstructive interference patterns in angular scattering. When superimposed on smooth, regularly shaped scattering functions from naturally occurring background particle populations, these unique scattering functions can be readily discriminated and then used to derive concentration, size, and density of the suspended emulsion.

The entire sensing system will consist of an in-water sensing package, surface deck unit with laptop computer and integrated GPS, and a deep cycle 12 VDC battery if ship power is not available (Balsley et al., 2013). Data in the form of mapped oil properties will be broadcast wirelessly through the cellular network from the laptop computer and will thus be made available to all interested parties with cellular access.

The Environmental Characterization Optics (ECO) sensor will transfer raw data to a surface deck unit with operator Graphical User Interface (GUI) and display data on a laptop. There is the possibility of wireless broadcasting of compressed, low file size jpeg pictures of relevant data for any parties involved in an oil spill response via easily accessible smart phone technology. Larger files in kml format compatible with Google Earth will also be broadcast that will contain several additional layers of information that will plot automatically for computers equipped with free Google Earth software.

The primary objective of Phase I lab testing at the WET Labs’ facility was to quantify the accuracy and sensitivity of the technique for emulsions of different oils in purified salt water and natural seawater. Six total experiments were conducted. Three sets of experiments were carried out with emulsions suspended in purified salt water and three sets were with emulsions in natural seawater collected from Narragansett Bay. Inversion algorithms in various forms of refinement were then applied to the data to derive the concentration, size distribution, and refractive index of the emulsified oil. Accuracies in size distributions and concentrations were evaluated from coincident measurements with a digital holographic imaging microscope.

Figure 3 shows derived oil densities from inversion results. The emulsion oil density was estimated as the average of the densities of each subpopulation weighted by their respective concentration. The solid points at Measurement No. (number) zero (0) and the associated dashed lines are the presumed densities of the oils from the literature. Derived oil densities are in satisfactory agreement with literature values.

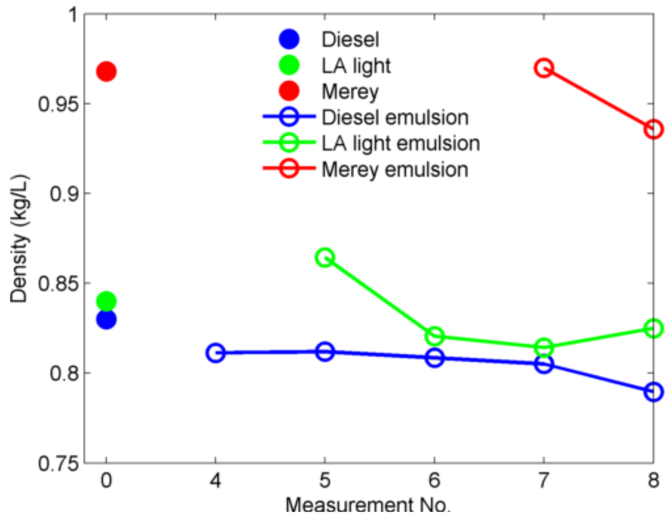

Figure 3. Derived oil densities from inversion results.

WET Labs summarized the test results as follows:

- The inversion technique is effective in identifying the presence of oil droplets and quantifying their concentration with accuracy better than 10 percent.
- The inversion technique is effective in quantifying size distributions of emulsified oil droplets with precision of 1-2 microns (μm) in determining modal droplet size.
- The inversion technique is effective in quantifying emulsified oil density with accuracy generally better than two percent. Because a high degree of aggregation of particles did not occur during this experiment, scattering functions representing aggregate subfractions were not used in the inversion library.
- Optical windows can be rapidly fouled by dispersed oil, requiring wiping of the interface to ensure accurate results.

The major challenge associated with the technology appears to be the workload in developing the inversion algorithms implemented in the Look Up Table (LUT) that accounts for the wide variety of oil types that might be encountered against varying backgrounds of other types of suspended material in a marine environment. The situation is further complicated by the existence of oil droplet-particulate material aggregates which will require separate inversion algorithms. There is an inherent assumption that the dispersed oil plume is constant and homogeneous outside of the sample volume, and that the oil has not been affected by weathering which changes the properties from those registered in the LUT.

WET Labs FINDS OIL

The Fluorescent IN-situ Detection System for OIL (FINDS OIL) system is comprised of a towed body containing multiple sensors, software, and a data transfer system. Sensors for multi-parameter sensing provide hydrographic properties, oil detection, oil property estimation, and are used to minimize false positives. The mixing integration sensor will measure fluorescence and backscatter and be mounted at the rear of the towed body to sample the mixed volume of water entrained behind the towed body. The other sensors (Multichannel WETStar; dissolved oxygen sensor; and conductivity, temperature, and depth (CTD) sensor) are flow-through sensors such that water is pumped through the sensor from an intake at the center of the nose cone to an exit port on the side of the towed body.

The WETStar fluorometer allows the user to measure relative chlorophyll, colored dissolved organic matter (CDOM), or other concentrations of fluorescing materials (e.g. hydrocarbon aromatics) by directly measuring the amount of fluorescence emission from a given sample of water illuminated by an ultraviolet (UV) light source. The sample media is pumped through a quartz tube mounted through the long axis of the instrument. These samples, when excited by the WETStar internal light source, absorb energy in certain regions of the visible spectrum and emit a portion of this energy as fluorescence at longer wavelengths. The WETStar utilizes three excitation and emission (Ex/Em) pairs for CDOM discrimination, fluorescence intensity ratio (FIR) calculation, and oil concentration. The FIR is used as an index to explain how well oil is dispersed in a given water body (Kepkay, et al., 2011). Please see the RDC report written by Balsley et al. (2013) to learn more about its experimental results.

The primary limitation of previously used towed fluorometers is that they sample the water column at a specific point and do not provide information on the areal extent of the hydrocarbon contamination measured (such as the 3 feet by 3 feet areal sample window specified in the BAA). The FINDS OIL system seeks to correlate measurements in the flow-through fluorometer with fluorescent backscatter measurements from a sensor mounted in the rear of the towed body facing backwards (aft). The concept is that water in front of the towed body will be entrained and homogeneously mixed in its wake such that if the fluorescent backscatter from the entrained water indicates the presence of oil even with the mixed volume 2 to 4 feet away from the instrument, then it can be assumed that the instrument is in an oil plume. However, the sensor on the rear of tow-body requires turbulence to gain proper mix of oil and water.

As with other optical sensors, fouling of the sensor window in heavy oil concentrations may be a problem and require periodic cleaning, particularly in the flow-through WETStar fluorometer. Fouling should not be a problem with the backscatter sensor facing aft.

REQUIREMENTS MATRIX:

Table 1 summarizes how each system meets the BAA requirements, listed in order of importance.

Table 1. Requirements matrix.

Capability	NORBIT WBMS	WET Labs FINDS OIL	WET Labs WINDOWS
1. Provides results in near real time (less than 1 hour)	Depends on platform	Constant	Demonstration results provided in < 1 minute
2. Calibrates easily for different oils	Data processing is necessary	Factory calibrated	Factory calibrated
3. Detects oil at depths up to 200 feet	Depends on platform	Yes	Specified sensor package has a rating of 800 feet
4. Works in currents or tow speeds up to 5 knots	Yes	Yes	Function of deployment method
5. Reports minimal false alarms	Work needed	Multi-parameter data used to minimize false positives.	Reports of false positives or false negatives are not expected.
6. Allows smooth data flow from field to command center	Yes (wireless phone modem)	Yes	Yes
7. Detects dispersed oil at levels of 0.5 ppb or lower	More work needed to understand what is being detected; ppb not addressed.	Current system detection limits are 36 ppb.	Current detection limit for the scattering signal is about 10 ppb.
8. Sweeps an area of water column 3 feet by 3 feet	Yes	No	This is a point source measurement.
9. Provides digital readout or measured values and digitally logs field data	Yes	Yes	Yes
10. Is field rugged	Yes	Yes	Yes
11. Is portable	Yes	Yes	Yes
12. Compatible with fresh and salt water	Yes	Yes	Yes
13. Determine droplet size, density (specific gravity) and/or kinematic viscosity	Further tests are needed; probably not.	Oil density, dispersant-to-oil ratio, and an estimation of oil type will be provided.	Yes
14. Adapts to various depths (deep vs. shallow)	Yes	Yes	Yes
15. Operates from vessel in variety of conditions	Yes	Yes	There are no foreseen limitations in terms of environmental conditions from a vessel
16. Deploys quickly and easily	Yes	Yes	Yes
17. Measures dissolved oxygen	No	Yes	Yes
18. Grabs water samples for further laboratory testing	No	No	No

CURRENT WORK:

The Norbit WBMS and WET Lab WINDOW systems were chosen to proceed to the prototype development and testing phase. The following capabilities were tested at Ohmsett in December 2013 for each prototype:

1. Provides results in near real time (less than 1 hour).
2. Calibrates easily for different oils.
3. Works in currents or tow speeds up to 5 knots.
4. Reports minimal false alarms.
5. Detects dispersed crude oil.
6. Sweeps an area of water column 3 feet by 3 feet.
7. Provides digital readout or measured values and digitally logs field data.
8. Is field rugged.
9. Is portable.
10. Determines droplet size, density (specific gravity) and/or kinematic viscosity.
11. Deploys quickly and easily.
12. Grabs water samples for further laboratory testing.

Plans for 2014 to 2016 include design concepts and prototype developments of oil mitigation systems.

Descriptions of Tests Performed at Ohmsett

Diesel and Anadarko crude oil were chosen to be released into the oil based on their residence time in the tank without Corexit 9500 and their wide range of droplet sizes. Each plume lasted approximately 4-6 minutes, which was adequate to allow the prototypes to collect a sufficient amount of data. With Corexit 9500, the average residence time of the plume of each type was approximately 15 to 20 minutes.

Figure 4 shows an oil release in the Ohmsett tank that is set 6 inches from the bottom, which will be the typical setup. It was equipped with three to five nozzles and the Laser In-Situ Scattering and Transmissometry (LISST) instrument will serve as a validation tool.

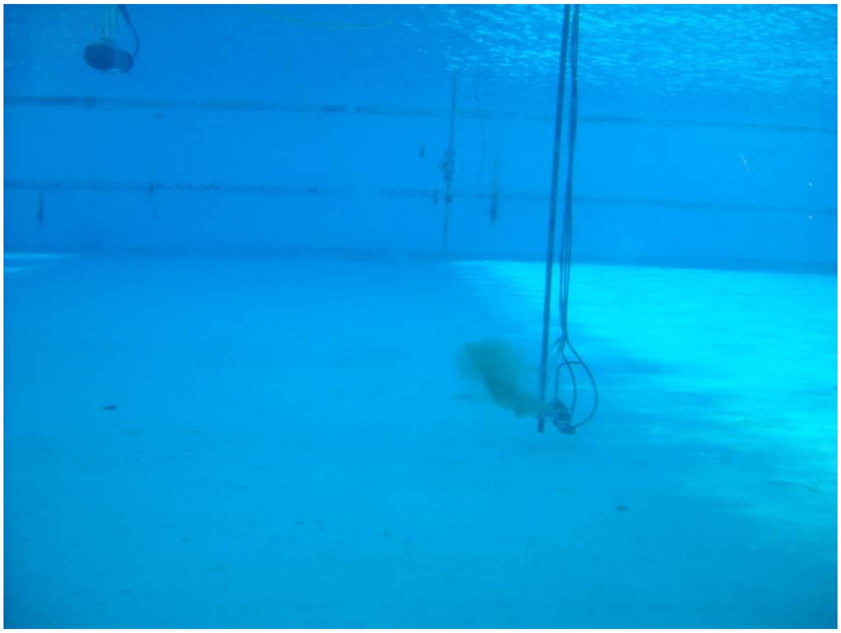

Figure 4. Oil release mechanism in the Ohmsett tank to be used for Phase II.

Figure 5 and 6 show the prototypes of WET Labs and Norbit, respectively.

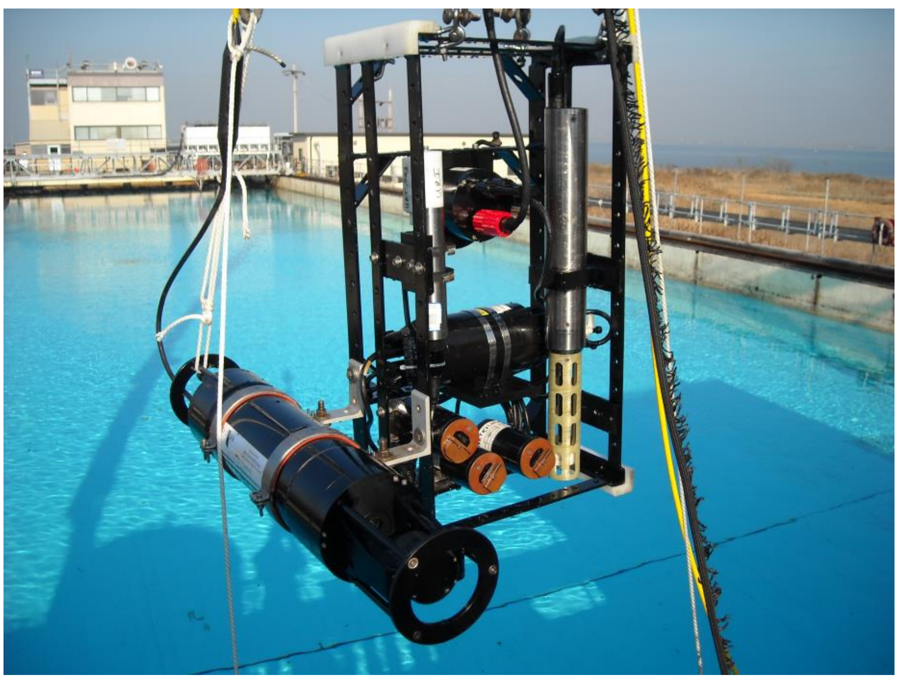

Figure 5. WET Lab WINDOW prototype held by the main bridge crane.

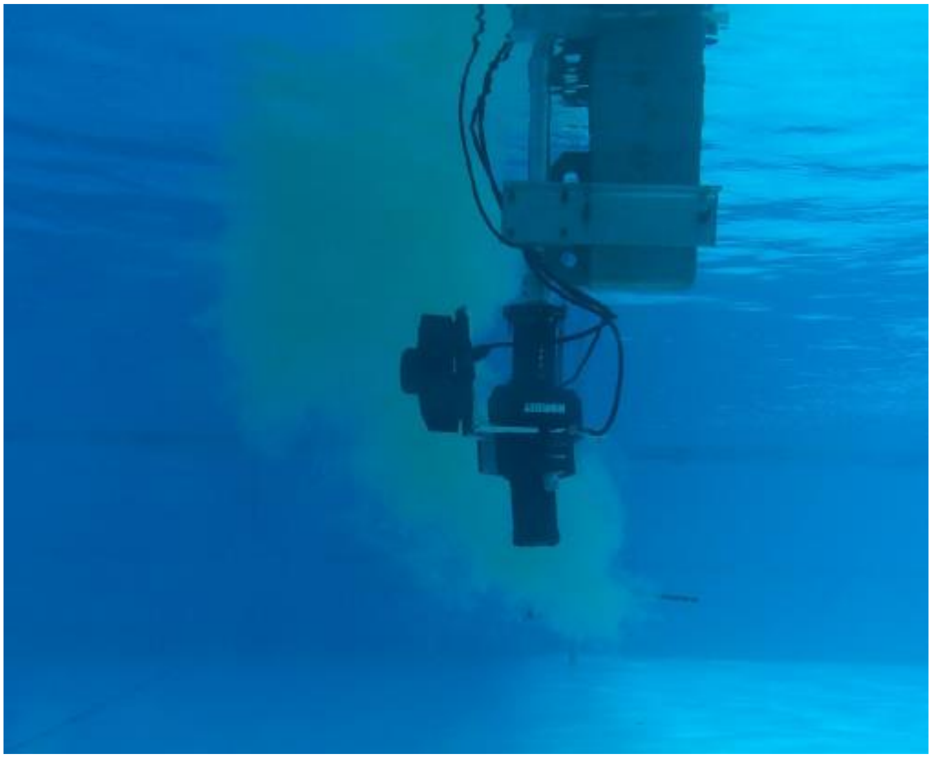

Figure 6. NORBIT WBMS prototype in action.

During WET Lab's week of testing, stationary plumes of each oil type were released into the main tank and WINDOW was able to detect the oil droplets during stationary and pass-through runs. East-West (across the width of the test tank) plumes of 30 feet (6 minute release) were created with Anadarko crude with Corexit 9500 and Diesel with Corexit 9500. Straight oils were not used for the East-West plumes because of their low residence times in the tank. With the East-West plume test runs, the cage was located at the west end of the bridge and after a pass through, it was moved five feet to the east. With the sensors facing in the direction of travel, the prototype again performed a pass through the oil plume. At the end of the pass-through, the prototype was rolled five more feet to the east and the process was repeated until the prototype reached the 25 foot mark on the bridge. It was then moved five feet to the west, back to the 20-foot location and the process was repeated until the cage reached its original location at the west end of the bridge. This is a mowing pattern and could be used to survey a river with suspected oil release in the real world. WET Labs indicated it obtained good data during these test runs.

An additional test included an oil release of differing droplet sizes by outfitting the oil release mechanism with four different size nozzles. The oil was released through this setup for approximately 100 seconds. The prototype was then moved vertically in the water column, starting from the bottom to the top, then from the top to the bottom, and then from the bottom to the top again. From the bridge, it appeared that the water column was heavily saturated with the oil- most likely due to the larger droplet sizes. The prototype was still able to collect data. Finally, because the pass-through runs had been operated at 0.5 knots, it was desired to see if the prototype could detect oil at a higher speed. Even though the prototype is not designed to be towed (their tow design was not used), the bottom of the cage was tied down to the bridge and it was moved through the plume at a maximum speed of 3.5 knots with successful data collection.

NORBIT collected a large amount of sonar data during its test week. The cement sides and bottom of the Ohmsett tank caused a large amount of extra noise through bouncing signals and reverberation. The biggest offenders, besides the tank, also included the frames of the viewing windows and the post supporting the nozzles and camera that recorded the video. There appeared to be a small current in sections of the tank due to the circulating pump and wind causing the plumes to move away from the original location for the first two of days. NORBIT was able to select positions based on the minimum amount of noise but could only collect reliable data up to about five meters from the edge of the plume.

For the first two days, the sonar was mounted near the bottom with the sonar pointed slightly upward. A rubber car mat was hung below the system and worked to damp out some noise but it still was not sufficient. The sonar system was switched on the third day after a faulty cable was replaced and this allowed the pan and tilt unit to operate, giving the operator better control of the device. The sonar system was placed closer to the surface looking down and it resulted in data being obtained from 18 meters away.

In general, the data taken in the two meter range is well above the local noise minimum and will be useful in calculating target strength of an oil droplet plume for the two oils both with and without dispersant. Much of the other data will be post-processed and calculations should be able to determine parameters for larger distances.

FUTURE WORK:

The RDC is currently working on consolidating all the data collected from WET Labs, Norbit and Ohmsett to put on one comprehensive, final report. The report will attempt to compare the vendors' data to the LISST data collected by Ohmsett. It is expected to be available to the public in July 2014.

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REFERENCES:

USCG Internal References: Vendor-Specific Design Reports

Eriksen, M. T., P. K. Eriksen, and A. Søraunet, USCG Contract HSCG32-12-C-R00005, Detection of Oil in the Water Column: Utilizing Ultra Wide Band Multibeam Acoustic Camera; Design Concept Final Report, Phase I. Norbit US Ltd, 2012.

Koch C. and M. Twardowski, Fluorescent IN-situ Detection System for OIL (FINDS OIL), Phase I Report. Western Environmental Technology Laboratories Inc., 2012.

Twardoswki, M., USCG Contract Number: HSCG32-12-C-R00012, Wide-angle-scattering Inversion to Detect Oil in Water (WINDOW). Western Environmental Technology Laboratories Inc., 2012.

Additional References

Balsley, A., Fitzpatrick, M., & Hansen, K. (2013). Detection of Oil within the Water Column, *Arctic and Marine Oilspill Program*, June 4-6.

Kepkay, P., Bugden, J., Li, Z., Lee, K., Coble, P., Conmy, R., & Wood, M. (2011). Tracking Oil Dispersion in the Gulf of Mexico by Fluorescence Intensity (FI) and the Fluorescence Intensity Ratio (FIR), *2011 International Oil Spill Conference*, American Petroleum Institute, poster.

Vargas, F.M. and Chapman, W.G. (2010). Application of the One-Third rule in hydrocarbon and crude oil systems, *Fluid Phase Equilibria*, 290, 103-108.