Advances in Remote Sensing Research on Oil and Ice from the IOGP Arctic Oil Spill Response Technology JIP

David Palandro[1], Joseph Mullin[2]

[1]ExxonMobil Upstream Research Center, 22777 Springwoods Village Parkway, Spring, TX USA 77384

[2]International Association of Oil and Gas Producers, 40 Basing Hall Street, London UK E2CV5DE

ABSTRACT (2017-044)

The IOGP Arctic Oil Spill Response Technology Joint Industry Program's Remote Sensing Technical Working Group was initiated in 2012 with the objective to expand the oil industry's detection and monitoring capabilities for spills on, under, around or in ice. The first phase produced two state-of-knowledge reports assessing sensor capabilities above and below the ice. A key finding from these studies was that many existing remote sensing platforms and sensors originally developed for oil on open water can also provide effective sensing in a broad range of ice conditions. The second phase covered an integrated experiment that included sensor testing in a cold basin, followed by modeling to determine potential applicability of different sensors in a wider range of sea-ice conditions. Five above-ice (Frequency Modulated Continuous Wave Radar (FMCW), ground penetrating radar (GPR), visible and infrared cameras and laser fluorescence polarization [LP] sensor) and seven below-ice (high dynamic range optical camera, visible and infrared spectrometer, LP sensor, broadband and narrowband sonar and multibeam echo sounder) sensors were tested with varying ice thickness and oil concentrations at the US

Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) over a three-month period. All of the sensors used during this experiment showed some ability to detect oil on, in, or below ice under certain conditions and major advances in the knowledge of sensor applicability were made. Three follow-on projects (late 2016) include an operations guide providing a concise operationally oriented review of the different sensor technologies in key oil and ice scenarios, and additional field testing with medium to long-wave infrared, and the FMCW radar.

INTRODUCTION

The ability to effectively and efficiently detect oil spilled in the marine environment is critical for responding to a spill. The presence of sea ice increases the complexity of detecting the oil. Depending on the nature of the spill, the time of year, and the time elapsed since the spill, oil can potentially be found on, under, around, or in ice.

In 2012, nine international oil and gas companies and the International Oil and Gas Producers (IOGP) initiated the Arctic Oil Spill Response Technology joint industry program (JIP) to improve the technologies and methodologies to respond to oil spills in Arctic waters (www.arcticresponsetechnolgy.org). Six key areas of research were identified for further experimentation and study: 1) dispersants, 2) environmental effects, 3) trajectory modeling, 4) remote sensing, 5) mechanical recovery and 6) in situ burning. This report documents the research completed for the remote sensing program.

The overall goal of the remote sensing component of the JIP is to expand the oil industry's detection and monitoring capabilities for spills in ice-covered waters including darkness and low visibility conditions. Scenarios include four specific oil in ice configurations:

1) oil on water and/or located in brash and frazil ice between ice floes, 2) oil located on the ice surface with and without snow cover, 3) oil located under ice soon after rising from the discharge point and 4) encapsulated oil in ice with a layer of new ice grown beneath the oil. To meet the overall goal of the remote sensing component, the technical working group divided the project into three phases, where each initial phase was used to inform research in the subsequent phase. In brief, Phase 1 produced two state of the knowledge reports, Phase 2 included oil in ice mesocosm testing in a cold basin and Phase 3 included follow-on testing of two promising sensor technologies and an operational guide. This report serves as a summary of the results from all three phases.

PHASE 1: STATE OF KNOWLEDGE

In 2013, two state of the knowledge reports were completed for the JIP:

- Report 5.1: Oil Spill Detection and Mapping in Low Visibility and Ice: Surface Remote Sensing (Puestow et al., 2013)
- Report 5.2: Capabilities for Detection of Oil Spills under Sea Ice from Autonomous Underwater Vehicles (Wilkinson et al., 2013)

Each of these reports summarized the existing sensor technologies available to detect oil in, under and around ice from surface and subsea remote sensing platforms. A common finding from both reports was that responders already have access to a wide range of space, airborne and surface-imaging systems used from a variety of platforms such as satellites, helicopters, fixed-wing aircraft, drones, vessels and drilling platforms. While these systems were originally developed and tested for an oil on open water scenario, it was found that many sensors could potentially provide effective sensing in a broad range of ice conditions as well.

Surface Remote Sensing Report (Puestow et al., 2013)

The primary objective was to define the state-of-the-art for surface remote sensing technologies to monitor oil under varying conditions of ice and visibility. A review of existing and emerging technologies with the ability to detect oil on water was conducted, their potential for application in ice-affected waters assessed and near-term research recommendations were provided. Ice and low visibility parameters were defined to evaluate technologies, independent of the platform being used, aerial (e.g., fixed-wing aircraft, helicopter) or water-borne (e.g., vessel).

Airborne or vessel-based optical (visible) data are routinely used in the detection of oil in the surface-water marine environment. Extending visible (VIS) spectrum data in either direction to include ultraviolet (UV) or infrared (IR) by incorporating multispectral or hyperspectral sensors has also been demonstrated for oil detection. There are uncertainties and ambiguities in interpreting the remote sensing data visually or by automation. Oil signal data are often confused with signals from other ocean targets and there is little validated information available to assess sensor use in ice conditions. Limitations exist for VIS and UV data, as these require reflected sunlight energy (i.e., daytime operations only). Similarly, passive IR detection (energy emitted from source) requires a measureable temperature difference between the oil and its surroundings (usually related to solar heat gain). All of these sensors are limited by low visibility condition (e.g., fog).

Airborne Laser Fluorosensors (LFS) have the unique ability to detect oil with a high degree of certainty, classify oil type and determine the thickness of the oil. Despite this, LFS systems are not widely used for oil spill monitoring. LFS instruments require dedicated aircraft and due to power limitations of the laser their use is restricted to relatively low altitudes and correspondingly narrow spatial coverage. They are not effective in conditions of blowing snow or fog and are limited to scenarios where the oil is exposed on the surface.

Synthetic Aperture Radar, Side Looking Airborne Radar and high-speed marine radar are used routinely to detect and monitor oil spills on water. Satellite, airborne and vessel radars are effective in characterizing and mapping the general ice environment but their ability to detect oil spilled among ice is not well known. The main advantage of these sensors is that they can operate independent of darkness, cloud cover or fog. Their main limitation is that the sea surface needs to be moderately rough in order to discriminate between oil and clean surroundings – very calm seas or high sea states can mask the oil target. Sea ice effectively damps wind waves. Consequently, the oil in ice scenario where radar imagery has the highest chance of success is expected to involve very open ice coverage – up to about 30%.

A series of successful basin and field tests, initiated in 2004 have confirmed the capability of Ground Penetrating Radar (GPR) to detect oil under and trapped within the ice when operated from the ice surface (e.g., Dickins et al., 2010). The same commercial system successfully detected oil on the ice surface buried under snow when flown at low level from a helicopter in 2006. A prototype specialized airborne system for oil in ice detection, Frequency Modulated Continuous Wave (FMCW) radar was designed and built in 2011 but its capabilities are not fully tested.

Nuclear Magnetic Resonance (NMR) is an evolving technology that may provide an operational system for detecting oil in and under ice (Palandro et al., 2015). Recent field tests of a 6 m ruggedized helicopter-deployed NMR antenna was able to detect oil in and below an ice surrogate (neither ice nor the ice surrogate provide an NMR signal and therefore do not interfere with the detection of oil). The current system can nominally detect ~1 cm thick oil under ~ 1 m thick ice.

Key recommendations from the surface remote sensing state of knowledge report included the testing and validation of existing technologies, such as such as hyperspectral (UV, VIS and IR), laser-based systems, and microwave radiometers, in varying oil and ice scenarios (e.g., oil concentration, ice thickness and type). Recommendations also included support of ongoing research on FMCW and NMR, programs for embedding trained oil observers in ongoing operations, developing and implementing integrated multi-sensor systems with automated data analysis and standardized products and processes for remote sensing of oil in ice environments.

Subsea Remote Sensing Report (Wilkinson et al., 2013)

This report summarized the existing and emerging oil spill remote sensing and mapping technologies that have the capability to detect and map an oil spill in ice covered seas from below the surface using unmanned underwater vehicles (UUVs) and provides recommendations for future development. The majority of remote sensing techniques developed for oil detection in ice-covered waters have focused on airborne or on-ice systems, which rely on the ability to detect oil through the ice and, potentially, snow. Sensors mounted on UUVs hold the potential to overcome some of the constraints encountered with airborne or surface based methods, such as the need to sense through snow and more importantly highly nonhomogeneous ice.

UUVs, specifically autonomous underwater vehicles (AUVs), can be deployed in a range of ice and weather conditions and have the potential ability to directly detect oil trapped under ice. The direct view of oil under the ice provided by UUVs allows the use of existing sensor technologies (e.g., cameras, radiometers). However, the ability to detect the oil through visible sensors may be limited by new ice growth beneath the oil layer.

Recommendations from this report were to test a suite of existing sensor technologies that can be operated from a UUV, which include camera, sonar, laser fluorometer and radiometer systems. The test should quantify the advantages and limitations of each of the sensors under different sea ice and oil conditions, focusing on sensor signal response for oil in and under ice. Further consideration may also be given to enhancing AUV platform technology and logistics to potentially develop a dedicated, easy-to-use, operational oil spill response platform.

PHASE 2: TECHNOLGY TESTING

Introduction

Based on the results and recommendations from Phase 1, sensor technology testing was initiated at the US Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH in November 2014. Goals of this phase were to acquire data from various surface and subsea sensors to determine their capabilities under different oil and ice conditions. Subsequent to the testing, modeling the performance of the sensors under more realistic environmental conditions was considered. A final report, 'Detection of oil on-in-and-under-ice' documented the Phase 2 testing (Pegau et. al, 2016).

Methods

The two-month long test covered an ice growth phase and one-month of partial ice melt. A 70 cm thick sea ice sheet was grown under quiescent sea surface conditions in the CRREL test basin, which measures 37 m long, 9 m wide, and 2.4 m deep. Six containment hoops were placed along the length of the tank to make up the primary experimental area. The hoops were numbered one to six from west to east. Six smaller hoops received the same treatment as the primary hoops to allow for coring to examine ice properties. Another four hoops were provided for additional experiments (Figure 1).

During the sea ice growth phase, the basin temperature was brought down and held near 24° C. At predetermined stages Alaska North Slope crude oil at 0° C was injected into each of the experimental hoops from below. Camera systems were used by CRREL personnel to ensure proper placement of oil within the hoops. Within a short time, ice began to form below the oil. The test matrix provided a good mix of different ice and oil thicknesses, which in turn presented a series of realistic oil detection scenarios. Overall, the combination of injections provided seven different experiments in which to quantify the detection of oil by sensors mounted above and below the sea ice. After each injection, the oil in the hoop was monitored daily for at least three days with a suite of sensors, from both above and below the ice. A weekly transect was made both above and below the ice to allow sensors to collect data along the length of the ice sheet.

Above-ice sensors were mounted on a 5 m long boom mounted on the carriage 2 m above the ice and included (Figure 2):

- Frequency modulated continuous wave (FMCW) radar
- Ground penetrating radars (GPR, 2 frequencies)
- Visible and infrared cameras
- Laser fluorescence polarization (FP) sensor
- GPR and optical measurements were also collected at the ice surface

Below-ice sensors were mounted on a trolley running on rails mounted on the tank bottom at a depth just over 2 m, and included (Figure 2):

- Spectral radiance and irradiance sensors
- FP sensors
- Optical cameras
- Broadband acoustics (3 frequency bands)
- Narrowband acoustics (4 frequencies)
- Multibeam acoustics (3 sensors)

Oil-in-ice detection modeling was implemented to address a set of field scenarios based on two diameters of oil pools (2 and 200 m) and monthly ice growth. Specific ice parameters, such as temperature and salinity, were used to determine optical, acoustical, and radar properties of the ice in various situations and times of year. In addition, models also used the test-basin ice characteristics and the measured sensor performance in the laboratory for model validation. Test ice properties: temperature, salinity, density, crystal characteristics, and skeletal layer shape provided the information necessary for understanding sensor performance and as inputs into the subsequent modeling. Three-dimensional CT scans provided detailed information on brine and air inclusions, along with the crystal structure of the boundary layer.

Results and Discussion

This was the first experiment of multiple coincident surface and subsea sensors analyzing the same ice and oil parameters in a controlled setting. All sensor types used during this experiment showed an ability to detect oil on, in, or below ice under certain conditions.

The on-ice operated GPR confirmed the known potential of commercial radar systems in this application, detecting both fresh and encapsulated oil. In addition, the GPR was able to detect encapsulated oil in an airborne mode when the ice was cold, confirming previous model predictions. The FMCW airborne system had difficulties in terms of reliability and signal to noise that are to be expected from a prototype device, but the limited data obtained in these tests demonstrated the capability of detecting an encapsulated oil layer. Modelling indicates the further potential of this system to expand the detection capabilities of airborne radar systems in the future.

The optical sensors (cameras, radiometers, and FP) were able to detect oil on top of bare ice and at the bottom surface of the ice, as well as being the only technologies able to reliably detect oil in the brash ice from either above or below. From below, the cameras and radiometers could detect oil at various depths in the ice, and the FP sensor was able to detect oil with up to 6 cm of ice below the oil. The near IR spectra showed potential for discriminating oil from other dark targets. The thermal IR sensors were also able to detect "solar" heating of oil at the surface of the ice.

The acoustics systems were able to detect the presence of oil as well as to measure the thickness of oil below the ice. Systems using frequencies in the 200 – 400 kHz range were able to detect oil through < 6 cm of new ice grown beneath.

Based on the results of this project and the state of knowledge of oil in ice remote sensing, the expected field performance of different sensors was assessed (Table1). Not surprisingly, the capability matrix shows that in pack or drift ice offshore, below-ice sensors are best at detecting fresh oil under the ice and existing airborne sensors are best at detecting oil on the surface or buried under snow. The greatest limitation is in consistently detecting oil that is encapsulated in the ice sheet with more than 6 cm of new ice growth beneath the oil. This synopsis of capability assumes that on-ice methods using GPR only apply to scenarios involving oil spilled under stable fast ice that provides safe working conditions nearshore.

Using the Beaufort Sea as a benchmark Arctic location, almost all oil will be on the melting ice surface during the summer months, making below ice methods not applicable (N/A). On-ice activities are also N/A throughout these months due to safety considerations, leaving only airborne methods. Airborne radar systems will have difficulties in fall or spring when the ice is generally too warm and conductive. Provided there is sufficient light from above, under-ice optical methods can detect oil under ice, in the interior of ice (when encapsulation thickness is relatively small compared to the oiled area), and on top of thin ice. FP is possible for oil on new and young ice (with minimal snow cover). IR should work with oil on top of the ice during the early part of the ice season as long as there is enough daylight to create detectable temperature differences (October and early November). IR utility should return in spring with increasing sunlight.

The results of this phase of experiments confirms the results of the phase 1 state of knowledge reports: no one sensor has the capability of detecting oil in all situations. Rather, some sensors may complement each other in terms of oil thickness resolution vs. area coverage or swath width. Future operational systems will likely employ suites of different sensors operating from various platforms under, on and above the ice surface to provide the means to detect oil in a range of ice environments at different times of the year. Further, based on these experimental results, an effective underwater detection unit should consider the following suite of sensors:

- Low-light camera

- Radiometer and/or FP
- Broadband or multibeam sonar (multibeam offers the added ability to map the underside of the ice in three dimensions, allowing the responder to see potential oil pooling locations)

An aerial system should consider the following suite of sensors:

- VIS and thermal IR imagers
- Radar (may provide the best potential for detecting oil on the ice surface or under snow, but requires further development to reach operational use)

Ground penetrating radar operating from the ice surface is an appropriate tool as long as there is a stable and safe working environment.

Further recommendations on testing from this phase include evaluating the capabilities of multiple IR wavelengths (i.e., short, medium and long wave) systems at different times of the year and retest a modified FMCW with improved signal to noise ratio and better reliability.

PHASE 3: REMOTE SENSING CLOSE OUT

Phase 3 of the program was initiated in 2016 and is ongoing. Three projects were selected based on previous phase recommendations. Two projects are extensions of Phase 2 and will continue testing FMCW radar and multi-wavelength IR at CRREL. The third project will create an oil spill detection guide for ice-covered waters. A description of each project is below, but results are pending.

CRREL Phase 2 results showed promise for the use of FMCW radar for oil in and under ice detection. This project seeks to determine if a developed form of FMCW technology can provide the basis for an operational airborne oil in ice detection system in the near future (1-2 years). The testing includes the construction of a small, temporary ice basin in a controlled cold room environment at CRREL and growing a 30 cm ice sheet. Oil will be released under the ice to be encapsulated.

Similar to the extended FMCW testing, further effectiveness tests on commercially available IR sensors in the medium and long wavelengths will be completed at CRREL. Tests will attempt to detect surface oil with and without snow on a thin ice sheet, during daytime and nighttime conditions.

The final Phase 3 project is a guide to oil spill detection in ice covered waters, which will serve as an operational tool that responders can use to select the most effective appropriate remote sensing systems and platforms. The guide covers a variety oil and ice scenarios that could result from realistic incidents. While, there are operational remote detection guides currently in use for oil spilled in open water, none exist for Arctic ice covered waters to deal with oil detection in, on, among or under ice.

CONCLUSIONS

The overall objective of the remote sensing component of the JIP was to expand the oil industry’s detection and monitoring capabilities for spills in ice-covered waters including darkness and low visibility conditions. This goal was met by implementing three phases, each building on the results of the previous phase. These phases included: 1) two state of knowledge reports on surface and subsea sensors, 2) concurrent testing of surface, on-ice and underwater sensors under experimental conditions over an entire ice growth and melt cycle and 3) extended testing of multi-wavelength IR and FMCW radar, as well as the creation of an operational Arctic remote sensing guide. The results and recommendations of this research have directly informed the manner with which the use of remote sensing technologies can be used to detect oil in, under and around ice in the event of an actual spill.

REFERENCES

Dickins, D., Brandvik, P.J., Bradford, J., Faksness, L.-G., Liberty, L. and Daniloff, R. 2008. Svalbard 2006 Experimental Oil Spill under Ice: Remote Sensing, Oil weathering under Arctic conditions and assessment of oil removal by in-situ burning. In: International Oil Spill Conference Proceedings: 2008(1): 681-688. doi: http://dx.doi.org/10.7901/2169-3358-2008-1-681.

Palandro, D., Nedwed, T., DeMicco, E., Thomann, H., Fukushima, E., Chavez, L. and Altobelli, S., 2015. The detection of oil in and under ice using nuclear magnetic resonance. In: Proceedings of the 38th AMOP Technical Seminar on Environmental Contamination and Response, Environment Canada. Ottawa, ON. 38: 1-7.

Pegau, W., Garron, J. and Zabilinsky, L., 2016. Detection of oil on-in-and-under-ice. International Oil and Gas Producers Arctic Response Technology JIP. 406 pp.

Puestow, T., Parsons, L., Zakharov, I., Cater, N., Bobby, P., Fuglem, M., Parr, G., Jayasin, A., Warren, S. and Wabranski, G., 2013. Oil Spill Detection and Mapping in Low Visibility and Ice: Surface Remote Sensing. International Oil and Gas Producers Arctic Response Technology JIP. 84 pp.

Wilkinson, J., Maksym, T. and Singh, H., 2013. Capabilities for Detection of Oil Spills under Sea Ice from Autonomous Underwater Vehicles. International Oil and Gas Producers Arctic Response Technology JIP. 104 pp.

TABLES

Table 1. The expected field performance in level first-year ice of sensors tested during the Phase 2 experiments and based on modeling results. The P (possible) rating indicates that there are conditions that may allow the system to work. A yellow P2 rating indicates that there is still insufficient data to fully assess performance. N/A indicates that sensor application in this scenario is not relevant, e.g., using below-ice sensors to detect exposed oil on the surface. Notes: [1]On-ice operations apply only to stable ice. [2] Snow covered oil on ice, oil beneath ice, or encapsulated oil is unlikely. [3] Thermal IR detection depends on temperature differences between oil and ice due to solar heating, detection during winter is unlikely. [4]The performance of optical systems is based on sufficient sunlight penetrating through the snow and ice. [5] The ability will depend on the thickness of ice below the oil and the width of the pool of oil. [6] The low signal to noise ratio in the tank environment prevented the sonar systems from operating at full power, acoustic systems may be able to detect oil encapsulated by more than 6 cm new ice.

Location	**Airborne**					**On ice[1]**	**Below ice**		
Sensor	GPR	FMCW	Optical	FP	IR	GPR	Optical[4]	FP	Acoustic
Fall-Winter-Spring									
Exposed oil on ice	Y	P2	Y	Y	P2[3]	Y	P2	N/A	N/A
Snow covered oil on ice	Y	P2	N	N	N	Y	P2	N	N
Fresh oil under ice or with up to 6 cm new growth)	P2	P2	N	N	N	Y	Y	Y	Y
Encapsulated oil (more than 6 cm new growth)	P	P2	N	N	N	Y	P[5]	N	P2[6]
Summer[2]									
Exposed oil on ice	P2	P2	Y	Y	Y	N/A	N/A	N/A	N/A

FIGURES

Figure 1. Hoop setup at CRREL test basin for oil in and under water detection experiments.

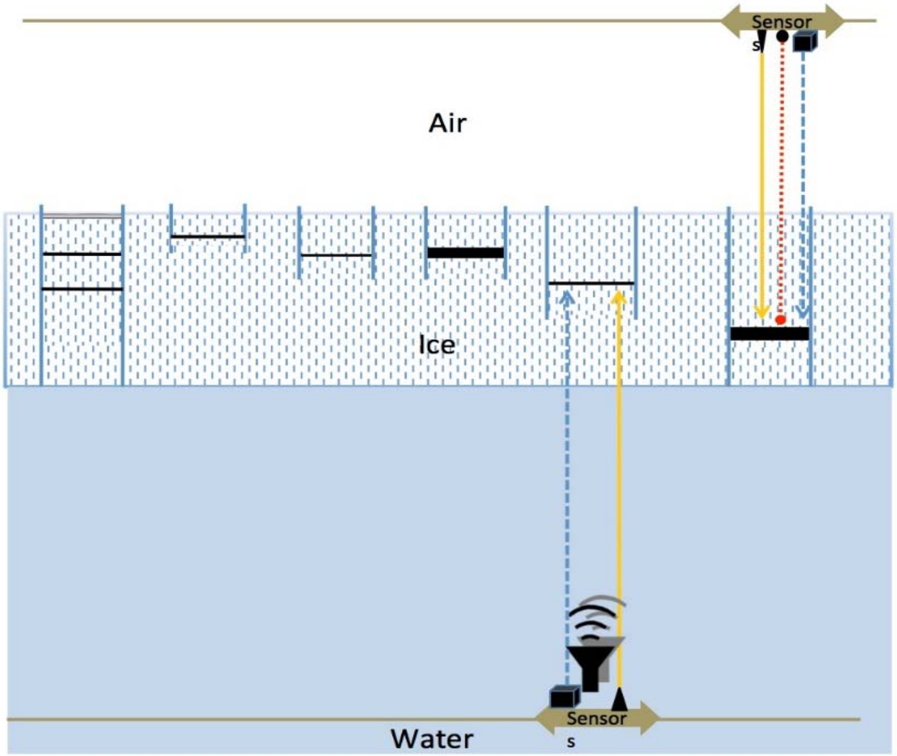

Figure 2. Simplified schematic of CRREL test basin showing above and below ice sensor carriages and the result of releasing oil at different stages in ice growth cycle.