Report to BSEE: Oil Leak Detections with a Combined Fluorescence Polarization Instrument and a Wide Band MultiBeam Sonar

Phase II Final Report

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Executive Summary

EIC Laboratories, Inc. and Norbit US Ltd. have developed a combined telescopic fluorescence polarization (FP) sensor and wide band multibeam sonar (WBMS) as dual sensors for detecting underwater oil leaks and plumes. In response to the need for reliable tracking and mapping of heavy oil spills, EIC has developed a prototype, forward-looking, fluorescence polarization instrument that can detect oil at a standoff distance. The instrument responds only to materials showing fluorescence polarization, and therefore is able to distinguish oil from other fluorescing species in water. Norbit has been developing WBMS for mapping and water column imagery for oil and gas. The combination of the two sensors will result in a more definitive identification and mapping of oil in the water column co-registered in time and space. The sonar provides a 3-dimensional map of the oil while the FP sensor will confirm the presence of oil in the sonar image since the FP sensing scheme is specific to the presence of oil, whereas the sonar detects differences in reflectivity and attenuation within the water.

In Phase I, we designed a new FP instrument that enhanced the sensor long-range detection capability and with improved electronics. The FP instrument employed a 4" telescope objective lens, resulting in 4x improvement in the telescope collection efficiency over the old FP instrument. A 404 nm laser was incorporated into the new FP instrument to better enhance the light absorption of oils. The aromatic hydrocarbons in oil will absorb more energy if the excitation wavelength is shifted to lower wavelength resulting in stronger fluorescence emission. In addition, the laser emission power is 400 mW, which is much more intense than the 50 mW, 532 nm laser used in the previous FP. As a result of these improvements in the instrument, it was shown that the FP instrument is capable of detecting oil fluorescence in air at 100 feet distance.

Integrated detection software, which controls both the FP and WBMS instrument, was developed in Phase I. This LabView based software automated the detection and verification of leaks using data from the WBMS and FP instruments. The detection process is started by acoustically sweeping the space in front of the sensors looking for motion in the water column. If motion is detected, the data is then processed and if the persistency exceeds some predefined threshold, that area is considered as a leak and an alarm is generated. The topside software processes the alarms and decides if they should be verified with the FP instrument. The FP instrument, which is mounted in a pan/tilt positioner, is then directed in the proximity of the detected leak. A scan is then performed in the predefined sector. If a response from the FP is generated during the scan, the scanned sector is then flagged as a hydrocarbon leak.

The integrated FP and WBMS instruments were tested in a controlled tank at the US Army Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH. An underwater mounting scheme was developed that mounted all the instruments on a common platform so that they could interrogate the same area. A high definition video camera was also included in the instrument suite. Two sonars were mounted in the platform, a 200kHz WBMS and a forward looking sonar (FLS). The 200 kHz sonar was used to obtain a wide view of an area and used to identify probable oil leaks. Three sensors were mounted on a pan-tilt positioner: the FP, FLS and video camera. Through software, the pan-tilt can be programmed to obtain several point measurements in a suspected leak areas. The FLS is mounted on the pan-tilt so that it's field of view overlaps with the FP scan range. The FLS, which has a narrower field of view than the 200 kHz WBMS, provides a close-up image of the probable leak. In addition to the sonar, the HD

camera, with its field of view also directed to the FP scan range, provides an additional visual image of the area that the FP instrument is interrogating. All the instruments are connected to a processing bottle that contains an embedded computer and power supply that powers all the instruments. The embedded computer contains the software that controls the operation of all the instruments and connected to a computer above via Ethernet. The top computer is used by an operator to remotely control the bottle computer, run the control software in the bottle computer and execute the detection scheme.

The CRREL in tank testing was able to demonstrate that a combined fluorescence sensor and wide band multi-band sonar works very well in tandem to identify and verify the presence of oil in the water column. Two different targets were presented to the leak detection instrument suites. One target was a small plastic container containing oil dropped into the water column and an actual release of oil in the water column. In both cases, the sonar was able to identify the targets as possible oil leaks which then triggered the FP instrument to be positioned into the suspect area and verified the leak to be hydrocarbon by the fluorescence signature.

In Phase II, the integrated FP and WBMS instruments were tested in open water using oil simulants and targets. The open water testing was conducted at the California Polytechnic State University pier at Avila Beach in San Luis Obispo, CA. Since it was not possible to actually release oil in open water, simulated oil targets that emit fluorescence and that can be detected with the sonar were used to challenge the sensors. First, ground up kelp that was suspended in water and then introduced into the water column as plume was used as target. A submersible nozzle assembly connected to a pumping mechanism up top was used to generate the kelp plume. However, because of the strong swell encountered during testing, it was not feasible to keep the plume suspended in the water column and be detected. The swell quickly carried and dispersed the kelp plume as the plume was released from the pump nozzle. Immobilized targets were made from a kelp solution contained in a plastic bottle and a buoy wrapped with a fluorescent cable. These targets were attached to a string and then suspended in the water column. The 2 sensors successfully detected these targets, although only at short distances (1-2 meters) with the FP sensor. The limited detection range of the FP sensor is due to poor visibility in the water column. The complimentary detection scheme of the combined FP and WBMS sensors, however, was further demonstrated in the open water environment to work effectively in detecting possible oil leak targets.

1 Introduction

Global demand for oil has resulted in an increase in oil production and its byproducts. The transportation of oil through pipelines and tankers increases the risk of polluting bodies of water. Even with strict rules and regulations of oil transportation and oil explorations, accidents leading to oil spills still frequently occur. Numerous accidents occur annually, with thousands of tons of oil being spilled into aquifers, resulting in the contamination of marine environments and endangering marine ecology. The Deepwater Horizon oil spill in the Gulf of Mexico clearly shows the magnitude of environmental problems that can occur with an oil spill. Reliable oil spill and leak detection instruments are needed that can be used as early detection and warning systems for oil leaks and spills so that proper and effective remediation measures can be implemented immediately. Ideally, sensors that can operate at a standoff distance and interrogate a wide area are preferable and will be more effective in tracking oil leaks and plumes in the water column.

2 Background

Several oil spill detection methods based on radio wave reflection suppression and oil fluorescence or contact electrical sensors have been developed. Radio wave radars operate well in open seas, where sea surface waves are stable, but in closed coastal areas they are much less effective. On the contrary, application of contact electrical or fluorescence sensors is limited to small high-risk areas. Remote laser induced oil fluorescence is probably the most reliable method allowing oil detection on any surface. A number of airborne fluorescence lidars have been developed as well. Some of them currently operate to monitor spills in active sea traffic regions. However, airborne lidar fluorescence is very expensive, not applicable for long term continuous spill monitoring, and not able to detect deep underwater oil contaminants. It is also susceptible to interference from other fluorophors in water such as humic compounds and chlorophyll. The high cost of lidar fluorescence is mainly due to the pulsed excitation/gated detection scheme employed in the instrumentation in order to minimize backscattered ambient light background during daylight operation. Thus, in order for fluorescence detection to be more effective in oil spill detection, these limitations will need to be overcome. Other technologies to detect oil leakages involve aircrafts, long-range radar and surface vessels. However, in many oil leaks, the leak may originate kilometers under the surface. Current oil leak detection methods are expensive and difficult to operate efficiently and rely on unsophisticated visual reports, which are not consistently accurate, and more importantly a leak detected at the surface may be far from its origin. Submersible oil detectors are more appropriate and reliable since they can be deployed in situ and near the leak.

In response to the need for reliable tracking and mapping of heavy oil spills, EIC Laboratories has developed Oscar™, a forward-looking fluorescence polarization instrument. The instrument responds only to materials showing fluorescence polarization, and therefore is virtually free from false positives. The FP sensing scheme has been patented by EIC Laboratories. Figure 1 shows a photograph of the FP sensor. Unlike traditional fluorimeters used for underwater measurements, Oscar™ employs a laser projected telescopically outwards from the instrument body. As it is deployed near the seabed, the laser is automatically focused on the subsurface using feedback from a sonar altimeter. Fluorescence from the focused, polarized laser source is collected in 180^{o} backscatter by the same telescopic optics and is separated optically into its vertically and horizontally polarized components. After passing through wavelength selective filters, the intensity of these components is measured using separate photomultiplier detectors. As currently configured, Oscar™ is capable of detecting fluorescent objects at distances ranging from near contact to 25 meters away. Recently, a scanning version of the FP sensor has been developed that allows 2-dimentional FP mapping without moving the instrument.

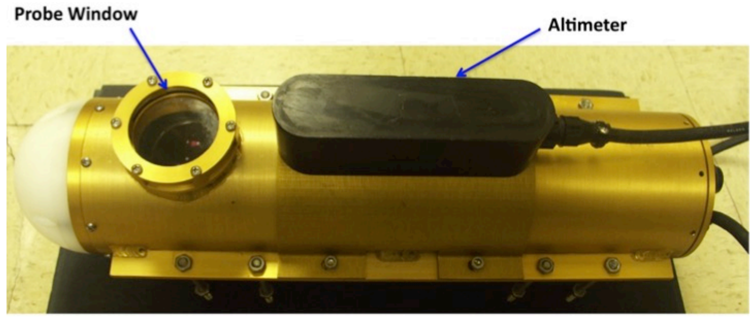

Figure 1. Photograph of the fluorescence polarization sensor.

In a typical FP measurement, the sample containing the fluorescing species is excited with linear polarized light, and the vertical and horizontal components of the intensity of the emitted light are measured. The polarization (P) is calculated as

$$P = (I_v - I_h)/(I_v + I_h)$$

where I_h and I_v are the fluorescence intensity for the vertical and horizontal components. The amount of polarization retained in the emitted fluorescence will depend on how much the molecule has rotated during the lifetime of the fluorescing excited state. Thus, the fluorescence polarization depends on the fluorescence lifetime and the rotational correlation time (θ). The rotational correlation time is given by $\theta = \eta V/kT$, where k is the Boltzmann constant, T is the absolute temperature, η is the viscosity and V is the molecular volume. Thus, viscous samples favor fluorescence polarization. In particular, heavy oils, which are very viscous, show significant fluorescence polarization when excited with polarized light while typical interfering fluorophores, such as from marine vegetation, do not. Furthermore, sunlight is unpolarized, and causes less interference than direct fluorescence when measurements are made in daylight.

The FP instrument dimensions are 20" length x 4.5" diameter, and weighs 16 lbs. The power requirement is 31W at 24V. The housing and optical window are currently rated to 200 ft, but are readily modified for deeper diving capabilities. The instrument also features:

- 50mW 532 nm diode pumped solid-state laser
- Narrow bandpass emission filter that is tuned in to oil fluorescence emission and discriminate from algae and vegetation fluorescence
- Autofocusing telescope for coaxial excitation and fluorescence emission collection. Refractor design consisting of a 50 mm diameter, 100 mm focal length objective lens and a 9 mm diameter, 11 mm focal length eyepiece.
- Employs modulated excitation and phase detection technique via a lock-in amplifier to discriminate against the strong solar background during daytime operations.

- Embedded computer.
- Automation software in the embedded computer allows the FP instrument to be controlled remotely or to perform the detection in an automated fashion including GPS tagging of the data.

NORBIT has developed a wide band multibeam sonar (WBMS) platform as an acoustic sensor to provide 2D as well as 3D topology. Figure 2 shows a picture of the Norbit WBMS. Norbit has previously demonstrated the capability WBMS in mapping oil plume, both in the water column as well as in water interfaces e.g. seafloor and ice. The sonar has been operated under all water conditions including very low temperatures (-20 °C). Acoustically there is no difference as long as the acoustic transmitting media is water. The WBMS also features:

- Size: The sonar head weighs 4.4 lbs. and ultra compact.
- Range: >100 meters.
- Power consumption: The sonar uses 25W and can be operated in a power save mode down to approximately 10W. It has been proven that 8 hours operation can be obtained with battery packs < 2.2 lbs.
- Wide Band: Detection capabilities of impedance mismatch, attenuation variation and scatters in the water column are significantly improved utilizing wide band technologies. The sonar can freely be operated from approximately 200kHz to 450kHz with a native 160kHz bandwidth (adjustable). Processing gain from this wide-band approach is in the order of 20-40dB over conventional continuous wave (CW) based multibeam sonars, which have commonly been utilized to detect plumes in the water column. The wide bandwidth also ensures possibilities to process frequency response in a given water volume segment of the acoustic ensonified area.
- Multi sensor operation: The sonar can be operated in simultaneous “dual” mode with two sonars illuminating the same volume. This enables a true 3-dimensional description of part of the water volume. The sonars are operated in wide band mode with orthogonal pulses to ensure minimum interference.
- Processing: Processing is performed in the sonar head to detect the presence of hydrocarbons in the water column. This further enhances the flexibility of data processing without the need for an uplink to a topside processing unit.
- Acoustics: Norbits multibeam sonars employ a focused field programmable gated array (FPGA) based beam forming with an acoustic resolution that is less than 1 degree. Circular array topography ensures a more uniform beam-opening angle across the coverage area. Range performance is comparable to top performing commercial multibeam sonars due to the narrow angles and wide band processing
- Topside requirements are very flexible. Raw data can be stored in the sonar head or sent to topside sonar software via a RS485 link (100MB/S uplink).

Figure 2. Photograph of Norbit's wide band multibeam sonar.

EIC Laboratories, Inc. and Norbit US Ltd. have developed a combined telescopic FP sensor and WBMS as dual sensors for detecting underwater oil leaks and plumes. There is an advantage in combining the data from the 2 sensors, since the two sensors are complementary. The sonar provides a 3-dimensional map of the oil by detecting differences in reflectivity and attenuation within the water. The FP sensor provides confirmation in the presence of oil since the FP is responsive to the presence of fluorescent oil hydrocarbons. As a result the combined data from the 2 sensors will have a definitive identification and mapping of oil in the water column co-registered in time and space.

3 Objective

The program objectives are to develop a combined telescopic fluorescence polarization sensor and wide band multibeam sonar as dual sensors for detecting and mapping underwater oil leaks and plumes. The goals of the Phase II are to demonstrate the operations of the combined FP and WBMS sensors in open water and to demonstrate the effectiveness of the combined sensor detection results in identifying oil targets.

4 Phase II Results

4.1 Open water Testing of the Integrated Sensors

On December 3-4, 2015, the combined telescopic FP sensor and WBMS sonar was tested in open water at the California Polytechnic State University (CalPoly) pier at Avila Beach near San Luis Obispo, CA. Figure 3 illustrates the in-water testing of the instruments. The sensors (FP and sonars), video camera and underwater computer were mounted on a tripod. Figure 4 shows photographs of the tripod structures with the instruments mounted. The top computers and power supplies were setup in the pier and connected to the instrument below with umbilical cables. The tripod was dropped into the water underneath the pier using a winch and was positioned in the bottom of the seafloor. The same winch mechanism was also used to position test targets at some distance away from the tripod. For the plume generator mechanism, a support boat was used to position the pump underwater nozzle at some distance from the tripod and also used to house the instrumentation for the plume generator.

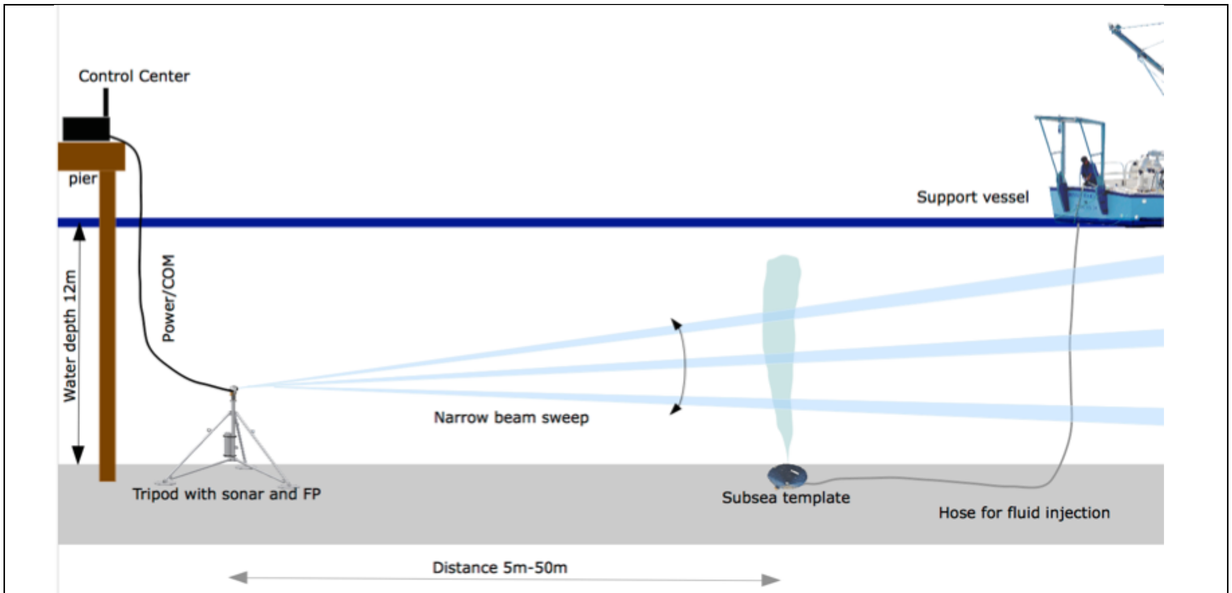

Figure 3. In-water testing setup for the integrated FP/WBMS instruments.

Figure 4. Photographs of the combined FP and WBMS sensors mounted on the underwater tripod along with a video camera and underwater control computer.

Kelp native to the area was used as a simulant for oil. Kelp fluorescences and also has sonar signature so it is a good simulant for oil. The kelp was ground up and then mixed with water to create a kelp slurry. This slurry was then pumped into the water column using a pump mechanism. The pump system consists of a submersible injection template that is connected to a pump up top via a hose. Figure 5 shows a picture of the submersible injection template and the pump mechanism, which consists of a variable speed pump, a solution reservoir and a mixer. The injection template is specifically designed to be the flow constricting part where nozzle sizes determine the flow rate independent of the length of the flow line. The injection template is designed to minimize acoustic interference both in terms of reflections and absorption of sound waves at the relevant frequency.

Figure 5. Photographs of the injection template (left) and the pump mechanism for introducing solution plume of simulants into the water column.

Because of the strong swell (4-5 knots) in the bay throughout the duration of the testing, detection of the kelp plume, specially with the FP sensor, was very difficult and no useful data were obtained with this oil simulant target. First, the injection plate was placed in the bottom of the seafloor; however, kelp plume could not be generated because the current just swept away the kelp as it comes out of the nozzle. Since the nozzle was close to the seafloor and the sensors were positioned at about 7 feet from the seafloor, the kelp plume could not make it to the field of view of the sensors. To remedy this problem, an extension pipe was attached to the injection template nozzle so that the plume is generated at the level of the sensors field of view. Figure 6A shows a picture of the injection template with the nozzle extension. Figure 6B shows results of the kelp plume detection from the FP and sonar sensors. The result shows that the sonar can detect the plume but the FP sensor could not. Because of the strong current in the water column, the kelp plume was being swept away too quickly and then dispersed and diluted resulting in the fluorescence signature of the diluted kelp plume to be too weak for the FP sensor to detect.

A	B

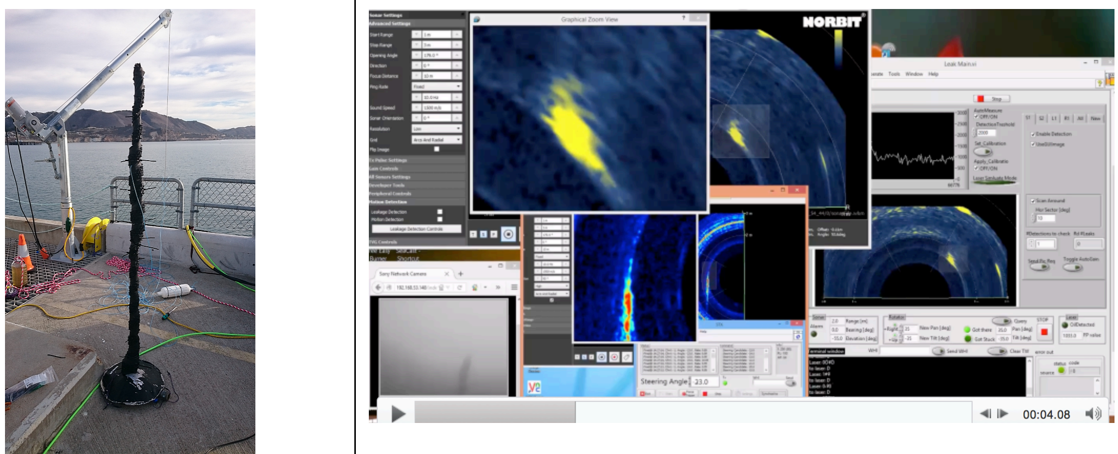

Figure 6. Photograph of the injection template with an extension pipe nozzle (A) and detection test result of the kelp plume release (B).

In the Phase I testing of the sensors at Cold Regions Research and Engineering Laboratory (CRREL), a contained oil test target was successfully used as a test target simulant for oil. This was made by placing oil in a transparent plastic bottle that was then attached to a string and suspended in the water column. A similar contained test target was created from the water suspension of ground up kelp. Figure 7 shows a photograph of the plastic bottle containing the kelp solution. The bottle was attached to a rope and weighted with lead, and then lowered down from the pier into the water column. The bottle was positioned in the field of view of the instruments at some distance away from the tripod. Figure 8 also shows a still picture of the water bottle in the water column that was recorded with the video camera. The white spot in the picture is the laser beam hitting the bottle.

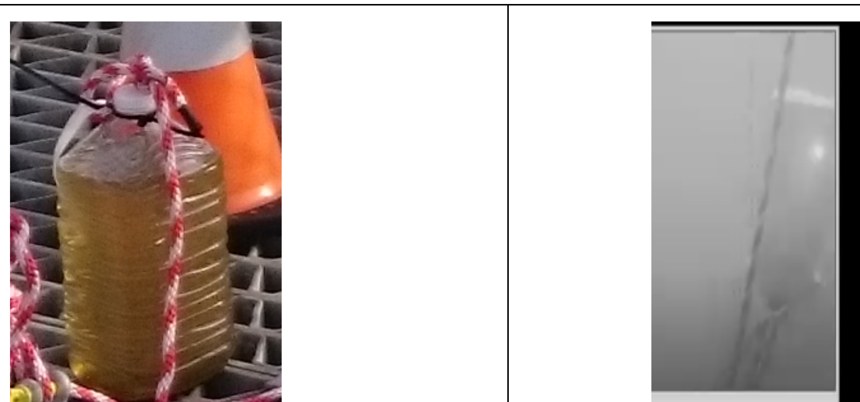

Figure 7. Photograph of the transparent plastic bottle target containing ground up kelp water suspension (left) and a video image of the suspended bottle in the water column.

Figure 8 shows detection test results from the sensors for the kelp solution bottle. Both sensors registered positive detection of the target. Figure 8 shows that the FP sensor was able to detect successive passes of the bottle into the sensor field of view. Because of the strong water surge, the bottle oscillates back and forth in the water column. Even with this oscillation, however, detection of the kelp in the bottle was still feasible. The bottle image is also very clear in the sonar results. The video camera was also able to record the passing of the bottle into the sensors field of view and with the laser hitting the bottle. The distance of the bottle from the sensors ranged from 1 to 2 meters as it oscillates. The bottle was positioned at longer distances, however, because of the poor visibility in the water column, the FP sensor was not able to register any detection at distances greater than 2 meters. There was a significant disturbance of silt from positioning the sensors and from the strong sea swell.

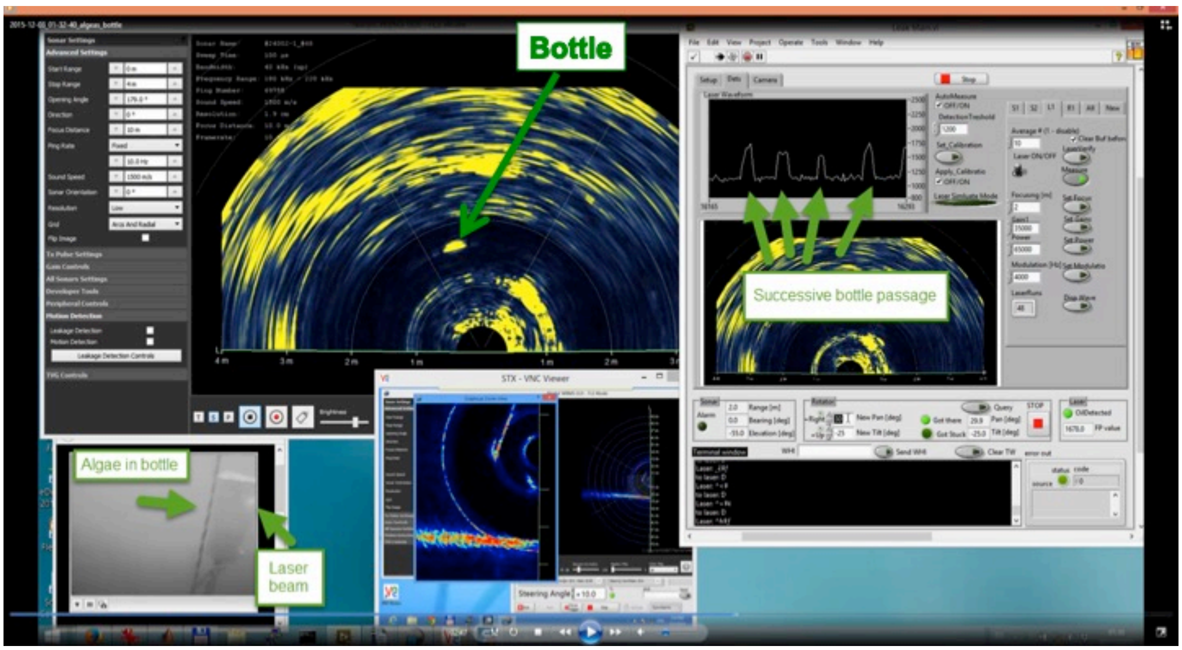

Figure 8. Detection results of the kelp solution contained in a plastic bottle.

Another fixed target constructed from an electrical cable that is wrapped around a buoy was also used as a test target. It was found that the cable plastic sheeting emits very strong fluorescence signal. Figure 9 shows photographs of the buoy target. To anchor the buoy in the seafloor and suspend it into the water column, the buoy was attached by a rope to a weighted and stabilized ladder. The ladder was then dropped under the pier and positioned at some distance away from the sensor platform. The buoy floats on top of the ladder and suspended above in the water column within the field of view of the sensors. Figure 10 shows detection results of the buoy from the sensors at a distance of 2 meters. It is clearly shown in Figure 10 that the buoy registered strong fluorescence signal from the FP sensor and that it was detected several times as the buoy undulates back and forth in the sensor field of view because of water surge. An image of the buoy can also be seen from the video camera as it passes by the sensors.

Figure 9. Photographs of the buoy test target (left) and the buoy attached to a ladder for positioning on the seafloor.

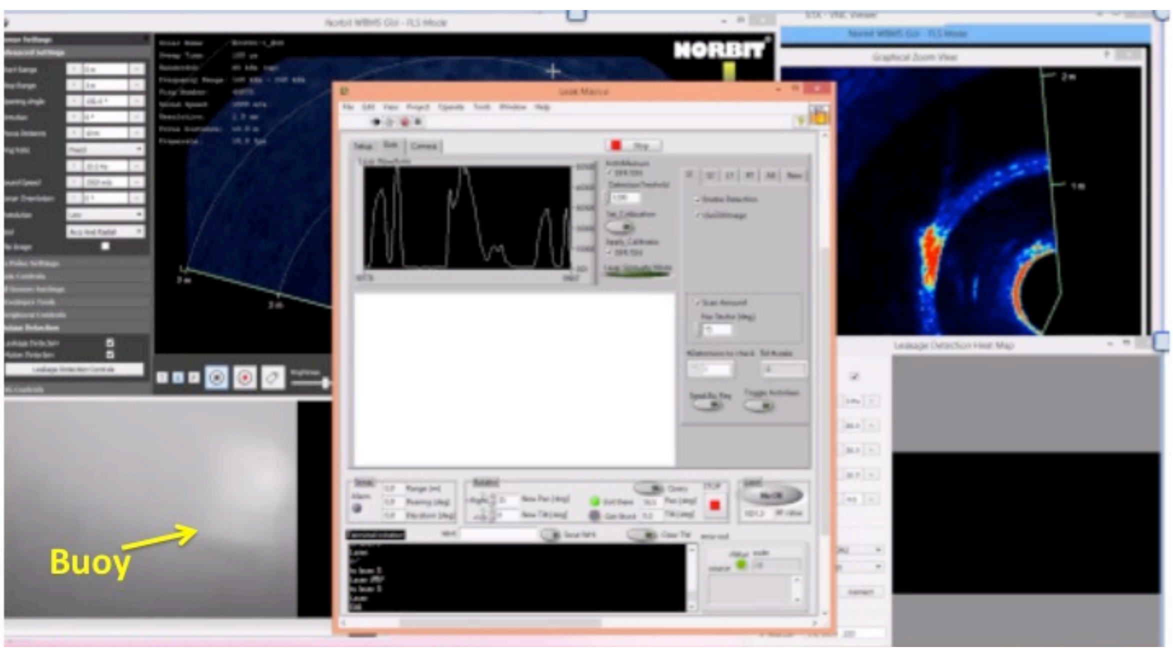

Figure 10. Manual detection results from the sensors of the buoy test target suspended in the water column.

An automatic detection of the buoy was also performed to test the automated detection capability of the instrument software. Leakview, a LabView software that implemented an automated oil detection and verification process using both the sonars and the laser FP was developed in Phase I. Figure 11 shows a diagram of the oil detection and verification process. The process is started by acoustically sweeping the 3D space. The steerable antenna transmits the narrow beam vertically while the receiver spatially filters the space in the horizontal direction. The process forms 3D matrices, which can cover the half-space dome. The space is then divided into a selected number of vertical slices. Inside each slice the motion detection is performed. The motion detection data is then passed to the leakage detection, which is a temporal filter and exemplifies the persistent motion areas. If the persistency exceeds some predefined threshold, that area is considered as a leak and an alarm is generated. The alarm consists of five locations (bearing and range) of the largest leaks. The size in dm2 is also passed along with the alarm as a National Marine Electronics Association (NMEA) text message to use minimal bandwidth. This information is easily passed through the acoustic modems or slow links to the topside operation software. The topside software processes the alarms and decides if they should be verified with the laser. The laser verification utilizes the underwater pan and tilt mechanism to position the laser in the proximity of the detected leak. The scanning is performed in the predefined sector, e.g. 5 degree around the bearing given an alarm message. At the same time video is recorded and still high-resolution camera images are recorded. Also the forward-looking sonar, which is mounted on the pan/tilt mechanism, is constantly logging the imagery data for future processing and verification.

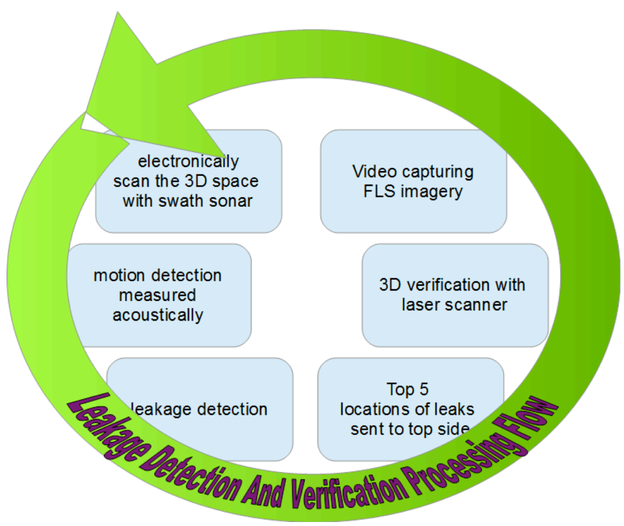

Figure 11. Leak detection and verification processing flow chart.

Figure 12 shows a result of the automatic detection of the buoy target using Leakview. The undulation movement of the buoy in the water column caused the WBMS to report it as a leak and flagged it in the sonar image. The coordinate that was recorded by the WBMS was then sent to the rotator so it could position the FP sensor to the detection spot. The rotator scanned a predetermined angle sector around the spot so that the FP could confirm that the detected leak was a hydrocarbon. Once it was confirmed as oil, the sonar image changed the yellow marking to red as shown in Figure 12. The FP signal displayed in the FP panel showed very strong fluorescence signals detected from the target. The FP display panel also showed that the buoy was detected several times as it passed by the sensor field of view.

Figure 12. Leakview automatic detection of buoy target.

5 Discussion and Conclusions

The Phase II objective was to demonstrate and evaluate the performance of the integrated FP/WBMS leak detection system in open water. The integrated sensors were tested and evaluated in open water at Avila Beach, CA using oil simulants. Since oil or any type of materials that are not native to the environment cannot be used for open water testing, simulants with both fluorescence and sonar signatures were used as target analytes. One simulant was ground up kelp that is native to the area that was introduced into the water column as plume. A plume generator pumping mechanism was used, which employs a submersible nozzle platform connected by a hose to a pump mechanism on the surface. However, because of the strong water surge in the bay during testing, it was not possible to keep a plume of the kelp to stay suspended in the water column long enough for the sensors to detect. A contained test targets were then devised that keeps a fluorescent target in a confined space for the sensors to detect. Two immobilized test targets were developed: ground up kept solution in a transparent plastic bottle and a buoy wrapped with a strongly fluorescent electrical cable. Both of these test targets were attached to a rope and then suspended in the water column. Although it was meant for the targets to be a stationary object in the water column, the surge, however, caused the targets to undulate in the water column. Even with these challenges, however, test results from the immobilized test targets showed that both the FP sensor and the WBMS can detect the targets. The detection range, especially for the FP sensor, however, was limited to short distances (1-2 meters) due to the poor visibility in the water column. Automatic detection of the test targets was also performed using Leakview. Leakview is a LabView based software that was developed for the integrated sensor that employs an algorithm to scan the water column with the sonar and identify possible oil leaks that are then flagged and confirmed with the FP sensor. The Leakview detection of buoy target successfully flagged the undulating buoy in the water column as possible oil leak and then successfully confirmed by the FP sensor as an oil leak. The results of the Phase II open water testing further confirmed the effectiveness of the dual sensor platform.

6 Recommendation for Future Work

The next development phase will be to bring the sensor suite closer to a real life TRL 7-8 deployable operational package. The current instrument setup includes 3-dimensional multibeam sonars and the FP sensor. Adding a "single beam" functionality to the multibeam sonar as well as forward looking sonar functionality will ensure a full sensor suite for mobile platforms providing the agility and performance needed to successfully and robustly detect hydrocarbon in the water column. The proposed tasks for the sonar work are to build custom transmitter module for multibeam echo sounder to enable single beam functionality and to optimize processing of multibeam to be able to beamform single beam data from multibeam receiver. The size of the FP sensor may be too bulky for integration into underwater vehicles; thus, further miniaturization of the FP will need to be done. A folded telescope optical layout and a smaller telescope objective lens will be investigated as means to reduce the packaging of the FP system.

Remotely Operated Vehicle (ROV) platform integration and operation is the next deployment scheme that will need to be developed for the dual sensor systems. Based on Norbit's use of Ocean Modules V8 and M500 in previous trials, utilizing ROV significantly decreases complexity and budget. The use of either the Ocean Modules ROV or a SAAB ROV vehicle will need to be evaluated due to their inherent stability. Sh ould an Autonomous Underwater Vehicle (AUV) trial be preferred, NORBIT has extensive experience with hydrocarbon detection trials with multiple different platforms, e.g., Bluefin 12D, Bluefin 21D, and Seastick.

Testing of the ROV integrated sensors will be done at natural oil seep off the coast of Santa Barbara, CA. Using an ROV, Norbit has previously tested sonars mounted on ROV at these natural seeps. Initial dialogs have been conducted with SINTEF to determine feasibility of testing the sensors at real life spill in an ice/artic context. They have programs and experience doing this at Svalbard in Norway. The options for real spill detections are the following.

a) Dedicated program tailored for BSEE (quite expensive)

b) Piggy back on existing program already in place between BSEE and SINTEF on dispersant efficiency (Must be further examined)

c) Piggyback on planned activities planned for April 2017 in Svalbard with live spill of oil.

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