REPORT

Oil in Ice - JIP

Report no.: 30

Project P5: Remote Sensing Summary Report

David Dickins (Editor) - DF Dickins Associates

SINTEF Materials and Chemistry
Marine Environmental Technology

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Preface

SINTEF has in cooperation with SL Ross Environmental Research Ltd and DF Dickins Associates LLC on behalf of the oil companies AGIP KCO, Chevron, ConocoPhillips, Shell, Statoil and Total initiated an extensive R&D program; *Joint industry program on oil spill contingency for Arctic and ice covered waters.* This program was a 3-year program initiated in September 2006 and finalized in December 2009.

The objectives of the program were;

- To improve our ability to protect the Arctic environment against oil spills.
- To provide improved basis for oil spill related decision-making:
- To advance the state-of-the-art in Arctic oil spill response.

The program consisted of the following projects:

- P 1: Fate and Behaviour of Oil Spills in Ice
- P 2: In Situ Burning of Oil Spills in Ice
- P 3: Mechanical Recovery of Oil Spills in Ice
- P 4: Use of Dispersants on Oil Spills in Ice
- P 5: Remote Sensing of Oil Spills in Ice
- P 6: Oil Spill Response Guide
- P 7: Program Administration
- P 8: Field Experiments, Large-Scale Field Experiments in the Barents Sea
- P 9: Oil Distribution and Bioavailability

The program has received additional financial support from the Norwegian Research Council related to technology development (ending December 2010) and financial in kind support from a number of cooperating partners that are presented below. This report presents results from one of the activities under this program.

Stein Erik Sørstrøm
Program Coordinator
(stein.e.sorstrom@sintef.no)

Funding Partners

R&D Partners

Cooperating Partners

DF Dickins Associates LLC

9463 Poole Street
La Jolla CA 92037 USA

Tel.: 858 453-8688
dfdickins@sbcglobal.net
www.dfdickins.com

TITLE

Project P5: Remote Sensing Summary Report

EDITOR

David Dickins (DF Dickins Associates)

CLIENTS

AGIP KCO, Chevron, ConocoPhillips, Shell, Statoil and Total

DATE	PROJECT MANAGER	CHECKED BY
2010-05-24	David Dickins	Jörn Harald Andersen

ABSTRACT

The main objectives of this report are threefold:

(1) Summarize the findings of the primary JIP remote sensing activities from 2007 to 2009.

(2) Draw conclusions recommending the most effective combination sensors and systems based on information gathered through the JIP, including the initial technology screening and assessment and field experiments offshore and on Svalbard.

In addition, the report highlights several evolving technologies and/or research that could enhance industry's capabilities in the next few years.

Key messages are:

A flexible combination of sensors operating from aircraft, helicopters, vessels, satellites and the ice surface is recommended for future Arctic oil spill emergency preparedness.

The most useful remote sensors and systems for spills in ice are expected to be: aircraft and vessel-based Forward Looking Infrared (FLIR) for oil on the surface in a broad range of ice concentrations, trained dogs on solid ice, Ground Penetrating Radar (GPR) operated from helicopters and the ice surface for oil under snow or trapped in the ice, and Side-Looking Airborne Radar (SLAR); Satellite-based Synthetic Aperture Radar (SAR) for large slicks on the water in very open ice covers.

The current generation of all-weather SAR satellites can play a valuable support role in mapping detailed ice conditions and directing marine resources.

Existing commercial GPR systems can be used from a low-flying helicopter to detect oil trapped under snow on the ice and to detect oil trapped under solid ice.

Detecting isolated oil patches trapped among closely packed ice floes is a major challenge with any current remote sensing system, especially during periods of extended darkness, low clouds or fog. The most effective solution is to deploy closely spaced GPS tracking buoys to follow the ice and the oil.

Trained dogs can reliably detect very small oil volumes and map oiled boundaries on solid ice and in sediments on Arctic shorelines under extreme weather conditions

New technologies may enhance our ability to detect oil over a broader range of Arctic spill scenarios in the near future. Examples include more capable GPR, autonomous underwater vehicles and drones.

The optimum mix of remote sensing technologies depends heavily on the spill characteristics and prevailing weather and ice conditions.

Arctic spill contingency plans need to account for the operational constraints of aircraft and helicopter endurance, weather, and the likelihood of competing demands on limited remote sensing resources.

	ENGLISH	**NORWEGIAN**
Group 1	Remote Sensing	Fjernmåling
Group 2	Oil Spills in Ice	Olje i is
Selected by Authors	Sensors	Sensorer

PROJECT TEAM

Project Managers and Advisors

- DF Dickins Associates Ltd. – Project Manager (David Dickins)
- SINTEF - Internal Co-coordinator (Ivar Singsaas)
- Norconsult - Advisor (Jörn Harald S. Andersen)

Subcontractors and Cooperating Organizations

- Boise State University, Idaho
- Shell International E&P
- Kongsberg Satellite Services KSAT, Tromso
- Nansen Environmental and Remote Sensing Centre
- Norwegian Coastal Administration
- Norwegian Space Centre
- Swedish Coast Guard
- Trondheim Dog Training Centre

PARTICIPANTS BY TECHNICAL AREA

Using dogs to detect oil hidden in snow and ice

Co-funders: JIP and Statoil

Per Johan Brandvik (SINTEF)	Project Manager with Dachshund "Tara"
Turid Buvik (Trondheim Hundeskole)	Director dog training with Border Collie "Jippi"
Reidun Mangrund (Trondheim Hudeskole)	Dog trainer with Border Collie "Blues"

Methane emissions from oil spills in ice

Bill Hirst (Shell International Exploration and Production) Project Manager
Simon O'Connor (Shell International)

Airborne GPR to detect oil under snow

Co-funders: Oil in Ice JIP and MMS

John Bradford (Boise State University)	Project Manager
Per Johan Brandvik (SINTEF)	Field Manager
David Dickins (DF Dickins Associates LLC)	Contract Manager

Satellite images for FEX09

Richard Hall (KSAT)	Project Manager
Mohamed Babiker, Kjell Kloster, Stein Sandven (Nansen Environmental and Remote Sensing Centre)	

Airborne remote sensing systems

Jörn Harald S. Andersen	On-site coordinator

Hand-held IR imagery collected during FEX09

Per Daling (SINTEF)

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In addition, the project team would like to thank NOFO for contributing flight hours to cover a portion of the costs involved in participation by the Norwegian aircraft in 2008.

Finally the Editor would like to express his gratitude to Jörn Harald S. Andersen of Norconsult for his valuable advice and insight from long experience throughout the course of this project.

SUMMARY AND CONCLUSIONS

Spill detection and mapping are particularly important for Arctic spills as oil may be hidden from view under snow and ice during periods of almost total darkness. Close to 24 hours daylight in the spring and summer months facilitates monitoring spilled oil during the break-up and open water periods but fog and low cloud ceiling remain as serious impediments. During freeze-up and through much of the winter, long periods of darkness and multiple oil/ice scenarios add to the challenges of detection, mapping and tracking oil in ice.

The overall goal of Project 5 was to establish whether “off-the-shelf” technologies and sensors could detect oil in the presence of ice in particular scenarios. Specific objectives were to:

- Assess the limitations and capabilities of currently operational or available remote sensors and systems for spill surveillance in the ice regimes encountered in the offshore field experiments (FEX) in 2008 and 2009.
- Draw conclusions and make recommendations as to the most effective sensors to use in a variety of oil and ice situations based on what was learned during the field experiments offshore and on Svalbard, and on the existing state of knowledge from previous experiences with different sensors in open water and ice covered environments.

Project activities and findings are summarized here along with the current state of knowledge regarding remote sensing of oil in ice. The main sensors and platforms are treated independently and then followed by a matrix that integrates a mix of technologies and oil/ice scenarios as an overall review of expected capabilities.

Airborne remote sensing

Multispectral airborne remote sensing supplemented by visual observations by trained observers remains the most effective method for identifying and mapping the presence of oil on water. Many of the existing airborne sensors will theoretically detect and map oil among ice in some situations but their capabilities in these conditions are not well understood. At some point the presence of ice will significantly affect slick behaviour by reducing the spreading rate, increasing the equilibrium oil thickness, and damping wind waves and swell. All of these factors can greatly affect the capabilities and usefulness of different sensors.

The airborne programs in 2008 and 2009 provided a real-world demonstration of the capabilities and limitations – technical and operational – of airborne surveillance. In 2008, the Norwegian surveillance aircraft was forced to abort its mission on four hours notice in order to respond to a real spill from an offshore platform. In 2008, the team secured the participation of the Swedish Coast Guard with their new Dash 8 Q300 MSA. However another marine emergency at Bear Island permitted only one flight over the experimental spill site, just after the oil was discharged. Within the closely packed ice conditions, the spill area was too small for detection with the airborne SLAR or satellite SAR. The low cloud prevented the high-resolution Wescam optical FLIR camera system – considered potentially the most capable sensor for viewing small spills - from acquiring the spill. Airborne SLAR - the least weather dependent sensor - provided a wide swath regional view on either side of the flight line but lacked the resolution to identify the spills contained within the ice.

The main conclusions from the 2009 field experience are that airborne systems are likely to have a high potential for large spills in very open drift ice, moderate potential in open drift ice and limited potential in close to very close pack ice. Available airborne sensors are constrained by combinations of low cloud, fog and darkness (UV/IR line scanners and FLIR) and pixel resolution (SLAR/SAR). Operational constraints of long transit distances and few alternate airports may result in very short times at the scene of the spill. Unpredictable emergencies such as vessels in distress, and search and rescue can lead to an aircraft being called away on short notice.

Satellite Systems

SAR satellites can resolve small targets down to 1 metre or less independent of clouds and light conditions
A series of satellite images were acquired by KSAT, Tromso to determine if the latest generation of high-resolution radar satellites (e.g. Radarsat 2, Cosmo SkyMed) could detect the 2009 experimental oil spills in ice. The oil spills in close pack ice (7/10 and greater) were too small to be detectable on the imagery. Objects that could be identified included: the ice-filled booms alongside the vessel being used for skimmer tests, the ice filled fire-resistant boom being towed behind KV *Svalbard*, and the telescoping dispersant spray arm extending out from the side of RV *Lance*. Ship tracks through the ice could be seen for some days after the ship had passed, depending on the ice motion. The noise or speckle present in all the 2009 imagery greatly obscured surface details and is likely caused by the composition of ice cover made up primarily of small floes that corresponded closely in size to the pixel dimensions in the imagery.

It may be possible to use SAR satellite imagery detect and map slicks in the presence of ice, given the right combination of circumstances – floe size, ice concentration, slick dimensions, wind speed etc. However, the main value of radar imagery lies in their ability to document the changing ice conditions in the vicinity of the spill, providing a valuable tactical planning tool for deploying vessels safely and effectively. The ability to directly detect oil in ice is with satellites most likely limited to very open pack conditions (<4/10) and large spills where the oiled water surface produces a unique radar signature compared to the surrounding non-oiled water, as observed in previous spills at sea.

Combination Airborne and Surface Systems

Ground Penetrating Radar: A series of previous tank tests and field experiments demonstrated that surface-based ground-penetrating radar (GPR) can clearly detect and map the presence of oil films as thin as 1-3 cm underneath the ice and trapped as layers within the ice. Numerical modelling indicated that the same system operating at low altitude from a helicopter should be able to detect thin oil layers under cold ice in mid-winter as well as oil on the ice surface buried under snow. This capability was tested and validated in an experimental on-ice spill at Svea in April 2008. The experimental site was prepared by constructing two test cells on the ice. The average oil thickness was in the order of 2 cm. Following the spill, high winds covered the test area with 5-20 cm of snow.

The data at showed a substantial decrease in the reflection strength of the radar signal over the oiled cell and agreed well with the model predictions. The results indicate that readily available, commercial GPR systems can be used effectively to detect crude oil spills within or under snow in the Arctic environment.

Hand-held IR: Low-cost, non-cooled, hand-held IR systems can detect oil under certain conditions, as demonstrated by a collection of images obtained from RV *Lance* in 2009. During daytime, the IR sensor was able to distinguish between oil (white), ice-free water (light grey) and snow and clean ice floes (dark grey). Performance is less reliable at night and in fog.

Optical gas sensors (Shell LightTouch): Shell Exploration and Production collected baseline data on methane emissions from oil on the ice surface at Svea in April 2007. The primary goal was to obtain a useable estimate of the hydrocarbon emission rate resulting from oil spills onto icy water; and to use the data to assess the potential for detecting and locating such spills using ultrasensitive gas sensors represented by Shell's LightTouch™ hydrocarbon seepage detection technology.

The study concluded that a hypothetical spill into open drift ice could emit methane for about 100 or more hours and be detectable by low flying aircraft from a distance of ~5 km with current generation methane sensors. These conclusions were based on the assumption that the experimental setup at Svea accelerated the weathering process and increased the loss of methane and other volatiles by a factor of 20. Extensive lab and field data shows that Svea meso-scale experiments closely mimic weathering rates found in actual spills. Without the accelerated weathering assumption, the practical detection time for methane could shrink to less than five hours. Based on this limited window of operability the decision was made not to conduct any additional gas-sniffing evaluations in the JIP beyond the initial trial.

Surface-based systems

Depending on the ice conditions (floe size, thickness, stability) it may be possible to deploy a variety of remote sensing systems to work directly from the ice surface or from the deck or bridge of a nearby vessel. Surface-based sensors may include: hand-held IR, dogs, X-band Marine Radar, and integrated systems combining IR and low light level camera technologies e.g. Aptomar SECuras system.

Dogs: The training and field assessment of dogs in detecting oil in snow and on ice was a highly successful part of the JIP remote sensing program. Realistic tests conducted in April 2008 at SINTEF's research station near Svea on Svalbard followed positive early trials in Trondheim in 2007 and confirmed that dogs can be used to detect oil spills covered with snow and/or ice under harsh Arctic winter environments. The dogs maintained their full concentration and operative sensitivity for several days even after being transported in cages while strapped on scooter sledges and exposed to bumpy rides and exhaust.

Controlled field tests carefully documented with GPS transmitters on each animal showed that the dogs could reliably locate isolated small oil spills buried under snow in the ice surface and determine the approximate dimensions of a larger oil spill. The dogs also verified the bearing to a larger oil spill (400 litres, on top of the ice covered in snow) at distances up to 5 km.

Marine Radar, X-band (short and medium pulse): In the 2009 field experiment, Rutter Sigma S6 radar was tested on a background oil sheen on the water. No discernible spill target was visible on the radar screen. These radar systems have proven their ability to detect slicks at sea during tests sponsored by NOFO and there is no technical reason why similar results would not be possible at least in very open drift ice (10-30% ice coverage) where water predominates over ice. At this stage, the upper limit of ice concentration where marine radar would cease to be effective is not known.

Evolving Technologies

The JIP focused on technologies that already exist in a "proven" state. However there are a number of new technologies or new applications of rapidly evolving technologies that could play an important role in expanding remote sensing capabilities to a wider range of oil in ice scenarios in the near future:

- Nuclear Magnetic Resonance (NMR)
- Unmanned Air Vehicles or (UAVs)
- Autonomous Underwater Vehicles (AUVs)
- Next-generation GPR optimized for the oil in ice problem

The matrix below compares the different sensors for remote sensing of oil spills in ice according to the platform (AUV, ice surface, vessel, airborne, or satellite) and the oil/ice configuration (on, under, in, among ice) covering a mix of pack ice and fast ice environments. The expected capabilities of different systems are based on information gathered during the course of the JIP P5 activities, including: the preliminary technology screening, field experiences and reported performance in previous trials and spills, not necessarily in the Arctic.

A number of conclusions and observations are drawn from this matrix in the following points.

Platform	Ice Surface		AUV	Shipborne		Airborne					Satellite
Sensor	Dogs	GPR	Sonar	Marine Radar	FLIR	GPR	Visible	UV	FLIR	SLAR	SAR
OIL ON ICE											
Exposed on cold ice surface	Y	N/A	N/A	N	Y	Y	Y	N	Y	N	N
Exposed on spring melt pools	Y	N/A	N/A	?	Y	N	Y	?	Y	?	N
Buried under snow	Y	Y	N/A	N/A	N	Y	N	N	N	N	N
OIL UNDER ICE											
Smooth fast ice	?	Y	Y	N/A	N/A	Y	N/A	N/A	N/A	N	N
Deformed pack ice	?	?	Y	N/A	N/A	?	N/A	N/A	N/A	N	N
OIL IN ICE											
Discrete encapsulated layer	?	Y	N	N/A	N/A	Y	N/A	N/A	N/A	N	N
Diffuse vertical saturation	?	?	N	N/A	N/A	?	N/A	N/A	N/A	N	N
OIL BETWEEN ICE FLOES											
1 to 3/10 concentration	N/A	N/A	N	Y	Y	N	Y	Y	Y	Y	Y
4 to 6/10 concentration	N	N/A	N	?	Y	N	Y	?	Y	?	?
7 to 9/10 concentration	?	N/A	N	N	Y	N	Y	N	Y	N	N

LEGEND	
Likely	Y
Possible	?
Not likely	N
Not Applicable	N/A
Blocked by dark/cloud/fog/precip	

a. Very few sensors have demonstrated a capability to detect and map oil under or trapped within rough offshore pack ice. Sonar carried under the ice on AUVs may have potential in the future to deal with this difficult scenario.

b. GPR – surface or airborne – is the only sensor at present capable of detecting isolated oil pockets trapped beneath or within a solid ice sheet or on the ice surface under snow. Limitations and unknowns centre on its performance in warm saline ice and/or rough rubble and ridging. Ongoing developments are expected to result in more capable airborne GPR systems optimized for the oil in ice problem by 2011.

c. Extrapolating from their proven ability to detect slicks at sea, existing airborne sensors developed for open water applications are expected to perform reasonably well in very open drift ice (1-3/10). In heavier ice concentrations, the capabilities of different sensors will depend largely on the scale of openings and slick areas among the floes, oil thickness and wave effects.

d. Some form of Infrared (IR) sensor used from the surface, vessel, aircraft or helicopter is possibly the most flexible technology for detecting oil between floes or exposed on the ice surface, recognizing the constraints of darkness and cloud/fog. Recent systems that integrate X-band Marine radar with passive and active IR sensors have shown promise in trials with spills on open water in Norway and could provide equivalent spill mapping capabilities in very open ice covers.

e. Given the limitations of cloud cover and darkness, visible satellite sensors (e.g. Quickbird) cannot be relied on in an emergency to provide reliable coverage.

f. The latest generation of SAR satellites such as CosmoSKYMed, TeraSAR-X and RS2 are theoretically capable of resolving targets close to 1 m in size but their ability to discriminate between natural wind-roughened water between floes and the modified sea surface affected by the presence of oil is still unknown. Direct spill detection from SAR satellites and airborne

SLAR/SAR systems may be possible for large spills in very open drift ice (<4/10), and under moderate surface wind conditions (~5-10 m/s).

g. During freeze-up in fall and early winter any detection of oil among ice with SAR/SLAR sensors will be complicated by the presence of grease ice – the earliest smooth stage of ice crystals at the water surface. The presence of grease or new ice (nilas) in conjunction with an oil spill on the water will produce close to identical signatures in the radar imagery, making detection of an oil slick difficult or impossible to identify.
h. Trained dogs are able to reliably detect very small oil volumes and map oiled boundaries on solid ice and in sediments on Arctic shorelines under extreme weather conditions. The future utilization of dogs in this role will require established standards for training of new dogs and their certification, established procedures to protect the animals and long-term agreements with recognized dog training institutes. Cooperation with native communities in Alaska and Canada should be explored as a means of fully realizing the potential of dogs in this new role. The capability for oil detection can also be added to skills already routinely exercised with dogs trained for other cold climate emergencies such as avalanche search and rescue.
i. Future Arctic spill contingency plans need to account for operational constraints experienced first-hand during the JIP: aircraft range and endurance limitations with few airfields available as alternates, weather limits, crew duty cycles, satellite reliability and reprogramming time and the possibility of competing demands on limited remote sensing resources.

Complete details on all of the remote sensing activities included in Project 5, are provided in the individual Oil in Ice JIP technical reports: Babiker et al., 2010 (no.: 29); Bradford et al., 2010 (no.: 24); Brandvik and Buvik, 2010 (no.: 14); Dickins and Andersen, 2009 (no.: 22); Dickins and Andersen, 2010 (no.: 28); and Hirst and O'Connor, 2007 (no.: 23).

CONTENTS

SUMMARY AND CONCLUSIONS IV

AIRBORNE REMOTE SENSING IV
SATELLITE SYSTEMS V
COMBINATION AIRBORNE AND SURFACE SYSTEMS V
SURFACE-BASED SYSTEMS VI
EVOLVING TECHNOLOGIES VI

1 BACKGROUND AND OBJECTIVES 1

1.1 PROJECT SCOPE AND CHRONOLOGY OF EVENTS 1

2 TECHNOLOGY REVIEW AND INITIAL SCREENING 3

2.1 SELECTED TECHNOLOGIES FOR FIELD EVALUATION 4

3 REMOTE SENSING PROJECT ACTIVITIES 5

3.1 METHANE DETECTION – GAS SNIFFING 5
3.2 GPR TESTING FOR OIL ON ICE DETECTION 7
3.2.1 Svea experimental spill 8
3.2.2 Data acquisition. 9
3.2.3 Results 10
3.3 DOG TRAINING AND TESTING 12
3.3.1 Phase 1 13
3.3.2 Phase 2 14
3.4 AIRBORNE REMOTE SENSING SYSTEMS 18
3.4.1 Sensor Overview 18
3.4.2 2008 Program 20
3.4.3 2009 Program 21
3.5 SATELLITES 25
3.5.1 Basic Principles 26
3.5.2 FEX09 Image acquisition 29
3.6 SHIP-BORNE SENSORS OF OPPORTUNITY 36
3.6.1 Hand-held IR 36
3.6.2 Marine Radar, X-band (short and medium pulse) 37
3.6.3 Integrated FLIR and high resolution camera technologies 38

4 EVOLVING TECHNOLOGIES WITH POTENTIAL FOR OIL IN ICE DETECTION 39

4.1 NUCLEAR MAGNETIC RESONANCE - NMR 39
4.2 UNDER-ICE AUV 40
4.3 UNMANNED AIR VEHICLES (UAV'S) 41
4.4 NEXT-GENERATION GPR FOR OIL UNDER ICE 42

5 REFERENCES 43

1 Background and Objectives

Spill detection and mapping are particularly important for Arctic spills as oil may be hidden from view under snow and ice during periods of almost total darkness. Close to 24 hours daylight in the spring and summer months facilitates monitoring spilled oil during the break-up and open water periods but fog and low cloud ceiling remain as serious impediments. During freeze-up and through much of the winter, long periods of darkness and multiple oil/ice scenarios add to the challenges of detection, mapping and tracking oil in ice.

Under frequently encountered conditions of low visibility, blowing snow, lack of contrast and limited daylight, the apparently simple task of determining whether ice is clean or oiled can become extremely difficult. This is particularly true after a few days when the initially concentrated slick may be separated into smaller more diffuse patches, partly covered by drifting snow or obscured by frazil and slush in the water. Nearshore ice may contain surface sediments that confuse springtime observations.

The overall goal of Project 5 was to establish whether “off-the-shelf” technologies and sensors could detect oil in the presence of ice in particular scenarios. Specific objectives were to:

- Assess the limitations and capabilities of currently operational or available remote sensors and systems for spill surveillance in the ice regimes encountered in the offshore field experiments (FEX) in 2008 and 2009.
- Draw conclusions and make recommendations as to the most effective sensors to use in a variety of oil and ice situations based on what was learned throughout the JIP process – including the initial technology and screening and field tests offshore and on Svalbard.

Full details on all of the activities carried out as part of the Remote Sensing Project are contained within separate Oil in Ice JIP Technical Reports nos. 14, 22, 23, 24, 28, 29 and 30 – see References.

1.1 Project scope and chronology of events

The following points cover the evolution of the remote sensing project and progression of key activities and decisions over the period 2007-09.

System Screening 2007 - *Initial report issued January 2008 Rev. in final form Oct 2009*

- Summarized known capabilities of different sensors
- Selected technologies for field evaluation
  - Laser Fluorosensors (Canada and Germany) – subsequently dropped due to lack of available sensor systems to participate in field trials – decision in 2008
  - Multispectral airborne systems (e.g. Sweden)
  - GPR (linked to ongoing MMS project) – see 2008 field tests
  - Dogs (new project element added - P.J. Brandvik)
  - Other sensors (Satellites, Marine Radar etc.)

2007 Field Testing

Gas sensors

- Methane measurements from small-scale spills on ice at Svea provided baseline measurements for evaluating potential of Shell’s Light Touch™ - results indicated limited window of opportunity - decision not to include in FEX offshore trials

Dog Sniffing
- Initial training with positive results Trondheim 2007

2008 Field Testing

Ground Penetrating Radar
- Successful airborne mapping of oil under snow with exp. Spill on solid ice at Svea April 2008

Airborne Multispectral Sensors
- Norwegian aircraft forced to abort the JIP mission 4 hours prior to takeoff due to a real spill emergency off Bergen.

Satellite Systems
- Imagery acquired during the field period by KSAT –no oil present.
- Largest uncontained spill on the water for a very brief period – coordinated exactly with Radarsat 2 overpass. Satellite owners failed to acquire the image in Canada.

Dog Sniffing
- Successful detection of oil on the ice at Svea April 2008
- Successful detection of oil in beach sediments near Trondheim – Statoil funding

2009 Field Testing

Airborne Multispectral Sensors
- Two aircraft at Longyearbyen: (1) Norwegian aircraft with very limited capability – SLAR and cameras only – interim replacement for the main surveillance aircraft lost June 2008; (2) Swedish state of the art Dash 8 delivered 2008.
- Swedish aircraft deployed to Svalbard prematurely at request of NCA as result of Russian freighter grounding on Bear Is. –aircraft availability allowed a single flight over the test area 4 hours after oil release. Spill dimensions at this stage were far smaller than the SLAR/SAR sensor resolution – no oil detected
- Low cloud - below 300 m - prevented testing the electro optical IR camera system (Wescam MX15)
- Norwegian aircraft left Longyearbyen for the site of vessel grounding and then back to the mainland to maintain normal level of national spill preparedness. Decision based on NCA needs and continuing low ceiling and fog at the experimental site.
- **Satellite Systems**
- Daily Medium and high resolution radar satellite imagery acquired during the full field period coordinated by KSAT out of Tromso
- Close to very close pack conditions prevented the formation of a suitable target slick on the water surface for possible detection in the SAR imagery.
- Overall image quality much lower than 2008 possibly as result of surface roughness spacing and floe size in same order as pixel dimensions

Marine Radar – Rutter Sigma S6
- Tested on background sheen escaping from the fire resistant booms off KV Svalbard – no oil detected

Hand-held IR Camera from ship/surface and helicopter
- Suite of images captured by *Lance* team of P2#2 spill show potential to discriminate oil on water and mixed with snow during daytime – memo by P. Daling. Tests on the oil contained among ice within fire-resistant booms towed behind *Svalbard* showed no discernible temperature difference.

2 Technology Review and Initial Screening

A number of authors have summarized the history of oil in ice detection research employing a wide range of technologies (e.g., Dickins, 2000; Fingas and Brown, 2000 and 2002; Goodman, 2008). Much of this earlier research took place over an intensive ten-year period beginning in the late 1970's, largely in response to an active Arctic offshore drilling program in the Canadian Beaufort Sea. Researchers carried out analytical, bench tests, basin tests and field trials with a wide range of sensor types in an effort to solve the oil in ice detection problem.

Technologies evaluated and in many cases tested in laboratory and field environments included acoustics, radar, UV fluorescence, viewing trapped oil under UV light from a bare ice surface, IR (including active heating with a laser), Gamma Ray, Microwave radiometer, resonance scattering theory (USCG), gas sniffers and impulse radar. Following the demise of the Beaufort Sea drilling program in the late 1980's, very little new progress was made until about 2004. At that time, a series of projects sponsored by MMS and the oil industry in Canada and Norway began to evaluate and test a new generation of Ground Penetrating Radar (GPR), acoustics and ethane gas detectors (Shell's LightTouch™ system) – e.g. Dickins et al. 2005 and 2006.

More recently, in 2007 ExxonMobil began to pursue the concept of using Nuclear Magnetic Resonance (NMR) as a basis for future airborne detection systems (Nedwed et al., 2008). Wadhams et al. (2006) reported on the first successful 3-D high resolution mapping of the ice under surface with an Autonomous Underwater Vehicle (AUV). Statoil sponsored an initial evaluation of Unmanned Air Vehicles (UAVs) in the Arctic offshore surveillance role (2008 unpublished). Most recently, NOFO launched a coastal oil surveillance UAS project with NORUT/Aranica as part of the Oljevern 2010 Technology development programme. Several of these developing technologies, which may have important future implications for oil in ice detection, are covered briefly in Section 4.

At the outset of the JIP program a screening report (Dickins and Andersen, 2008 (2009Rev.)) was completed with two main objectives:

1. To provide a baseline summary of the current state of knowledge as to the potential capabilities of different sensors and systems in: a) detecting oil at sea (status quo); b) detecting oil on, under, or trapped within solid ice; and c) detecting and mapping oil spilled among drifting floes in a range of pack ice environments (focus of the JIP field tests)
2. To short-list the most likely candidate sensors and systems for testing in 2008 and 2009 based on their expected capabilities in a variety of Arctic offshore environments.

A general finding of the screening study was that although there is an overall lack of direct experience regarding the capabilities of different sensors in the presence of ice, reasonable estimates can be made based on: 1. Our understanding of oil behaviour in ice, especially how ice concentration affects spreading, 2. Our understanding of how different sensors perform with spills in open water, and 3. The effects of ice cover on wind waves and swell. For oil spilled among pack and drift ice, a combination of all or some of the existing suite of airborne sensors could provide a partial solution. The optimum mix of technologies and outputs will depend heavily on the spill characteristics and prevailing weather and ice conditions. An ideal system (mix of sensors) would have the capability of operating in both airborne and ground-based modes, and have the capability of determining first whether oil is present within a large area, and then to map the localized boundaries of contamination. There is no single system available at present that can meet these demanding requirements.

2.1 Selected technologies for field evaluation

Based on the outcome of the screening study, the following systems and technologies were selected for further evaluation in the 2008 and 2009 field programs:

1. Airborne (utilizing operational pollution surveillance aircraft with integrated multispectral sensors including: UV/IR, FLIR, SAR/SLAR and ALFS)
2. All weather SAR Satellite Systems
3. Dogs for surface oil detection
4. Ground Penetrating Radar (GPR) for low level airborne oil on ice detection
5. Ship-borne sensors of opportunity such as Rutter and/or MIROS oil spill detection systems utilizing raw data from navigation radars.

The screening study also recommended canceling plans for further field-testing of Shell's LightTouch™ system in the JIP based on results from the 2007 program pointing to limited applicability for batch releases where light ends are lost in a matter of hours. Further details of the 2007 methane detection field tests and subsequent discussion are provided in Section 3 below.

From the outset, going into the planning for the 2008 offshore field experiment the remote sensing team recognized that there would be no possibility of conducting large-scale uncontained spills solely for the purpose of testing remote sensing systems. All of the offshore remote sensing activities were designed to make use of spills of opportunity within the overall JIP program. This necessitated working with the spill parameters dictated by other elements of the program, including the size and duration of spills as well as the variable nature of the ice conditions. In addition the remote sensing project utilized several smaller, isolated spills on solid nearshore ice at Svea, Svalbard to test specific systems such as methane sensing, airborne GPR and dogs that would have no direct role to play in the offshore experiments.

Chapter 3 describes each of the remote sensing activities carried out between 2007 and 2009.

3 Remote Sensing Project Activities

A series of reports, internal and contractor-generated, were produced over the course of P5 covering field and analytical activities between 2007 and 2009. The following sections contain highlights from all of the main project activities, including further technical background on the different sensor systems. Section 5 contains a full reference list to the complete P5 JIP reports and other supporting documents used in their preparation.

3.1 Methane detection – gas sniffing

Shell Exploration and Production collected baseline data on methane emissions from oil on the ice surface at Svea in April 2007 (Hirst and O'Connor, 2007). The primary goal of this effort was to obtain a useable estimate of the hydrocarbon emission rate resulting from oil spills onto icy water; and to use this to assess the potential for detecting and locating such spills using ultrasensitive gas sensors represented by Shell's LightTouch™ hydrocarbon seepage detection technology.

Background: Work at the US Army's Cold Regions Research Engineering Laboratory, CRREL in 2004 by Shell Global Solutions, examined the potential for detecting oil under ice by using ultrasensitive gas detection (Dickins et al., 2005). The gas sensor was used in conjunction with a flux chamber on the ice surface to provide the first ever measurements of gas migration fluxes though a solid ice sheet.

When the sensor is used for oil exploration, atmospheric gas concentration measurements over a large area are combined with simultaneous wind velocity data and advanced gas dispersion modeling to remotely map surface emission fluxes. The system can detect naturally occurring microseepages of hydrocarbon gases from ranges of up to several km. Clearly, if oil spills produced comparable emissions, then the same approach could be used for detection and mapping. This would be attractive as ultra-sensitive gas sensors could be operated from aircraft, and readily deployed over
large distances and rapidly cover large search areas.

Key to assessing the feasibility of such an approach is knowing the flux levels (mass release rate per unit area per unit time) of hydrocarbons emitted from oil spills under the conditions of interest. The 2007 Svea spill programme provided a rare opportunity to address that question.

It was not feasible, within the timing/cost constraints of these tests, to deploy the LightTouch™ system in Svea. However, this step was not necessary for the purposes of the 2007 tests – scientists could approach the spills to within a few meters, and hence could use a significantly less sensitive but simpler battery powered Boreal Line-Of-Sight LOS methane sensor.

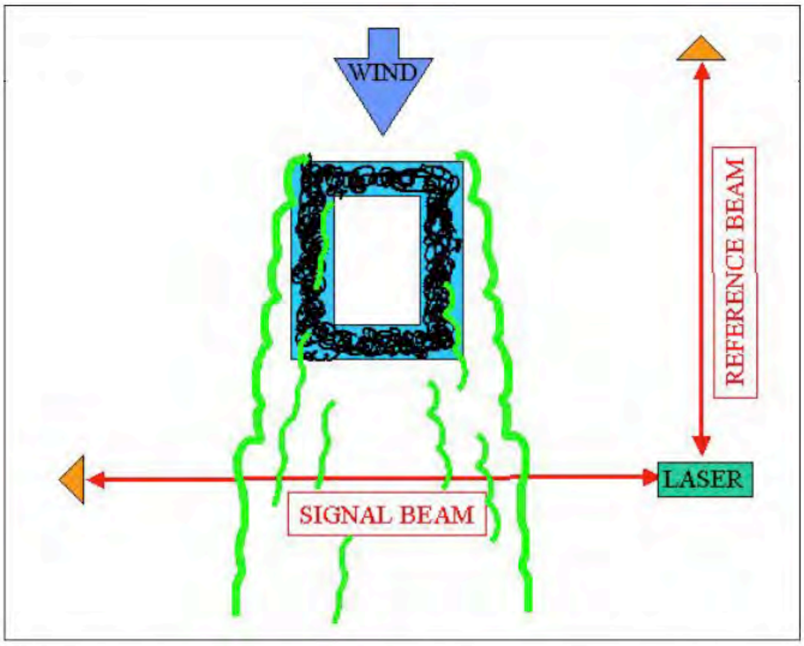

Figure 1. Experimental layout for the gas concentration measurements at Svea in 2007 showing the gas sensor beam orientation in relation to the circulating oil and water flume cut into the ice surface. Beam lengths were typically ~20 m operating ≤10 m downwind of the spill.

Figure 1. shows the basic experimental set up at Svea. The key parameter presented here is the difference between the upwind (background) gas concentrations and those of the downwind beams that traverse the dispersing plumes. The path-integrated concentration is most conveniently displayed as the effective average concentration along the full beam length. So no distinction is made between a short region of high concentration and a long region of lower concentration: it is the total mass of gas traversed that is being measured. The Earth's current atmospheric background methane concentration is approximately 1.8 PPM. Therefore any significant enhancement above that background concentration can be interpreted to reflect the contribution of local sources.

There were a number of practical issues noted as "distractions" affecting the interpretation of the results including:

- movement of open drums in the vicinity complicated the separation of signals from oil on the water vs. fumes escaping from the empties
- wind shifts
- gas from the ullage space created in the drum during pouring

Increases over atmospheric background levels in the order of 0.15 ppm were measured for 30 min to an hour after spilling the oil but some of these extended measurements were subsequently traced to emissions from the empty drums.

The authors concluded that a hypothetical spill of 1000 tonnes into open drift ice (4-6/10) would emit methane for about 100 or more hours based on an equilibrium film thickness of ~1 mm over an area of 1 km^2. The theoretical detection distance for an aircraft at 80 m altitude – very low level – was calculated as ~ 5 km with current generation methane sensors capable of ~200 PPT precision. These conclusions were based on the assumption that the experimental setup used by Sintef at Svea led to an accelerated weathering process that increases the loss of methane and other volatiles by a factor of 20.

SINTEF has extensive experience conducting oil-weathering studies on Svea and all of the results to date indicate that the outdoor ice flume closely mimics weathering rates that would be seen in an actual spill. Given the lack of any evidence to support this critical assumption of accelerated weathering, the findings with regard to potential windows of opportunity to utilize ethane or methane sniffers following a batch oil release could be exaggerated by an order of magnitude. If that were the case, the practical detection time for a batch spill (no continuous supply of fresh oil) would shrink to a few hours – much too short to be of significant operational benefit. Based on these uncertainties and logistics issues such as maintaining the measurement team at sea for up to two weeks, and the problem of separating spill emissions from multiple, largely uncontrollable emission sources in close proximity to the field spills (deck machinery, small motors, vessel stack gases) it was decided not to conduct any additional gas-sniffing evaluations going forward into FEX08 or 09.

In cases where the spill is a continuous release over an extended time period (e.g. blowouts) light hydrocarbon components would always be present. This situation would essentially result in an unlimited time window – as long as the oil is discharging to the environment - to use gas sniffing for spill detection but the need for a detection system in these situations would be correspondingly much less – presumably the operator will always be aware of the location of such a major event.

If it could be proven that ethane/methane components are detectable through ice over time, the use of gas sniffers to find oil trapped under the ice would be of interest. In such cases the operational window using this technique for oil spill detection could be extended, as oil trapped under ice does not weather to any significant extent. Preliminary testing of an early version of Shell's system in tank tests at CRREL, NH provided some evidence of ethane flux occurring through a 35-40 cm ice sheet but the concentration levels were very close to background and not sufficient to determine future potential (Dickins et al., 2005).

3.2 GPR Testing for Oil on Ice Detection

Since the earliest attempts to detect oil in ice in the 1970's, advances in data processing in geotechnical sciences and dramatic reductions in signal to noise ratios - among other improvements - has transformed the field of impulse radar or ground penetrating radar (GPR). Over the past four years (2004-08), significant progress was made in oil-in-ice and oil-under-snow detection utilizing the latest hardware and software technology represented by portable, commercially available GPR systems. Numerical modelling, laboratory trials, and field tests in a range of ice conditions have demonstrated that existing GPR systems in the 500 MHz to 1 GHz frequency range operated both from the ice surface and low altitude from a helicopter can detect oil layers in the 1-3 cm range trapped in relatively smooth ice (Bradford, 2007; Bradford et al., 2005; Bradford et al. 2010 – in press).

The GPR previously tested over an experimental under ice spill at Svea one year prior to the JIP was viewed having a high probability of airborne detecting and mapping oil on the surface of the ice buried under snow. This conclusion was based on the excellent profiles of the snow and ice surfaces obtained from a low altitude helicopter in previous field trials (Dickins et al. 2006). See Figure 2.

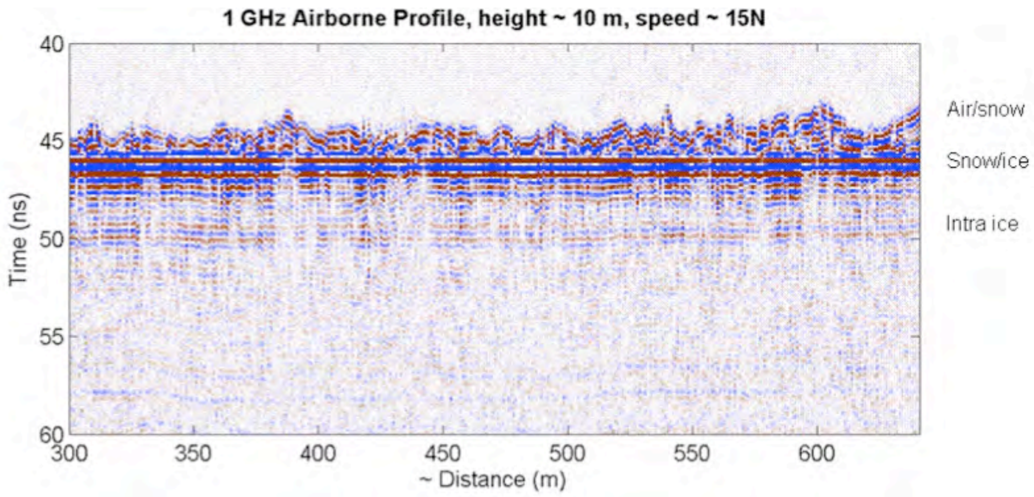

Figure 2. Airborne GPR profile of the snow surface on ice acquired March 2006. Radar modelling indicated that an oil layer of 1-2 cm on the ice would be detectable using commercially available GPR systems (Dickins et al. 2006/08; Bradford et al. 2010).

Numerical modelling sponsored by MMS in 2007 confirmed that GPR is sensitive to the presence of oil in the snow pack over a broad range of snow densities and oil types. Oil spills from the surface drain through the snow by the mechanisms of unsaturated flow and form geometrically complex distributions that are controlled by snow stratigraphy. These complex distributions generate an irregular pattern of radar reflections that may be differentiated from natural snow stratigraphy, but in many cases interpretation will not be straightforward. Oil located at base of the snow tends to reduce the impedance contrast with the underlying ice or soil substrate resulting in anomalously low amplitude radar reflections. In order to test this potential with an actual oil spill on the ice surface, ongoing JIP-sponsored activities at Svea in the spring of 2008 were integrated with ongoing MMS work (Bradford et al. 2010).

GPR detection of oil deposited onto snow or trapped at the base of the snowpack is substantially different than detecting oil within or beneath sea ice and requires alternate analysis and experimentation to verify its effectiveness. In particular, the electric conductivity structure of snow differs substantially from that of sea ice. Because electric conductivity controls radar signal attenuation and since snow has very low electric conductivity, the radar signal propagates very effectively through snow. Sea ice has much higher electrical conductivity (> 10^{-2} S/m). The conductivity structure of sea ice varies substantially both laterally and vertically (Morey et al., 1984) and can exhibit a high degree of anisotropy due to preferred crystal alignment (Kovacs and Morey, 1978; Nyland, 2004). Because of its relatively isotropic structure and low conductivity, the problem of oil detection is simpler to formulate for snow than it is for sea ice.

3.2.1 Svea experimental spill

The 2008 experimental site at Svea was prepared by constructing two ~4.5 m x 4.5 m test cells on the ice surface; the cells were constructed by clearing the snow, then scraping and smoothing the ice surface to promote uniform spreading of the oil. The snow surrounding the cell was a dense windpack and provided adequate containment of the oil. One cell served as the experiment control with no oil. In the oiled cell, 400 L of Stratfjord crude were first warmed to room temperature in an indoor facility then poured onto the ice surface (Figure 3). The oil flowed smoothly and formed a relatively uniform layer. Following the GPR surveys, the oil thickness was measured using a syringe sampling tube every 30 cm. Samples were collected along two perpendicular sides of the containment cell and located 60 cm from the outer boundary. The average oil thickness was 2 cm ± 1 cm. Approximately 1.5 m^2 area remained free of oil in one corner of the cell because of a minor variation in ice topography.

Figure 3. Photograph of Sintef personnel pouring oil into the spill containment area for the oil-under -snow field experiment.

Air temperatures during the spill reached a high of only -13C. At these temperatures, the oil rapidly became highly viscous and immobile, preventing further migration outside of the test cell. To prevent accidental contact of wildlife with the oil, a trip wire system with flares was installed around the perimeter of the spill. Following the spill, high winds resulted in natural windblown snow cover, 5 – 10 cm thick over the spill and 5 – 20 cm thick over the control cell (Figure 4). Since the oil was highly viscous, there was very little mixing of the snow cover and oil and we observed a distinct boundary between the oil and snow when measuring oil thickness.

3.2.2 Data acquisition.

Data were acquired with a Sensors and Software PulseEKKO Pro using 1000 MHz shielded antennas in bistatic mode with 17 cm separation between the source and receiver. When deployed in air, this system generates a pulsed waveform with a 500 – 2600 MHz bandwidth and a dominant frequency of 1300 MHz. The radar system was suspended from the helicopter's cargo hook mount (Figure 5) and flown across the test cells (Figure 4) at altitudes of 5, 10, 15, and 20 m and speeds of 2.6, 5.1, 7.7, and 10.3 m/s.

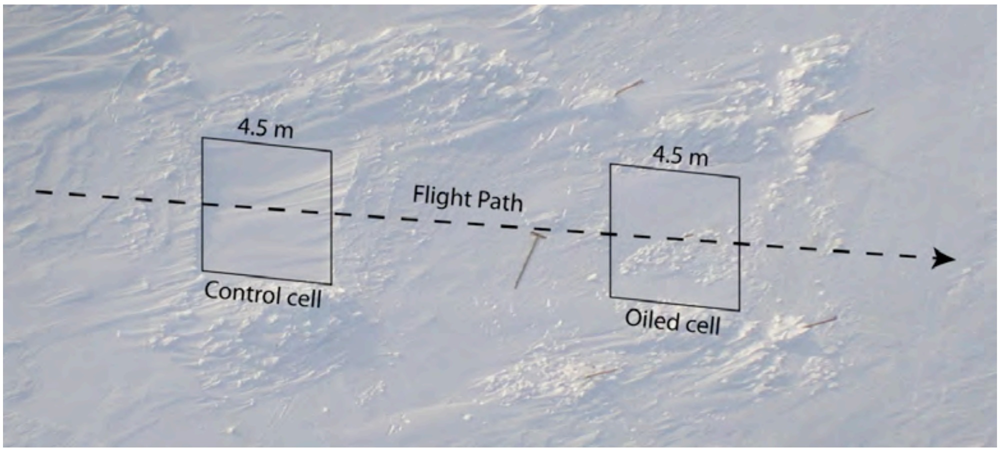

Figure 4. Overhead photograph of the snow covered test cells and helicopter flight path.

Figure 5. Photograph showing the 1000 MHz shielded antennas suspended from the cargo hook of the helicopter (photo from 2006 trials).

3.2.3 Results

With an oil thickness of 2 cm, the forward model predicted a reduction of 51% in reflection amplitude over the oiled cell relative to the control cell. This response is clearly observed in the field data. After extracting the peak instantaneous amplitude along the snow/sea-ice reflection and averaging over all traces acquired within the cell, we found that the field data at all altitudes and flight speeds show a substantial decrease in reflection strength over the oiled cell (Figure 6). Comparing the clean to contaminated reflection amplitude ratios and averaging over all flight speeds, the field data acquired at a flight altitude of 5 m differed from the model prediction by only 16% (Figure 7).

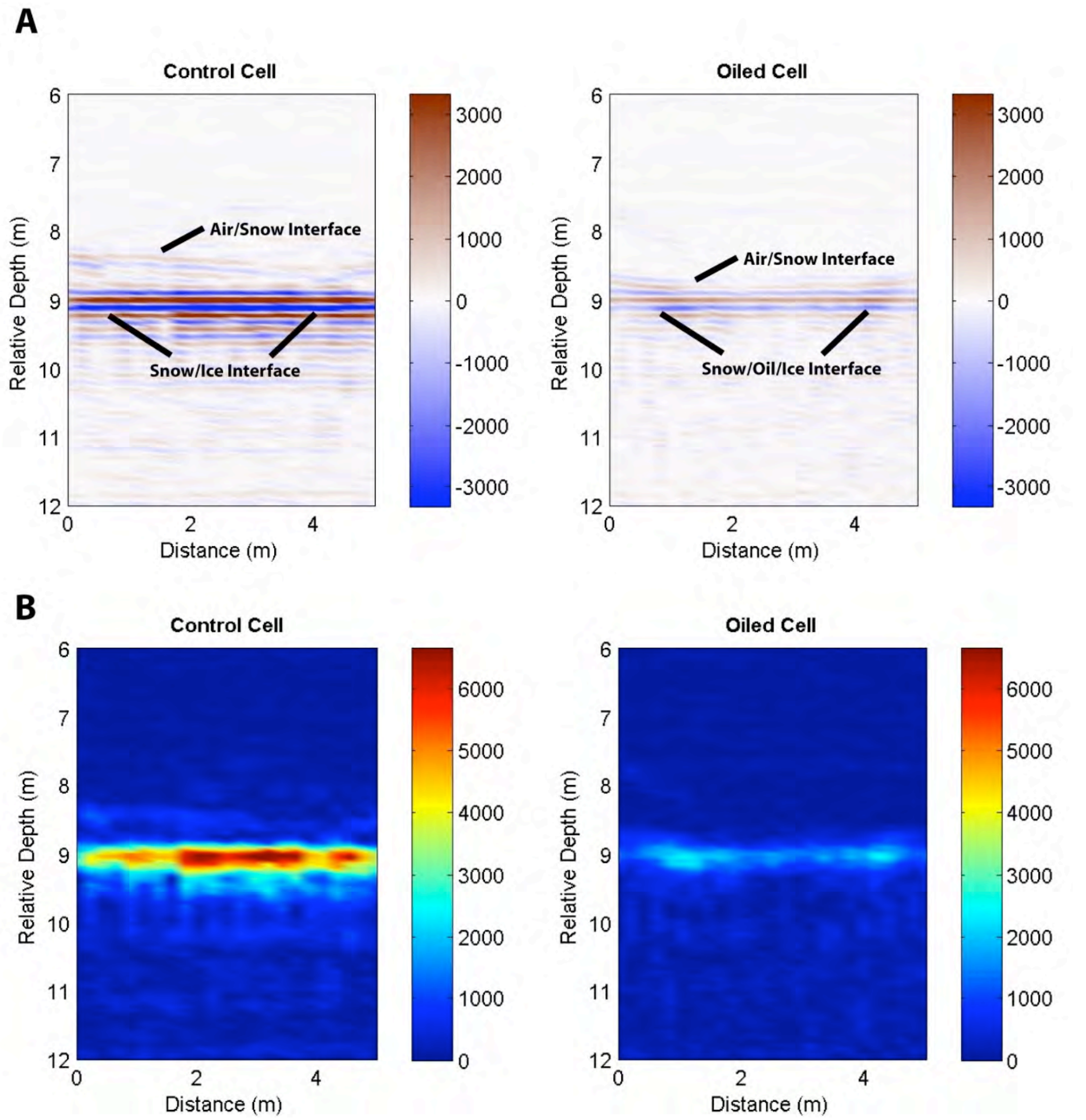

Figure 6. A) Plot of recorded GPR data acquired over the control and oiled cells at an altitude of 5m and speed of 2.57 m/s. B) Plot of reflection strength for the data shown in A. All data are plotted with the same amplitude scaling. Where the oil film is present, the reflection strength is reduced by ~ 45% as predicted by numerical modelling.

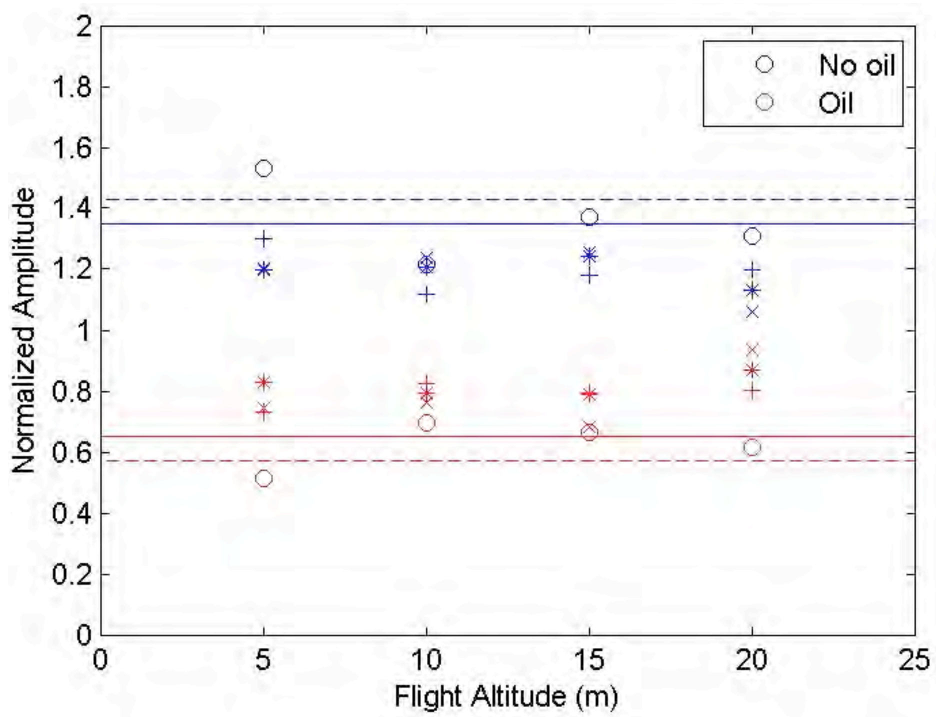

Figure 7. Summary of airborne radar results at speeds of 2.6 m/s (o), 5.11 m/s (+), 7.7 m/s (*), and 10.3 m/s (x). Solid and dashed lines show the predicted amplitudes using the wind blown (low density) and undisturbed snow (high density) properties respectively. Amplitudes are normalized to the average of the clean and contaminated reflections. In all cases the amplitude of the snow-ice interface in the oiled cell is significantly lower than that in the control cell.

The numerical and field results indicate that readily available, commercial GPR systems can be used effectively to detect crude oil spills within or under snow in the Arctic environment. Simple observations of reflection amplitude appear to be a robust indicator of the presence of oil trapped at the snow/ice interface, and a measurable response may be observed at oil thicknesses as small as 1 cm. Further, with measurement of the electric properties of the snow, oil, and underlying medium at a given field site, it is possible to quantitatively predict the GPR response or conversely to potentially estimate spill thickness based on the recorded GPR response. Oil contained within the snowpack may be more difficult to differentiate from the uncontaminated snow, particularly in a complicated snowpack such as a ripe spring snow that contains meltwater and ice layers. In all cases, spill responders must recognize that the GPR interpretations can never provide absolute information about the location of a spill but can be used to improve the efficiency of oil spill characterization and remediation.

3.3 Dog training and testing

A common feature with any remote sensing methods involving for example, GPR or FLIR is the high level of technology complicating their application in remote Arctic areas with highly variable weather conditions and darkness. An alternative to relying only on hi-tech solutions to the oil in ice problem is to utilise the large still largely unexplored potential of specially trained dogs to detect oil spills not visible to the naked eye or even the most advanced remote sensing detectors. It has long been known that dogs' ability to detect different odours is exceptional. This ability has been used for many purposes such as searching for: bombs or drugs (K9, 2009, Fält, 1997), missing children (Buvik, 2003), gas leakages in refineries and onshore pipelines, and pollutants such as polychlorinated -biphenyls (PCBs) and polyaromatic hydrocarbons (PAHs) in for example construction sites or old buildings. Mine-detecting dogs have shown their ability to work under harsh conditions and deliver reliable results. However, the methodology in which the dogs are trained and the quality of the training has a strong influence on the dog's work performance.

Recognizing the unexplored potential to use dogs in oil spill applications, the project "Detection of oil spills covered with snow/ice or sediments an alternative approach using specially trained dogs" was initiated in early in 2007. The different project phases leading to field-testing on the ice at Svalbard are described below.

3.3.1 Phase 1

The objective in Phase 1 was to show the practical feasibility of using specially trained dogs to detect hidden oil spills. The basic course consisted of training in the laboratory and different outdoor environments (beach, frozen ground, snow etc.). Results from the initial training clearly showed that dogs can be used to detect oil hidden e.g. in snow. Several of the most experienced dogs passed blind tests and detected different oil types (crude/bunker fuels) compared to blanks or other scents.

This first year of the project involved basic training of two new dogs and "conversion" of four already trained detection dogs. Basic training consisted of training in the laboratory and different outdoor environments (beach, frozen ground, snow etc.). Phase 1 ended with a practical, and as close to reality, test to show the feasibility of using dogs in this application (separate video). Pictures from this video are included here as Fig. 8.

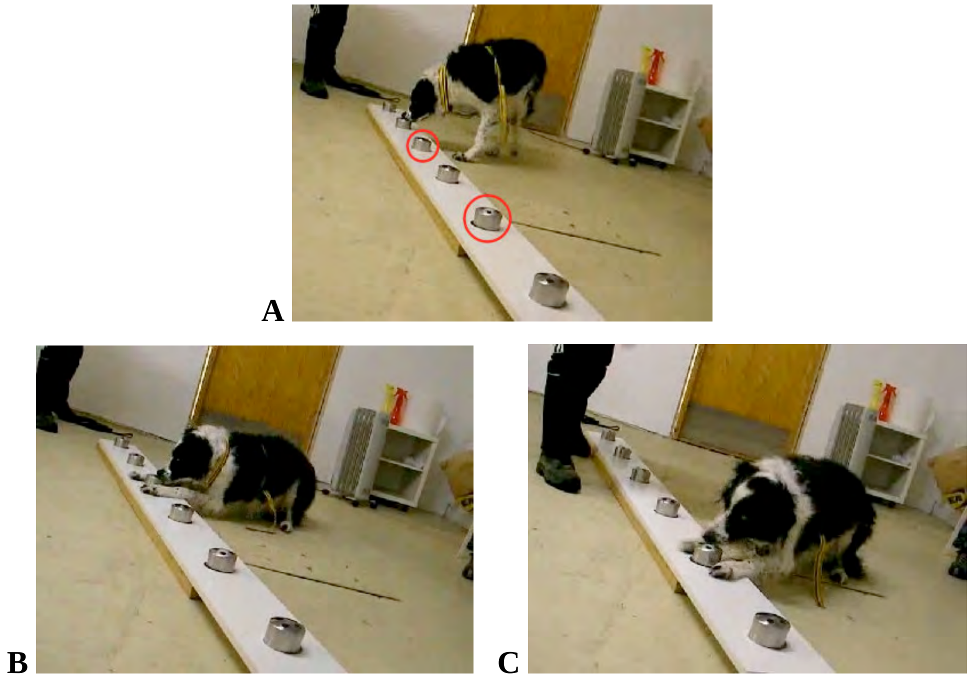

Figure 8. Blind testing of dogs during Phase 1: Pictures from enclosed video. Two boxes contain oil vapour (**A**) and are very visual and clearly detected by one of Turid Buvik's dogs "Jippi" (**B** and **C**).

Following the promising outcome of Phase 1 reported in Brandvik and Buvik (2007) plans were developed for Phase II testing on the ice at Svea in conjunction with already planned oil weathering and remote sensing tests.

3.3.2 Phase 2

The objective in the second project phase was to develop a new and innovative method to detect oil spills hidden in snow, ice or beach sediments by using specially trained dogs. The ability to detect oil is only a small part of the skills needed by the dogs in detecting oil hidden in snow or ice. Both the dog and trainer need to be able to handle challenges regarding the climate and logistics in Arctic areas. This was a vital element in the field training and evaluation conducted on Svalbard in April 2008 (Brandvik and Buvik, 2010). Different elements of the Phase 2 testing are summarized below.

Transportation of dogs: The dogs must be transported back and forth to the search area in a safe and effective manner. This means that the working capacity of the dogs should not be reduced due to stress, the risk of any harm to the dogs should be minimised and the search time should be as short as possible. Cost is also an important factor.

Through special permission from both the Norwegian airway authorities and SAS (Scandinavian Airline System) the dogs were able to travel in the cabin of the plane. This was done to avoid extra stress by freighting the dogs in crates as cargo without supervision. On Svalbard the dogs were transported in dog crates by small airplane and on the ice in the same crates strapped down on a scooter sledge with a warming suit (Figure 9). In future, helicopter transport of dogs offshore could be possible, but this was not explored in the JIP.

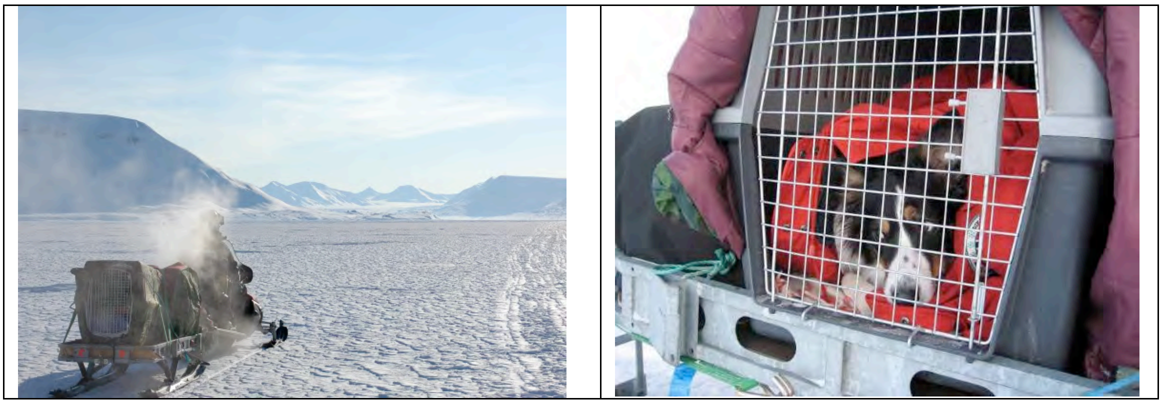

Figure 9. Transportation of dogs in crates on snowmobile sledge. The dogs had good insulation and wind cover in the crates to cope with the low temperature and high winds.

When the dogs were working outside in cold and windy conditions for several hours, even furry dogs needed an insulated crate and some kind of warming suit to keep warm in-between working sessions. Figure 9 shows how the dogs were kept warm during transport. The dogs worked effectively in air temperatures down to -20°C and strong winds (wind chill of -40°C).

Experimental layout: The experimental oil spills were placed on the fjord ice one week prior to the arrival of the dogs. The spills consisted of one large 10 m^2 oil spill (400 litres) also used to test the airborne GPR – see Fig. – below - plus 16 smaller oil spills (400 ml). These smaller spills consisted of oil released into a hole in the ice (0.5 meter deep) and then covered with ice and snow (see Figure 10).

Figure 10. Small training oil spills used for the field training. A: 400 ml of weathered Troll crude (200°C+) in a 30cm hole in the first year ice. B: The hole is covered with snow and ice chips and marked with a small white cord.

All the samples were tagged with a small cord wire as shown in Fig. 10. During the entire training period none of these cords were detected by any of the equipages (dog/trainer). No assistance in detecting the oil spills was given to any of the teams due to the visual detection of the cord wires by either the dogs or trainers. The sites were all tagged with GPS, which were used to find the locations for cleaning at the end of the fieldwork.

The dogs were equipped with two different GPS positioning devices, a Trackstick and a Garmin 220 tracking device (Figure 11). This was used to track the dog's search pattern and compare it with the oil spill positions, wind speed etc. The Garmin system gave the necessary accuracy and updating frequency (1-3 meters, updating every other second), and also offered real-time updating using a built-in UVF transmitter. This system made it possible to track the dogs during field training and to study each individual track in relation to oil and wind at the debriefing afterwards. Parameters such as distances, average search speeds etc. were displayed and calculated using the Garmin Mapsource software.

Figure 11. A: *Tara* with the Garmin 220 system and UVF antenna. Both the GPS receiver and the UVF transmitter are built into one compact unit. The positions are sent in real-time to a Garmin 220 hand-held map plotter.

Training: The dogs were evaluated and trained in a number of different search routines:

- Basic detection of a point source - all three dogs gave a clear indication after approximately 400 meters that oil was upwind
- Determining size and dimensions of an oil slick by triangulating of a series of small spills.
- Working with variable oil gradients and differentiating between the different point sources
- Sensitivity in long distance searching using the large 400 l spill as the target - the team used the dogs at three different distances downwind (approximately 800, 3000 and 5000 meters) and at approximately 200 meters on the upwind side of the oil spill. The tracks are given in Figure 11.

The maximum distance during this training from releasing the dog to the spill was measured to approximately 5 km with no indication of this being the maximal detecting distance. Time limitations prohibited further testing to determine the ultimate detection limits.

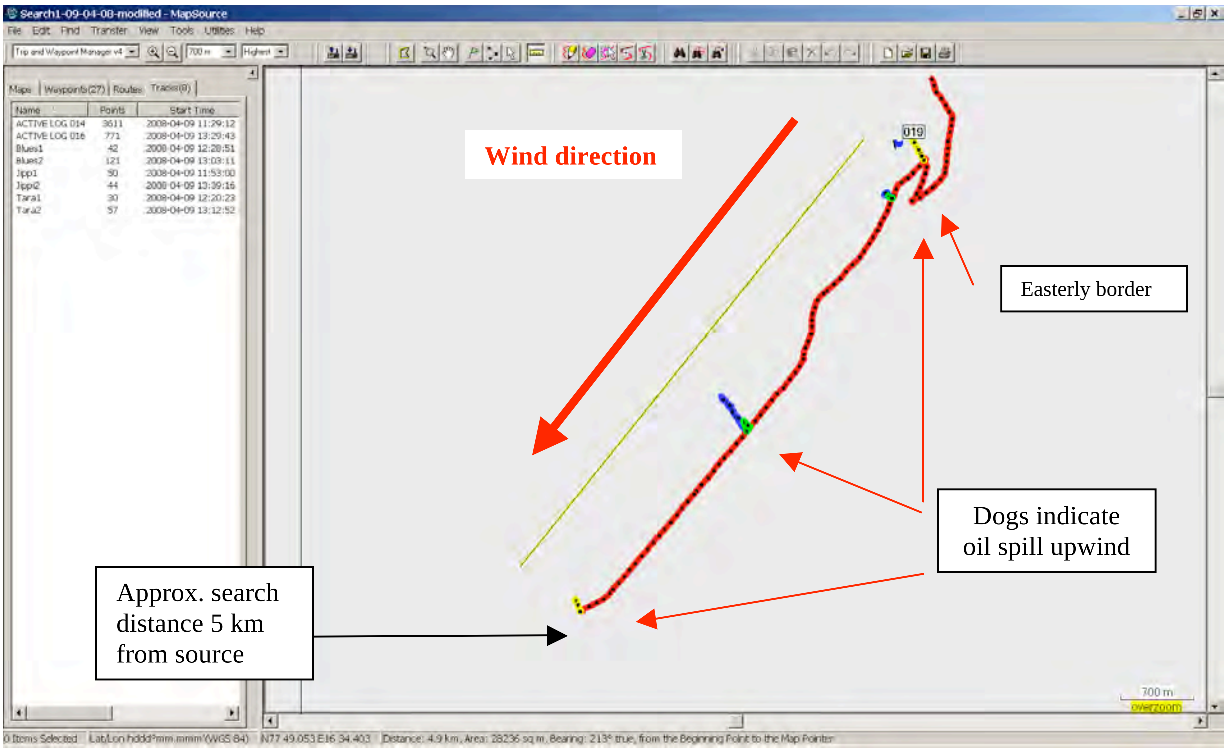

Figure 11. GPS tracks from the dog searches. The three dogs have tracks in different colours. Searches were performed at 0.8, 3 and 5 kilometres downwind and 0.2 km upwind.

Overall Conclusions: Based on the dog training and evaluations conducted in Phase II
During ordinary passenger flights the dogs were able to handle the stress at check-in, crowds/queues and security check very well. They also coped well with lying under the aircraft seat for extended periods (2 x 1.5 hours), and during takeoff and landing. In the small fixed wing aircraft (Dornier 220) the dogs were transported in their crates in the back of the cabin, together with the luggage. All the dogs handled this very well, with little stress and no complaints. There were no negative comments from the other passengers or airport staff. It is important to stress the need for special permits (both national authorities and local airline companies) to transport the dogs in the aircraft cabin.

The transport by snow scooter sledge was challenging. The dogs handled the bumpy and noisy rides very well, without showing any lack of concentration or large stress response. However, the snow surface was rather smooth due to favourable snow conditions prior to this fieldwork. Other more challenging snow or terrain conditions could make scooter transport difficult and create a possible need for helicopter transport. No helicopter training was included in this fieldwork.

The fieldwork showed that the temperature stress (10 m/s wind and -15°C) was manageable for both the dogs and handlers. The work was organised in two periods of four hours each, a total of eight hours per day. This could have been extended (due to 24 hours of sunlight), but time was also needed to evaluate the daily training and adjust plans for the next day.

The dogs also showed an ability to ignore the local wildlife. One search was performed with seals 20 meters away, and polar bear tracks were ignored. There were polar bears in the area, but prior training and motivation on-site helped the dogs to ignore the smell from other animals.

The documentation of the results from the spill detection training (oil properties, GPS-tracks, video and photos) is extensive. The dogs managed to:

1. Pinpoint the exact location of smaller oil slicks (400 ml of weathered oil, 30 cm into the ice, covered in snow and left for a week before it was tracked by the dogs).
2. Determine the dimensions of larger oil spills by indicating the borders of clusters of smaller oil spills (10 meter spacing).
3. Find the location of a larger oil spill (400 L, on top of ice covered in snow) based on the triangulation of detected plume dimensions. The oil spill was clearly detected by the dogs up to 5 km downwind of the spill location.

In a separate demonstration – funded outside the JIP - several of the dogs participated in a small accidental spill in Norway early in 2009 and successfully delineated the extent of contamination of beach sediments (Buvik and Brandvik, 2009).

If dogs are to be used in the future as an operational tool for detecting oil spills hidden by snow and ice, the following tasks must be completed:

1. Discuss with authorities and oil companies if and how such dogs can be utilised as a part of the oil spill contingency plan.
2. Establish a standard for the training of new dogs and the certification of equipages.
3. Establish operational procedures for the use of such dogs.
4. Draw up agreements between the dog training institutes (such as Trondheim Hundeskole) and contingency organisations for operational use of such dogs.

This concept should also be utilised outside Norway. One possibility is cooperation with native communities in e.g. Alaska and Canada adding this capability to dogs already trained for other purposes e.g. search and rescue.

3.4 Airborne remote sensing systems

P5 activities related to airborne surveillance focused on the deployment one of more state of the art multi-sensor surveillance aircraft – see examples in Appendix A - to Longyearbyen, Svalbard where they could conduct overflights of any uncontained spills associated with FEX 08 and 09. In summary, these involved several small spills less than 1 m^3 in very open drift ice (1-4/10) in the first year, followed by larger volumes up to 7 m^3 in the final year of the program with open drift to close pack (5-7/10) as the target ice condition.

These relatively small spills were anticipated to present major challenges for remote sensing for several reasons: because of the very small spill volumes expected for 2008 (1.5 m^{3} was planned but only 0.7 m^3 was actually discharged), and the very small contaminated area expected for 2009 in higher ice concentrations. Regardless of the challenges and concerns about being able to detect the oil in either experiment, the participation of aircraft was viewed as essential to:

- Assess which sensors are likely to prove most valuable in detecting and mapping oil among different types of ice in any future accidental spill.
- Provide flight crews an unusual opportunity of operating in an Arctic offshore environment.

3.4.1 Sensor Overview

This brief overview of the current state of knowledge deals with the demonstrated and expected potential of different airborne sensors to detect oil and map the contaminated boundaries in a range of oil and ice scenarios (based largely on experience with spills in open water) and extrapolated to account for the likely behaviour of oil slicks in different ice concentrations.

Multispectral airborne remote sensing supplemented by visual observations by trained observers remains the most effective method for identifying and mapping the presence of oil on water. There is extensive experience with a range of sensors over slicks in open water but very little is known about the capabilities of these sophisticated airborne systems in ice-covered environments. The few examples where aerial documentation was conducted of spills in ice include conventional vertical photography off the Canadian East Coast in 1986 (SL Ross and DF Dickins 1987), helicopter-mounted IR cameras off Svalbard in 1993 (Singsaas et al. 1994) and extensive remote sensing activities with various sensors during the Kurdistan tanker spill in 1979 (O'Neil et al., 1980; Dawe, 1981; C-CORE, 1980). There is no published record of any of the current generation of pollution surveillance aircraft developed over the past decade having responded to a major spill in ice.

Most developed nations operate aircraft equipped with a range of sensors specifically optimized for pollution surveillance over open water (Canada, Sweden, Norway, Denmark, Finland, Germany, Netherlands, Iceland, Japan etc). An example of the current generation of surveillance aircraft, the Swedish Dash 8 Q300 MSA, is shown in Fig. 12.

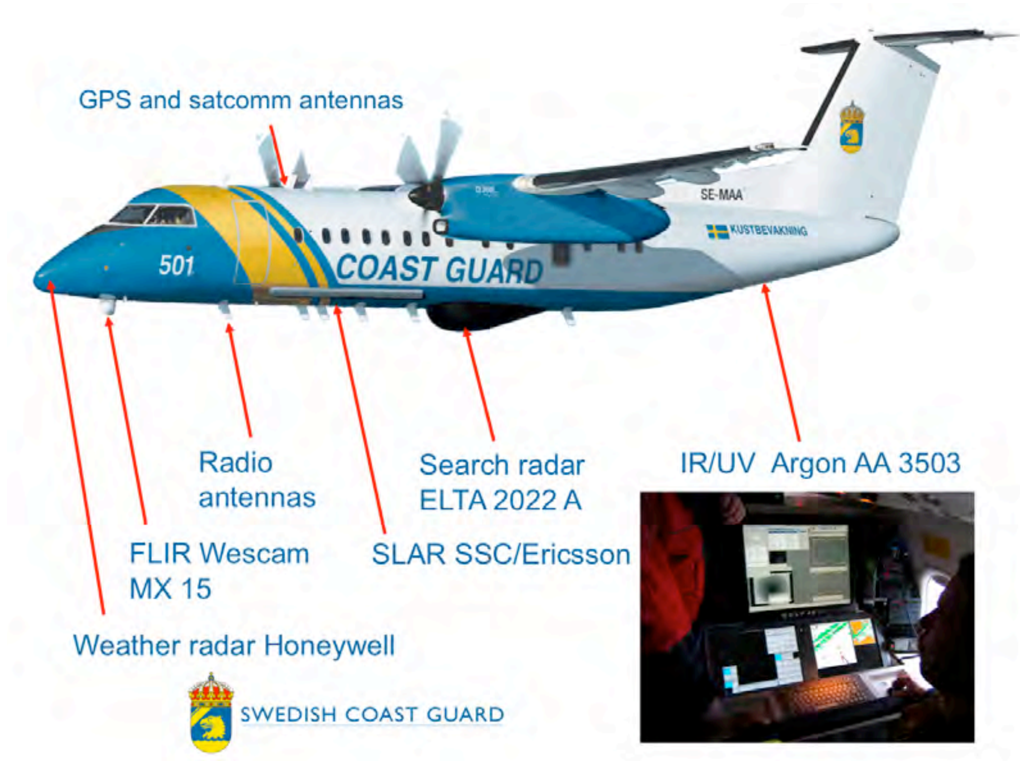

Figure 12. Swedish Dash 8 Q300 MSA aircraft representative of the state of the art in open water maritime pollution surveillance. Member countries of the Copenhagen, HELCOM and Bonn agreements, as well as Canada operate systems with similar capabilities. Source: Swedish Space Corporation

Many of the existing airborne sensors will theoretically detect and map oil among ice in some situations but the limitations on their use in different ice conditions are not well understood. There is no fundamental reason why traditional sensors will not work at least as well in very open drift ice – up to 3/10 – as they do in open water. In 4-6/10 ice cover the presence of ice starts to significantly affect slick behaviour by reducing the spreading rate, increasing the equilibrium thickness, and damping wind waves and swell. All of these factors will greatly affect the capabilities and usefulness of different sensors. In close to very close pack ice >6/10, oil slicks are much more likely to remain localized and confined within the ice as discrete patches rather than slicks in the traditional sense.

The long periods of darkness during the ice season and common occurrence of fog or low cloud over openings in the pack ice place significant constraints on which airborne sensors will be most effective for Arctic spills. Airborne sensors operating in the visible spectrum are mostly daylight, or at best twilight tools (night vision cameras can extend surveillance into lower light levels). UV and IR sensors are all seriously affected by the presence of clouds or fog near the surface.

The Airborne Laser Fluorosensor or ALFS was originally a key element of the remote sensing project motivated by positive results from earlier tests in Canada looking at oil on the surface mixed with snow and ice in test pans (Dick and Fingas, 1992). Laser fluorosensors are active UV sensors that take advantage of the fact that certain compounds in petroleum oils absorb ultraviolet light and become electronically excited by lasers. This excitation is rapidly removed through the process of fluorescence emission, primarily in the visible region of the spectrum. Since very few other compounds show this tendency, fluorescence is a strong indication of the presence of oil. To date, laser fluorosensors (LFS) have been developed for airborne applications only. Although capable of operating in low light or at night the LFS is impaired by variations in flight altitude and the signal is blocked by cloud cover and/or surface fog and precipitation. Lack of availability of operational systems became an insurmountable obstacle to evaluating ALFS capabilities in the JIP. Havariekommando in Germany employs the only system in routine operational use in Europe. They expressed interest in the project but were unable to commit to sending the aircraft away from its primary search area in the Baltic. Estonia was considering the use of a more compact unit in their aircraft but this was not operational at the time of the field experiments. The Canadian government operates the only other known airborne system on a quasi-operational basis, mounted in a 60-year-old aircraft – incapable of transatlantic deployment. No other nation has specified the ALFS as part of the suite of sensors in recent upgrades and acquisitions (Iceland, Finland, Sweden). On this basis, the project team had no option but to drop the ALFS from further consideration in the JIP in 2008.

Should operational systems become more readily available in the future, the LFS should be considered a potentially useful sensor for detecting oil on the surface of solid ice and slush or on the water between floes under Visual Meteorological Conditions (VMC).

For additional discussion of the state of knowledge regarding individual sensors the reader is referred to the initial remote sensing technology screening report prepared by Dickins and Andersen (2008).

3.4.2 2008 Program

The 2008 remote-sensing targets consisted of 2 small spills with sizes of 0.1 (pilot) and 0.7 m^3 (main spill) in very open drift ice (up to 4/10). From the outset it was recognized that even the largest of these slicks represented a marginal target for the aircraft and a very low probability target for the satellite. Recognizing these limitations, the 2008 spills were still viewed as a valuable opportunity to test the procedures and coordination required to carry out the more extensive and complex experiments planned for 2009.

In addition to the restricted spill volume, the largest 2008 spill was only planned to exist as an uncontained slick for tens of minutes, after which herders would be applied to significantly shrink its size and diminish its value as a remote sensing target. In almost every respect, planning and coordinating aircraft and satellite overpasses to correspond to this short-lived event represented an extreme challenge.

The intention was to employ the Norwegian aircraft LN-SFT on both of the 2008 spills, with the small spill acting as practice for the main spill of most interest that was anticipated to reach an equilibrium spreading slick diameter of 35 m and an overall sheen diameter of approx 80 m (5000 square meters) before application of the herder (Figure 13).

Figure 13. Large uncontained spill intended as the airborne remote sensing target in 2008. Photo: D. Dickins (from helicopter)

Planning for the 2008 experiment included invitations to Germany and Sweden in addition to Norway, to send aircraft, recognizing that the larger spills of greater potential interest would not occur until 2009. Sweden was in the process of taking delivery of an entirely new aircraft and systems (Figure 12) and so were unable to consider 2008 – however they expressed a strong interest in being involved in 2009. Germany declined on the basis that spill in ice, while interesting, were not of high enough priority in their operating areas to justify sending an aircraft. This left Norway as the sole provider of an aircraft to attend the 2008 spill. Overflights were scheduled on two separate days coinciding with the timing of the two uncontained herder tests and it was anticipated that the aircraft would have at least 45 minutes to an hour on station depending on winds and conditions at alternate airports. Extremely fine coordination of on-ice and airborne activities was required in order to document the maximum spill area during the tens of minutes available before herders were applied to shrink the spill.

Unfortunately, only four hours before scheduled departure of the aircraft from Longyearbyen to intercept the *Lance*, LN-SFT was called away on an emergency to Bergen to assist with an accidental spill at one of the offshore platforms. The outcome of the 2008 tests were particularly disappointing as the weather was perfect and the team managed to coordinate the spill exactly to coincide with both the aircraft and satellite. This experience demonstrates the uncertainty of working with operational aircraft on an experiment where the aircraft can be called away on short notice if a real emergency develops – this was always the understanding and a condition of participation by the Norwegian Coastal Administration.

3.4.3 2009 Program

The spill volumes planned for 2009 were up to 10 times the largest spill in 2008, but the proposed ice conditions in the 5-7/10 range were expected provide enough confinement in the worst case to produce a slick area that was actually smaller than in 2008. In fact, the concentrations ended up being closer to 9/10 in the test area on the day of the overflight – resulting in spill dimensions that were only a fraction of the uncontained slick in 2008 shown above in Fig. 13.

In the initial planning leading up to FEX09 the project team concentrated on confirming the commitment promised from Sweden in earlier discussions and to make every effort to bring other countries into the program. With this aim, the team proceeded to brief and contact aerial surveillance departments and flight divisions in Estonia, The Netherlands, Germany – following up on previous discussions, and Finland. Although interested in the project, for a variety of reasons none of these nations were able to commit valuable aircraft resources away from their primary mission areas of the North Sea and Baltic. The dedicated Norwegian surveillance aircraft LN-SFT was lost in a tragic accident in June 2008. Its temporary replacement LN-HTS has limited capabilities consisting of an MSS6000 SLAR and hand-held photo/video.

By November 2008 after exhausting all the possibilities, it became clear that Norway and Sweden were only two likely sources for aircraft to deploy to Svalbard in 2009.

On May 11/09 the Russian vessel *Petrozavodsk* ran aground at Bear Island between the Norwegian mainland and Spitsbergen, in an extremely sensitive environmental area (bird nesting area). On May 12, the Norwegian Coastal Administration and Swedish Coastguard therefore decided jointly to send the Swedish aircraft to Longyearbyen due to the incident and a 24 h delay of the Norwegian aircraft due to maintenance issues (Figure 14). This decision was made independently from the JIP program – the remote sensing team recommended delaying the deployment from Sweden, given the later than planned large spill release. As a result, the Swedish crew ran out of duty time on May 15, the day of the spill, and was only able to make one flight to the site during the transit back to Sweden.

Figure 14. Swedish Coast Guard crew with their Dash 8 Q300 at Longyearbyen

It was understood by the project team that any subsequent surveillance flights for the JIP must also accommodate Bear Island surveillance needs. On May 14, the Norwegian aircraft flew to Tromsø and then on to Longyearbyen on May 15 - Fig. 15.

Figure 15. Norwegian flight crew with LN-HTD at Longyearbyen.

The "large" 7 m^3 P1.2 spill took place between 0800 and 0900 (Local) on May 15 and the Swedish aircraft made several passes over the test site above the mist and cloud layer during a 40-minute period from 1250 to 1330 – approximately 4 hours after the oil release. Following this, the aircraft returned direct from the FEX09 field location to Sweden.

During the time when the aircraft was on site, the oil was contained in approximately 9/10 ice cover and prevented from spreading more than a few tens of meters by the very close pack ice and slush filled leads. The resulting spill target area on May 15 was far too small to be detected by any airborne or satellite remote sensing system. The original planning scenario envisioned a spill in open areas surrounded by 4-7/10-ice cover where the oil would have a chance to spread over hundreds of meters over at least 24 hours before the aircraft was called in.

Fig. 16 shows the spill taking place at 0854 with the oil being pumped through a hose on the ice from the *Lance* – four hours before the Swedish aircraft arrived over the site.

Figure 16. P1#2 Oil release May 15 at 0854. Photo: Jan Nilsen.

The persistent low cloud ceiling remained in the 150 – 200 m range throughout the first day of the spill. The sophisticated Electro-optical Infrared Camera System (Wescam MX-15) that could resolve fine details and target small spills in closely packed ice requires visual meteorological conditions (VMC) with cloud ceilings above 300 m minimum. Results from low-resolution hand-held imagery acquired by the Lance spill team (Daling 2008) indicate that the much more sensitive Wescam system likely has the capability to detect and map oil in the ice conditions present on May 15, but only as long as the aircraft can first make visual contact with the spill. The Wescam system tracks small targets with high zoom magnification. Resolution will depend on flight altitude but better than 1 metre is considered achievable with safe low-level surveillance beneath a cloud ceiling.

In the 2009 field experiment, the Swedish aircraft was forced to operate in a truly remote sense above the cloud layer. Not surprisingly, in the absence of any defined slick on the water surface, no oil was detected. The aircraft obtained a number of high-level SLAR and Elta SAR images of the site clearly showing the vessels and tracks in the ice. Examples of this imagery, normally used as a wide swath screening tool for slicks at sea, are shown in Figures 17 and 18. Ground resolution on the SLAR is in the order of 30x60 m.

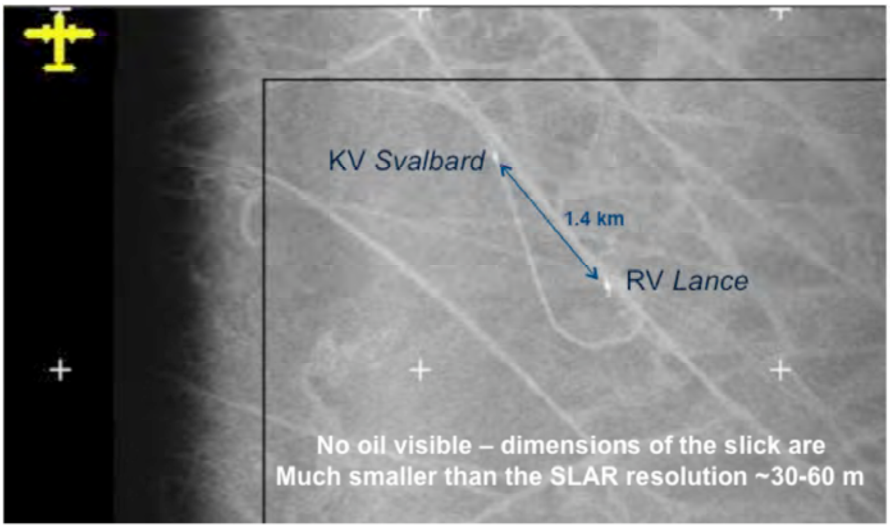

Figure 17. Enlarged right-hand segment from airborne SLAR imagery showing the two vessels and tracks left in the ice (within inset box). Aircraft is tracking NNW. KV *Svalbard* is slightly (~1.4 km) to the NW of *Lance*. Ice concentrations are 8 to 9+/10. Openings within the ice cover are smaller than the SLAR resolution. Source: Swedish Coast Guard

The Norwegian aircraft was scheduled to make one overpass early Saturday morning May 16, but the cloud ceiling at noon (latest time for aircraft holding due to Bear Island surveillance tasking) was still well below minimum 300 m necessary to make contact with the spill under Visual Meteorological Conditions (VMC). Given the limited capabilities of this aircraft, basic SLAR providing no chance of detecting oil in the prevailing very close pack conditions and no possibility of visual photo documentation, and with no improvement anticipated in weather conditions, the decision was made to fly the Norwegian aircraft back to the mainland via Bear Island where weather conditions over the grounded vessel were unusually excellent.

Figure 18. Elta Spot SAR low-resolution still capture from video showing KV Svalbard as bright target upper left. The dark patches on the starboard side of the ship (visible in the radar image) may represent openings in the pack that were generated to create sufficient clear area for skimmer testing the previous evening - May 14.

3.5 Satellites

The number of commercial radar satellites available worldwide is expanding at a rapid rate and the resolution continues to shrink exponentially. Up until 2006, the most developed commercial SAR platforms were the Canadian Radarsat 1 and European ERS 1&2 and Envisat, with most commonly used resolutions in the order of 25 m (the 8 m fine beam mode of Radarsat 1 is rarely used). In the period June to December 2007, a series of new very high-resolution SAR satellites were launched by Germany, Italy and Canada with the capability of resolving surface details down to a few metres. With the large number of platforms in polar orbit now it is possible to obtain multiple passes on any single day from different satellites. Swath width (coverage area) depends on resolution and typically ranges from 35 to hundreds of kilometres. In the past, reprogramming to position the satellite coverage in an emergency could take 3-4 days but the delay time is now less than 48 hours.

SAR imagery has been used in the past to document large, thick open ocean slicks. Historical examples include the *Sea Empress* spill in Milford Haven UK and the *Nakhodka* tanker spill off Japan (Brown and Fingas, 2003). Extensive use was made of SAR imagery during the *Prestige* tanker spill off Spain in 2002 (Palenzuel, et al., 2006; Peigné, 2007). See example in Fig. 19. While the contribution to real-time monitoring was limited in that case by late delivery of many images, the authors pointed to the likelihood of much improved utilization of SAR imagery in future incidents with new platforms and tools leading to near-real-time acquisition. Integrated aerial and satellite surveillance is now an important part of the overall marine pollution monitoring system for EU nations organised by the European Maritime Safety Agency (EMSA).

Figure 19. Example of previous radar satellite imagery clearly showing large slicks at sea. Envisat ASAR image (satellite) shows tanker *Prestige* 100 km off Spanish coast 20.11.2002 Credits: ESA

Satellite-based SAR can offer wide area surveillance coverage day and night, independent of cloud cover and weather conditions. A combination of aerial and satellite surveillance has proven to be the most effective system for large area monitoring, and satellite surveillance is now an important part of the marine surveillance system for national agencies and oil companies in northern Europe.

While the capabilities of radar imagery for sea ice mapping are well proven - all national ice centres today rely on this imagery as the primary data source - it is not known whether the same imagery can be used to discriminate between oiled and clean ice, or to detect oil on relatively calm water between ice floes. The key issue is whether the interruption to capillary waves on the ocean surface in the presence of oil will still occur to a sufficient degree with oil among ice to be observable in the radar reflection. The same concern also applies to SAR/SLAR airborne sensors discussed above in 2.1.5.

3.5.1 Basic Principles

The image brightness in a SAR image is dependent upon surface geometry. For this reason SAR data is extremely useful for observing the surface features of the ocean. The C-band radar backscatter (as in RADARSAT and Envisat SAR sensors) is caused by Bragg scattering by interaction of the incident radar waves with short gravity waves with wavelengths in the range of 5-7 cm. Under low wind conditions, the energy content in this part of the wave spectrum is low or almost zero, resulting in low radar backscatter and in dark patches in the SAR imagery. Surface films of high-viscosity material such as oil present on the sea surface will damp the capillary waves, and give rise to dark signatures.

Therefore the image is dark where the slicks occur not because of the colour of oil, but because the oil damps down small surface waves and the smoother surface reflects more of the transmitted signal away from the satellite.

Detecting oil in areas with ice cover becomes complicated beginning when new ice forms in the fall as a soupy layer of frazil crystals known as grease ice. This first ice also significantly dampens the waves thereby appearing the same as oil in SAR images, and especially single-band SAR images. Multiple polarization images or images from separate satellites over a short time interval may allow discrimination of oil from ice – this technique was applied in 2009 to the ordering of Radarsat 2 imagery listed in Table 2.

The critical factor in all cases where ice and oil are present in close proximity is going to be whether sufficient wave action exists to generate a distinct difference in wave damping between oiled and non-oiled areas. Without more testing and actual field data, it is impossible to set a clear bound on the upper limit of ice concentration where SAR imagery would cease to be of any direct value in detecting a large oil slick. The best estimate at present is judged to be around 3/10 concentration, still permitting the development of a distinct wave climate among the scattered floes.

The 2008 satellite acquisition program was designed around a single transitory event – 0.7 m^3 spill associated with the herder/burning experiment and shown above in Figure 13. As explained in the discussion of the airborne activities, the timing of the having the aircraft and satellite overhead within the 10 minutes when the uncontained slick was allowed to spread prior to herder application was extremely tight. In practice, the field crew expended a considerable effort and coordinated the simultaneous oil release with the satellite pass exactly. Unfortunately, for reasons that are still not fully understood the processing facility in failed to acquire the Radarsat image and the only chance to match imagery with an actual oil slick in 2008 was lost.

Figures 20 and 21 demonstrate the extremely high quality of the imagery that was obtained in 2008 – without oil. The level of resolvable surface ice detail and quality of satellite imagery varies greatly with surface conditions and the ice morphology as shown in subsequent imagery from 2009. See Figs. 22-26 following.

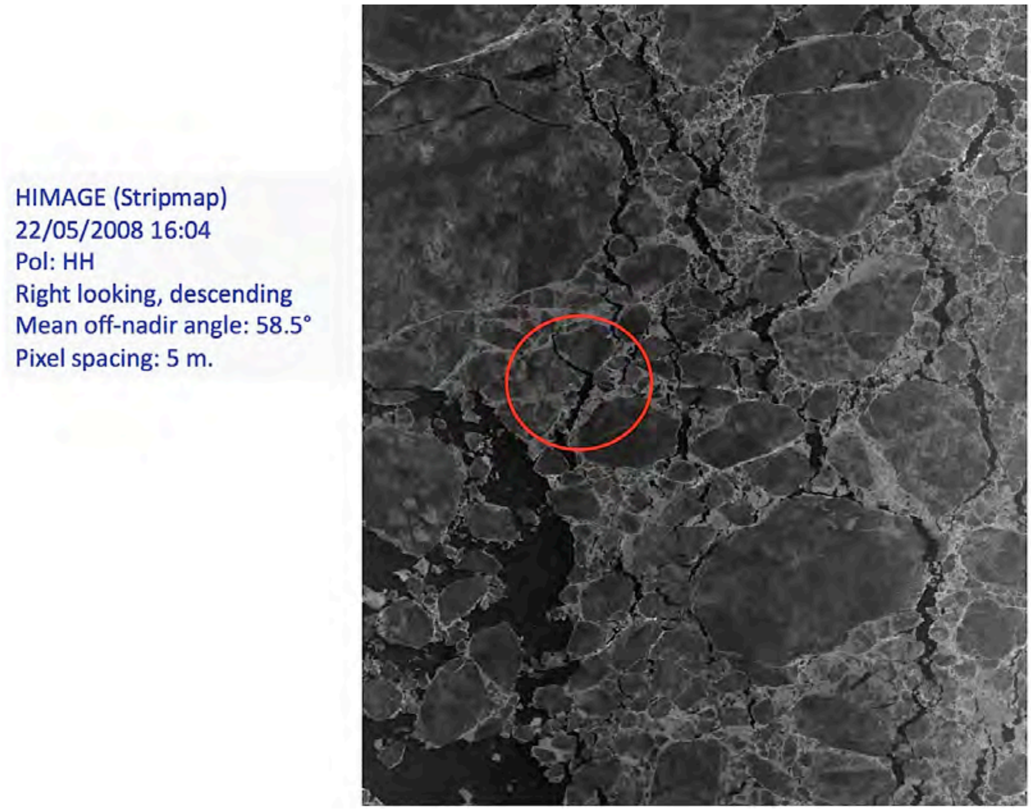

Figure 20: Cosmo-SkyMed image acquired in the vicinity of FEX08 May 22/2008. See Fig. 21 for a zoon subset from the red circle. © CopyRight 2008 Agenzia Spaziale Italiana

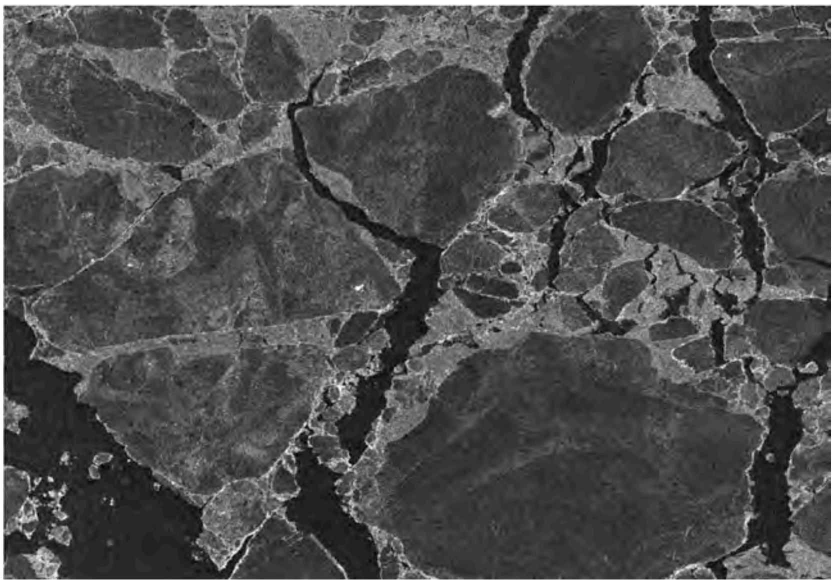

Figure 21: Zoom enlargement from the image shown in Fig. 20. Note the high level of detail showing rougher brash ice and smaller floes as a bright return, smoother ice areas as dark grey and open water or new ice in leads as close to black.

3.5.2 FEX09 Image acquisition

Three SAR satellite systems were employed to monitor the 2009 oil in ice experiment. All have the capability to operate at different modes, ranging from narrow swaths with high spatial resolution, to wide swath with reduced spatial resolution. The wide swath modes, also named ScanSAR, are the modes best suited for ocean and ice applications as they cover the greatest area, which is currently the strongest weighting factor when choosing a mode.

Due to the relatively small amount of oil planned to be released in FEX09 and expected small areas of contamination from the uncontained spills in high ice concentrations, the 2009 satellite acquisition program focused on obtaining the highest possible pixel resolution while ensuring a large enough image footprint to account for any uncertainty in the planned location of the experiment. In addition, it was decided to obtain dual-polarization image modes from Radarsat-2 to determine whether or not this could improve the distinction between oil and open water in calm conditions. In total, 26 images from three satellite systems were acquired. The images and technical specifications are detailed in Tables 1 to 3.

The composition of the ice regimes between 2008 and 2009 were very different. The 2008 experimental area was characterized by many well-defined medium floes (100-500 m) and leads about 75 km in from the ice edge in a mix of open to close drift ice (predominantly 6-7/10). In 2009, the main experimental area consisted of much smaller floes (in the order of 5-30 m) less than 35km in from the edge in higher ice concentrations ranging from 7-9/10. The marginal ice zone is a dynamic, relatively high-energy region where the floes are continually broken down in size by wave swells penetrating into the pack. The constant contact between the floes generates raised, rough edges around the floe perimeters that act as very effective radar reflectors.

The marked differences in ice surface morphology and floe size distributions between the two years are reflected in the quality of the imagery. There is a sharp contrast between the well delineated floes and fine surface detail shown in the 2008 image example (Fig. 14) and the overall lack of detail or floe definition across the 2009 images shown in Figs. 15 and 17. The 2009 airborne SLAR image (Fig. 13) and the airborne SAR both displayed a blended, diffuse ice texture similar to the satellite imagery. This indicates that the high noise levels and speckle found throughout the 2009 images were most likely tied to the specific ice conditions and not related to the technical specifications of the individual sensors or choice of satellite modes.

Figures 22 to 26 show examples of images obtained from different satellite platforms in 2009 at different stages of the experiment, with visual surface and low altitude photography of ice and oil conditions taken close to the same time. Non of the uncontained spills during the offshore field experiment were detected in the SAR imagery. This result is attributed to the very effective containment of the oil within the close pack ice, preventing any slicks from developing in the traditional sense that could be differentiated from surrounding unoiled open water areas. At this stage the upper threshold of ice concentration that could still permit detection of spills by satellite, is not known. Based on a basic understanding of how the presence of ice damps wind wave and swell activity, it is a reasonable assumption to consider satellite surveillance as probable in ice coverage up to 3/10, possible in ice coverage of 4-5/10 and unlikely to impossible in ice coverage of 6/10 or more.

Table 1: Satellite data available

ENVISAT ASAR Wide Swath	Radarsat 1	Radarsat 2	Cosmo-Sky-Med
14 May 2009	11 May 2009	12 May 2009	15 May 2009
15 May 2009	14 May 2009	16 May 2009	19 May 2009
16 May 2009	14 May 2009	17 May 2009	20 May 2009
18 may 2009	15 May 2009	19 May 2009	
19 May 2009	15 May 2009	20 May 2009	
20 May 2009	15 May 2009	21 May 2009	
21 May 2009		22 May 2009 (ScanSAR Wide)	
22 May 2009			
23 May 2009			
24 May 2009			

Table 2: Technical specification of the satellites used

Satellite	Swath	Polarization	Resolution	Pixel size	Number of looks / Noise
ENVISAT ASAR Wide Swath	400 km	HH	150 m	75 m	12 / ±1.1 dB
Radarsat 1	100 km	HH	25 m	12,5 m	4 / ±1.8 dB
Radarsat 2	50 km	VV ,VH	10 m	6,25	1 / ±3dB
Radarsat 2	500	HH	100 m	50	8 / ±1.3dB
CosmoSkyMed	40 Km	VV	~ 5m	2,5	

Table 3: Chronological order of the images used

Date	Time	Oil Spill status	Satellite
14 May 2009	15:18:59	Before oil spill	Radarsat-1
15 May 2009	16:12:45	Large spill – day 1	Cosmo-Sky-Med
15 May 2009	18:33:45		ENVISAT
16 May 2009	05:16:04		Radarsat-2
16 May 2009	09:45:31		ENVISAT
18 May 2009	18:39:27		ENVISAT
19 May 2009	09:51:13	Second dispersant spill	ENVISAT
19 May 2009	15:26:24		Radarsat-2
20 May 2009	14:57:07	Oil in fire resistant booms	Radarsat-2
21 May 2009	04.30:13	Oil in fire resistant booms	Radarsat-2
22 May 2009	05:40:49	After oil recovery	Radarsat-2 (ScanSAR Wide)

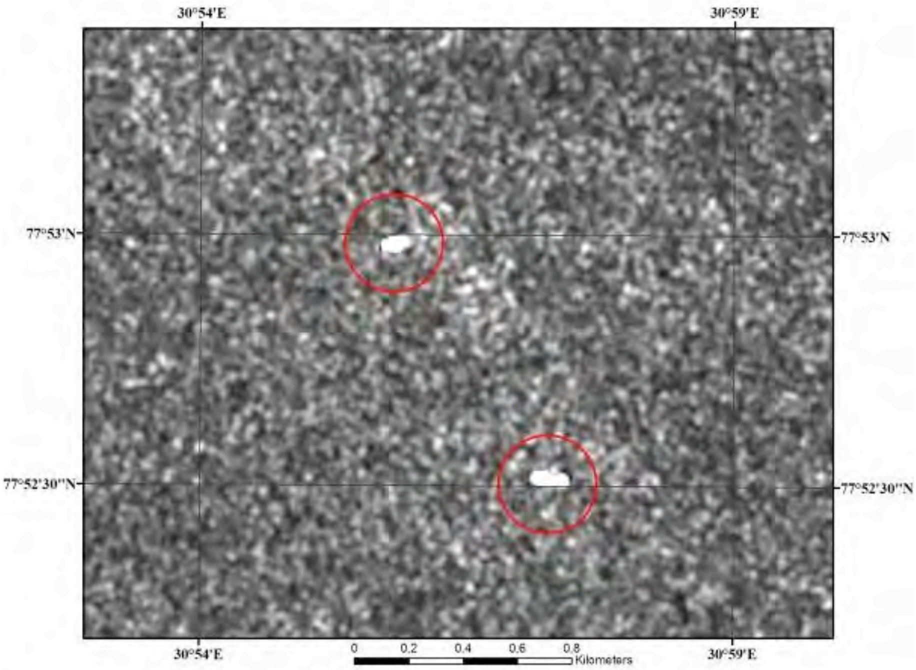

Figure 22. Radarsat-1 image, date 20090514, time 15:18:59. The image shows *Lance* to the north and *Svalbard* to the south. The ice edge is about 14 kilometres further south outside the image frame. The ice sis very close pack (80-90% concentration) with some leads filled with small ice floes. Small darks areas alongside the ships may be open water. In the original imagery, dark areas can be seen alongside the vessels, attributed to openings generated from the bow thruster and azimuthal drives on the vessels. A bright radar return is also visible on the original imagery close alongside KV *Svalbard* - this is attributed to the ice filled boom being prepared for skimmer testing. See photos below taken 20 minutes after the satellite image shows the overall pack composition off the starboard side of *Svalbard* with *Lance* in the distance.

Photos: D. Dickins

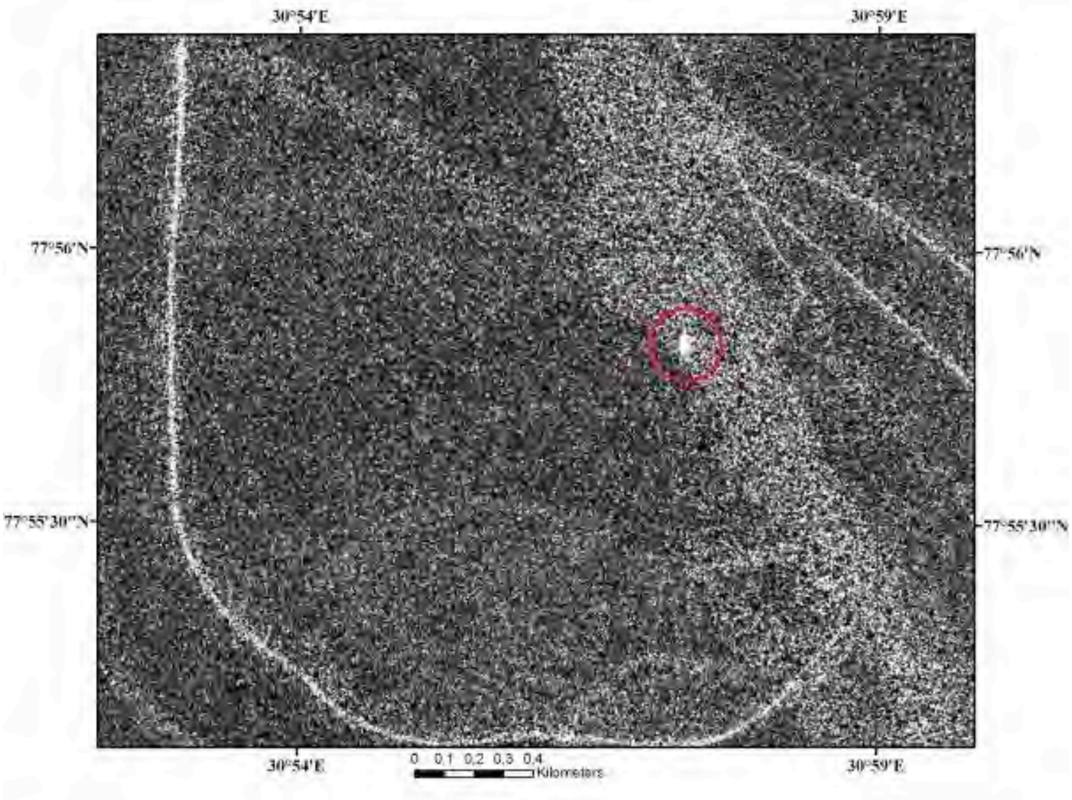

Figure 23: Cosmo-Sky-Med image, date 20090515; time 16:12:45. The image shows *Lance* within the red circle, the ice situation is similar to the day before. The tracks of the ships are clearly visible in the ice. *Svalbard* is to the west of this sub image. The image is acquired 8 hours after releasing the oil from Lance out on the ice – See Figure 16 above in Section 3.4.3.   No oil is visible (the small dark patches are ambiguous signatures). No oil is visible as the spill is confined to small patches tens of meters or less trapped between floes and in narrow leads.

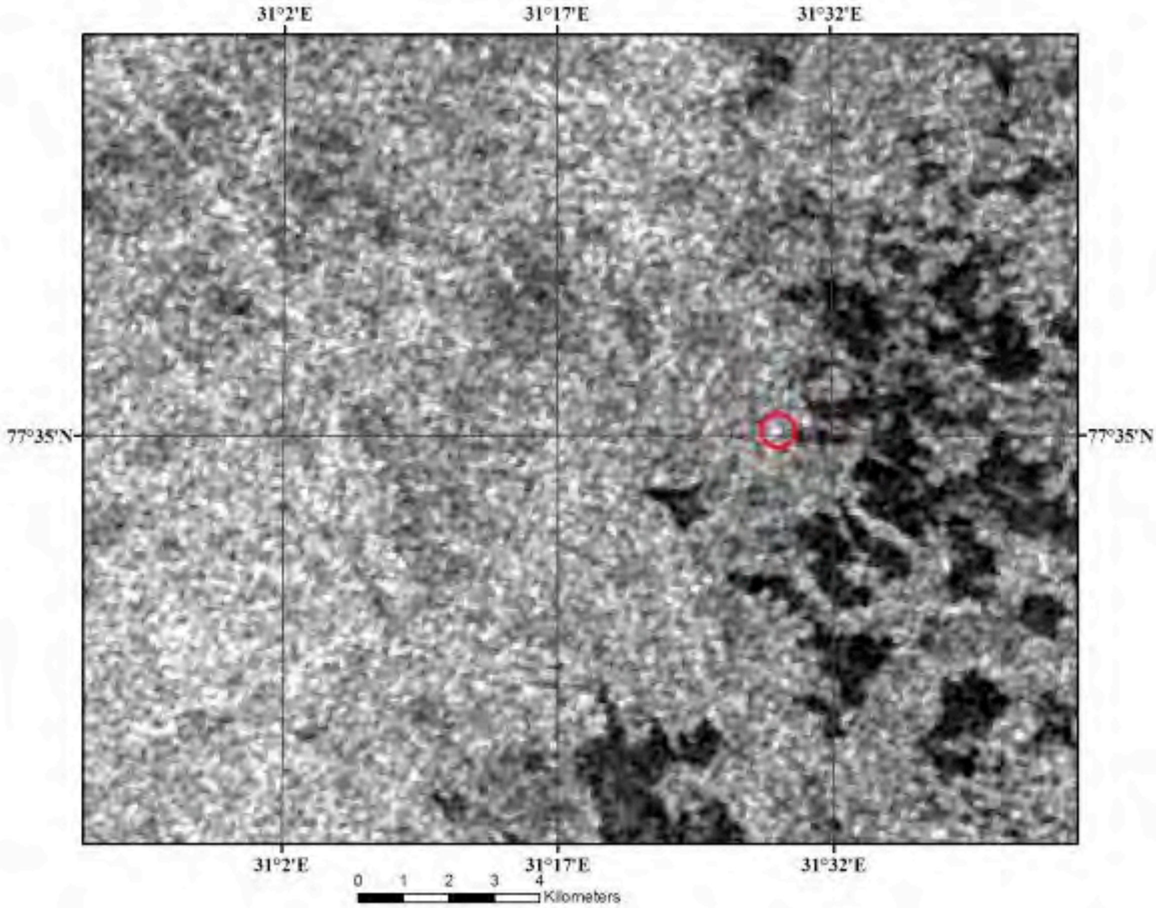

Figure 24. ASAR Wide Swath image, date 20090518, time 18:39:27. *Lance* is the small white spot inside the red circle. The ice coverage is much less than the previous days with large areas of open water to the east of the ship, indicating that it is closer to the ice edge. The ships tracks have disappeared in this image.

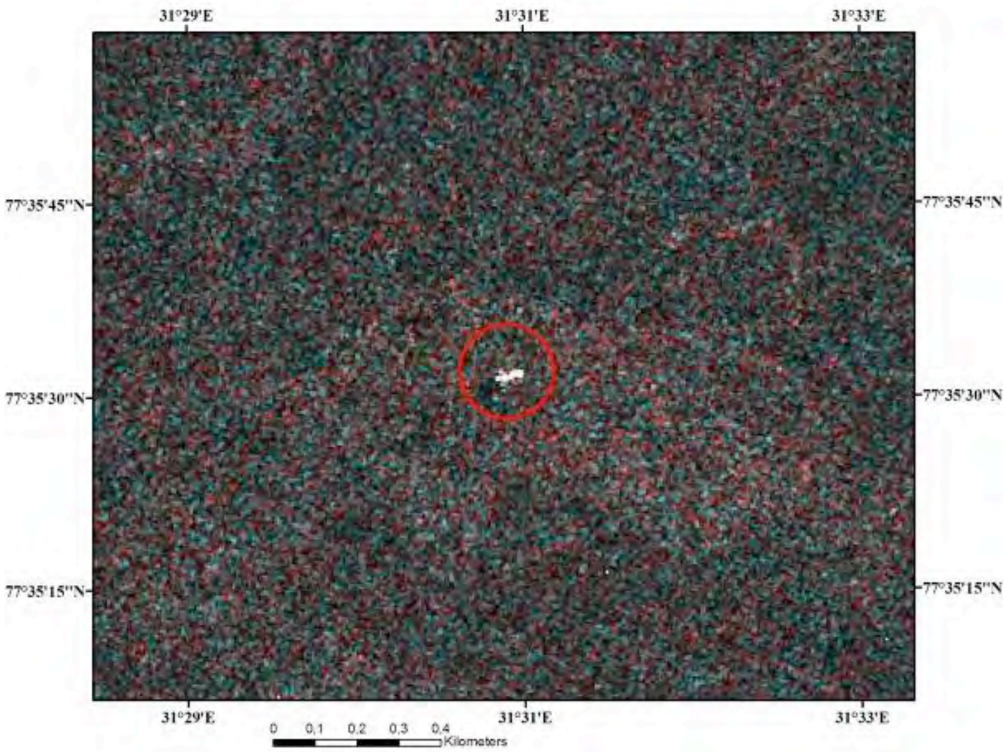

Figure 25. Radarsat-2 image, date 20090519, time 15:26:24. The image is a dual polarization, presented in RGB colour; Lance is clearly visible within the red circle. There is a dark area to the southwest of Lance; this can be either open water or possibly the oil spill. The photo of the spill with personnel on the ice is taken 3 hours before the satellite image, from the *Lance* "crown's nest" showing the oil as isolated brown patches between the floes. The linear return extending out from the side of the vessel is possibly the articulated metal arm used to apply dispersants to one of the 2 m^3 spills carried out on May 19 – see photo of this arm taken during the pilot dispersant test on May 17.

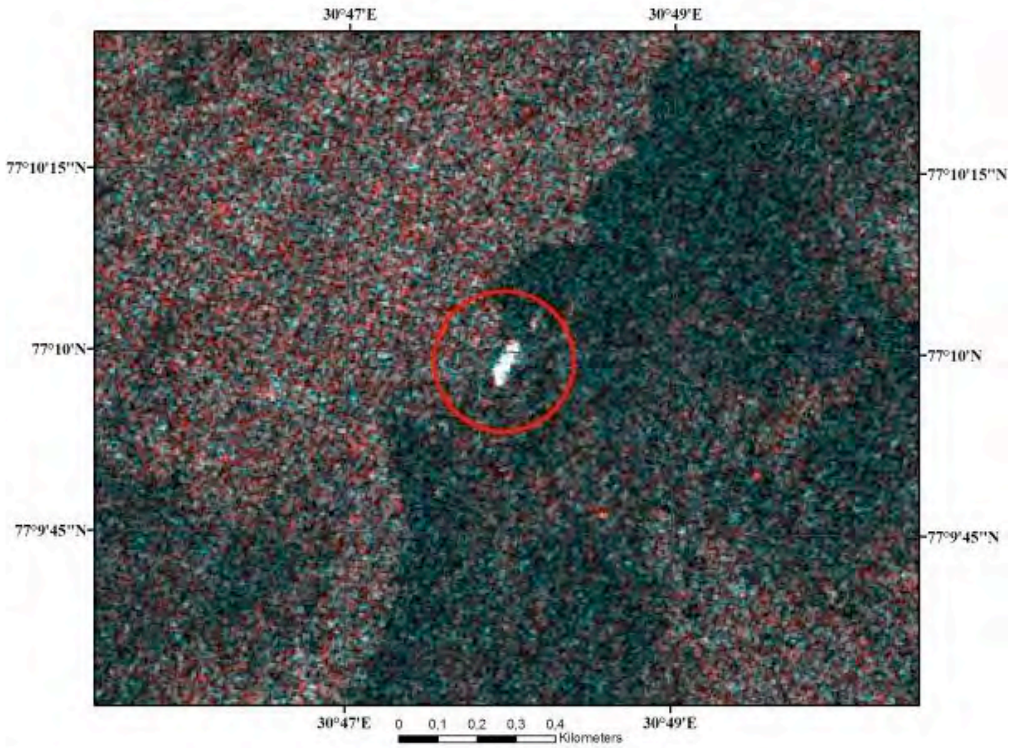

Figure 26. Radarsat-2 image, date 20090520, time 14:57:07. This is a dual polarization RGB coloured image. The ice is now very open (20%). The image shows *Svalbard* towing the fire resistant boom – visible as a separate bright return behind the vessel – see photo below taken 1.5 hours after the satellite image. The Rutter Sigma S6 marine radar image of ice in the same general area is shown below in Fig. 30.

3.6 Ship-borne sensors of opportunity

Although not part of the main project activities, it was always the intention of P5 to utilize sensors already mounted on support vessels attending the spills to assess the capabilities of proven open water remote sensing techniques in documenting and mapping slicks in the presence of ice. The primary Norwegian systems of interest are based on X-band marine radars developed for open water applications over the past seven years as a supplement to airborne and satellite remote sensing. Today, 14 of these systems (www.miros.no) are in operational use by The Norwegian Clean Seas Association for Operating Companies (NOFO).

In FEX09 it was possible to conduct a very limited assessment of two surface or shipboard systems:

1. Rutter Sigma S6 marine radar onboard KV *Svalbard* , and
2. Hand-held infrared camera (low resolution) onboard RV *Lance*

Findings are discussed briefly below.

3.6.1 Hand-held IR

Low-cost, non-cooled, hand-held IR systems can detect oil under certain conditions. They are in operational use on supply vessels, providing for example an overview of skimmer position relative to oil within booms as viewed from ship's bridge.

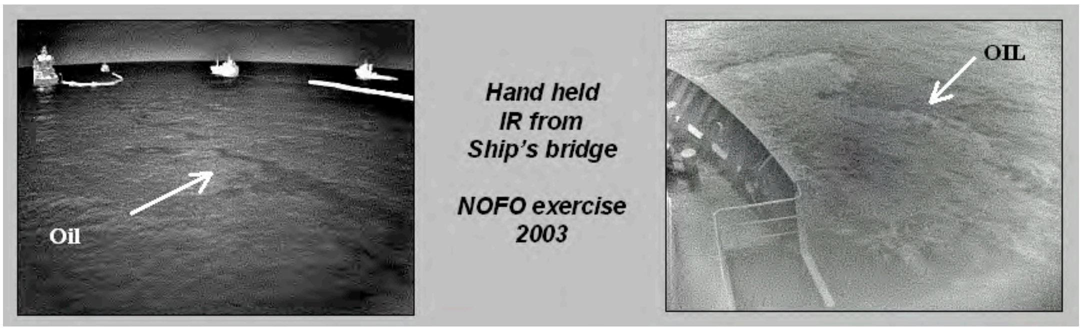

Figure 27. Example IR images during a NOFO open water exercise in 2003.

Relatively low sensitivity hand-held IR imagery was collected from onboard *Lance*, from the ice surface and the helicopter throughout the spill. Daling (2009) concluded in a preliminary memo following the field trial that the IR camera has a potential for detecting oil spills under the prevailing very close pack conditions, both as thin layers on the water between the floes and thicker oil mixed with snow on the surface of floes. The distinction between oiled and non-oiled surfaces tended to disappear at night in the absence of sufficient solar energy to heat the oil layers. The full suite of chronological images from the hand-held camera is contained in a SINTEF field memo (2009–05-28). An example is shown in Figure 28 below.

Hand-held un-cooled IR is in the order of 50 to 100 times less sensitive than cooled systems. NOFO trial results indicate that an oil film needs be more than 200 microns (0,2 mm) thick to be detected with the basic camera systems. For more sensitive cooled IR, the minimum film thickness is probably in the range of 50 microns.

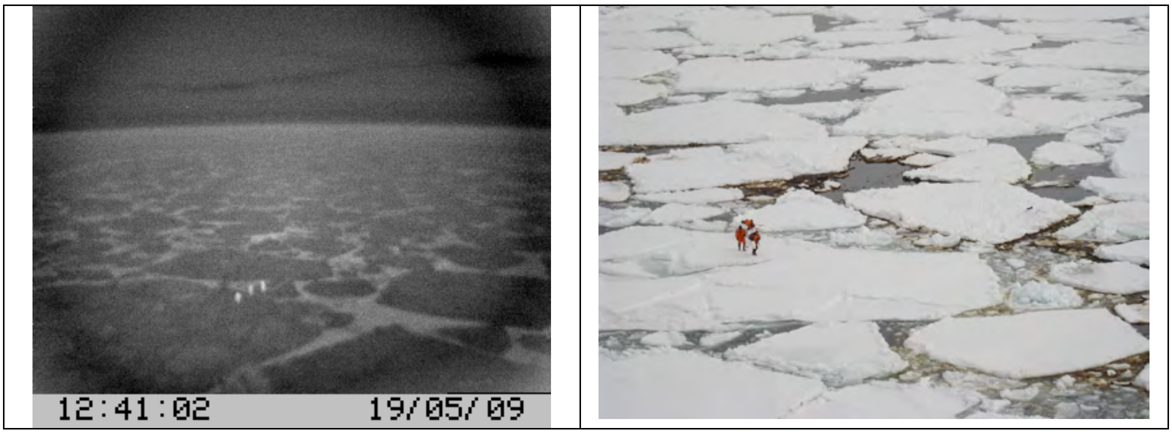

Figure 28. Large uncontained spill after four days at sea. Taken at daytime from the *Lance* crows nest. During daytime, the IR sensor (left) was able to distinguish between oil (white), ice-free water (light grey and snow and clean ice floes: dark grey. Photo: Per Daling

3.6.2 Marine Radar, X-band (short and medium pulse)

Since 2001 the petroleum industry in Norway has been a driving force in the development and utilization of ship-based sensors for short to medium range oil spill detection, supplementing airborne and satellite remote sensing. Today, 14 of these systems (www.miros.no) are in operational use by The Norwegian Clean Seas Association for Operating Companies (NOFO). See example results from an open water field trial in Fig. 29 below.

There are currently three oil spill detection (OSD) systems on the world market: Miros OSD (Norway), Rutter Sigma S6 (Canada) and SeaDarq (The Netherlands). The Norwegian systems are based on X-band marine radars and the collection of up to 128 scans. Processing constitutes averaging a high number of algorithms for oil detection optimalisation. An oil detection range of up to 3 km (antenna height 18 metres, medium pulse) has been proven. Both an assessment of sensor materials conducted by Aptomar and operational experience gained by NOFO show that a state-of the-art 3-5 mm cooled IR systems have equal oil detection capabilities to older 7-14 mm systems. This is due to the more sensitive 3-5 mm sensors compensating for weaker oil-water contrast (emisitivity difference) in this waveband.

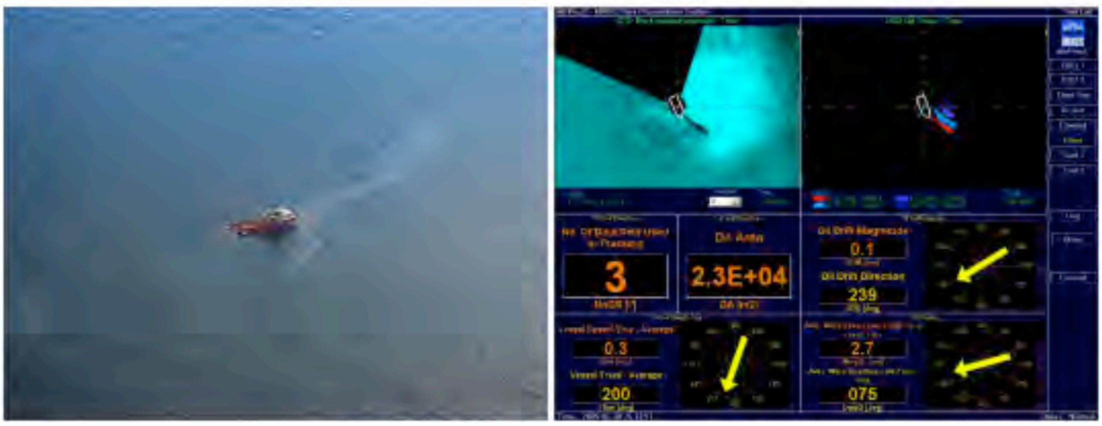

Figure 29. MIROS OSD, back-scatter oil oil tracking (Photo: MIROS & NOFO)

In FEX09, an attempt was made to “see” sheens escaping from the fire-resistant boom on May 21, 2009 with the Rutter Sigma S6 radar system onboard KV *Svalbard* – Figure 30. There was no opportunity to test the system on a well-defined thicker slick. Regardless of adjustments made to the system in terms of gain, clutter etc., there was no evidence of any oil on the display.

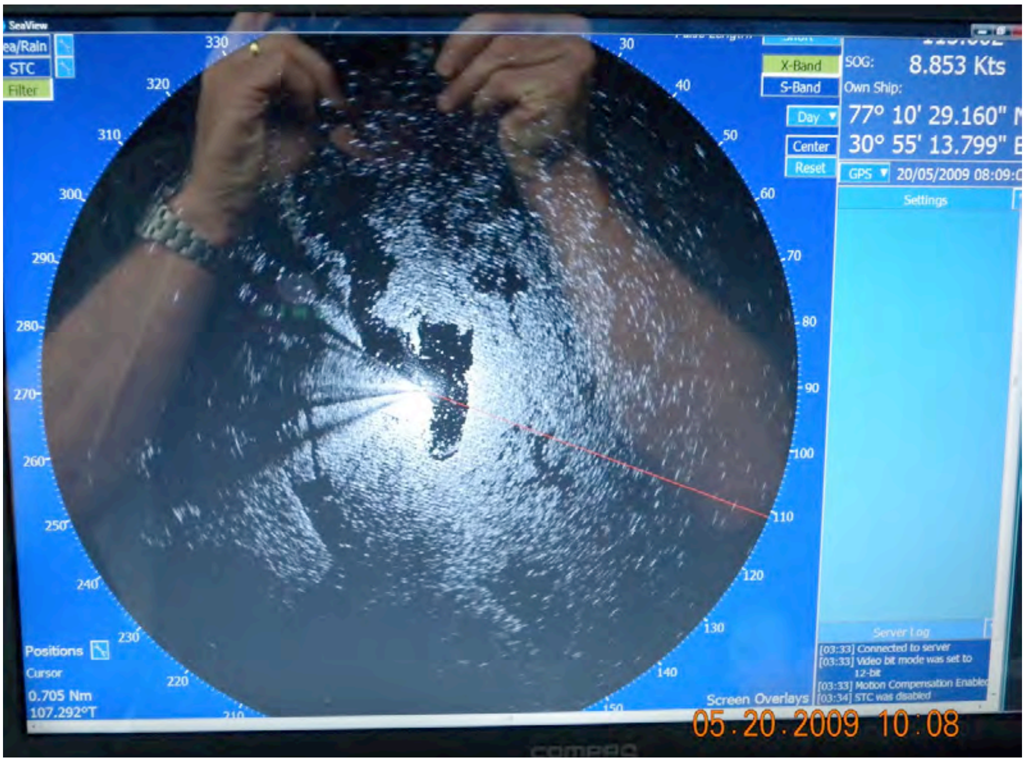

Figure 30. Example screen shot of Rutter Sigma S6 on KV Svalbard, May 20/09 clearly showing the ice around the vessel. No oil was detected.

3.6.3 Integrated FLIR and high resolution camera technologies

The SECurus System (http://www.aptomar.com/products/securus) incorporates a high-resolution day and low-light camera with 22x optical zoom (66x digital) in addition to night vision with a high quality Infrared (IR) Camera having three fields of view (FOV). This gives a crystal clear image in conditions of no light as well as in normal daylight. A Xenon searchlight gives a visual pointing tool for illumination of objects and areas.

The system is designed to show the extent of the medium and thickest parts of the oil, to track the movement and changes in formation of the oil spill and to provide an indication and track record on past and future oil spill movements. The oil spill viewed in the videos can be mapped over to the navigation chart, giving an indication where the operation should focus for the most effective recovery result. The navigator can use this information when maneuvering the vessel for optimal effect. All information of the oil spill, its movement and extent is logged and saved for further analysis or post decision-making.

4 Evolving technologies with potential for oil in ice detection

Project 5 focused on technologies that already exist in an operational or "proven" state of development. Several new technologies or new applications of existing technology were identified during the project that could play an important role in future oil in ice surveillance. Several of the more promising technologies are introduced here.

4.1 Nuclear Magnetic Resonance - NMR

Nedwed (2007) introduced the concept of NMR as a potential basis for an airborne oil in ice detection system. NMR works with magnetization of nuclei in a static magnetic field. The magnetization is caused by ordering of magnetic moments of nuclei in the field. These magnetic moments can be excited by one or a few radio frequency (RF) pulses. Electromagnetic energy is emitted and measured as the magnetic moments return to equilibrium. Features of the electromagnetic response are specific to the molecular environment of the nuclei. This allows separation of the NMR signals of oil and water due to different responses from these types of liquids. (Nedwed et al. 2008)

For applications in oil spill detection, a very important aspect of NMR is that the signals from ice and snow are not normally detected under the experimental conditions used to detect signals from oil or liquid water. Thus, the presence of snow or ice does not create the interference problems for the detection of oil under ice or snow that are inherent in other detection methods such as GPR.

A joint project to address the technical issues of applying NMR to the oil in ice problem was initiated by the research departments of ExxonMobil and by the Institute of Chemical Kinetics and Combustion of the Siberian Branch of the Russian Academy of Science. Initial findings are published in Shushakov et al. (2009 – in process). Research is now underway to determine if surface-based instruments currently used to characterize ground-water aquifers can be modified and placed on a helicopter (Fig. 31). The diameter of the transmitting/receiving antennae is roughly equivalent to the maximum measurement depth. For remote detection of oil spilled under sea ice, it is expected that a 5-m diameter antennae will allow measurements of a 1 cm oil layer below 2 m of ice with the antennae located 3 m above the ice. The antennae dimension could limit the ultimate altitude that is operationally feasible.

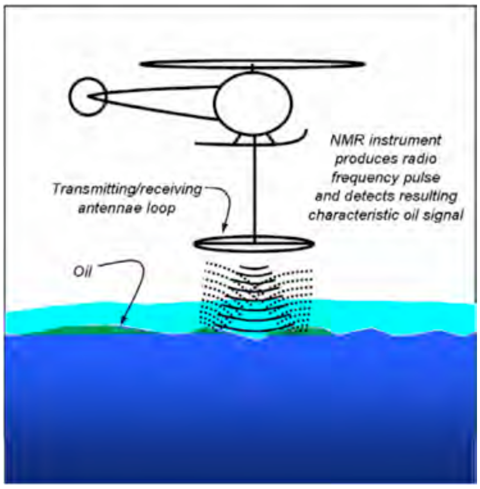

Figure 31. Drawing of the concept to use NMR in the Earth's magnetic field to remotely detect oil spilled under ice. Source: Nedwed et al. (2008)

4.2 Under-ice AUV

The technology needed to deploy wide-ranging autonomous underwater vehicles is maturing rapidly. The latest generation of large AUV represented by Autosub6000 is capable of an ultimate range under ice up to 1000 km. Wadhams et al. (2006) reports on the results of a field test in the NE Greenland Sea in 2004 where highly detailed 3-D sonar maps were obtained of the under surface of ice floes for the first time. Fig. 32

Figure 32. Autosub II AUV used by Wadhams in the NE Greenland Sea in August 2004.

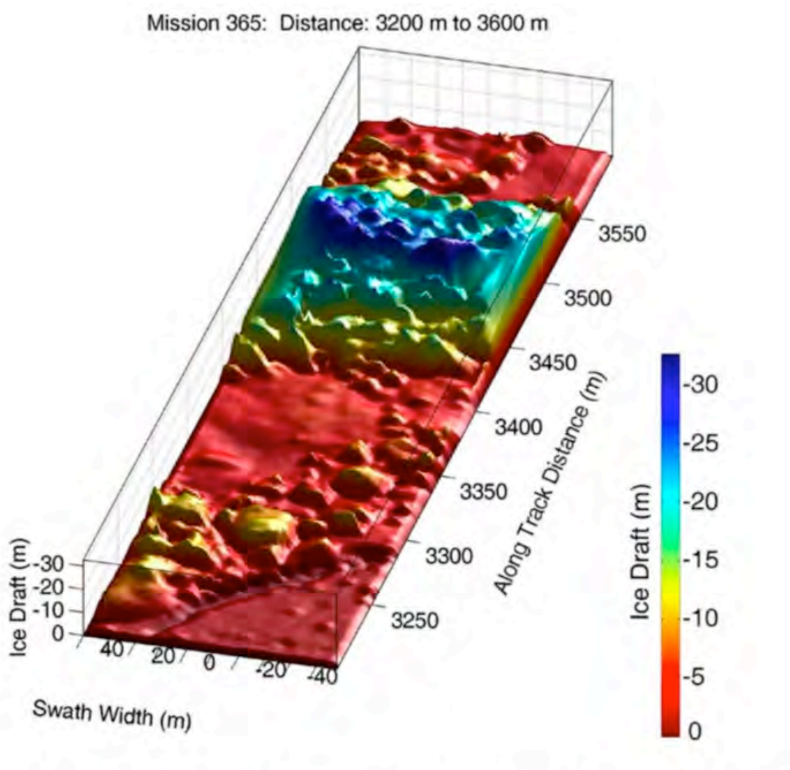

Figure 33. Deep 33 m ridge with shallower ridge in foreground surrounded by less deformed ice. Resolution of the mapping varies from 1-2 m. Total swath length of this mission was 23 km and up to 100 m wide. Source: Wadhams et al., 2006

Surface-mounted acoustic transducers are able to resolve oil layers trapped under ice. Researchers have commented on how much easier it would be to deploy this technology in an upward looking mode to detect oil under ice (Goodman 2008). There would be no need to conduct careful surface preparation by remove snow and wetting the surface or bonding the transducers to achieve acoustic coupling. Unpredictable influences of trapped air pockets and inclusions or irregularities in the internal ice structure would be eliminated and the number of interfaces involved in the return signal would be greatly simplified without having to penetrate the highly variable ice sheet to reach the oil. The AUV would serve as the carrier vehicle for the oil under ice mapping sonar.

The detailed 3-D representation of the ice underside could be fed into an oil spill model that predicts the likely pooling potential of different ice areas, effectively guiding other efforts to locate the areas with the greatest oil volumes for possible recovery. Wadhams' recent re-evaluation of under ice oil holding potential based on the new sonar mapping representations of under-ice geometry indicates that only about 5% of any given area of undisturbed first-year ice will be contaminated, making the probability of detecting and mapping an under ice spill through the old fashioned but still state of the art method of drilling holes very low.

Practical problems with this concept involve the speed at which oil would become incorporated in new ice growing beneath the spill. Depending on the location, time of year and type of ice, this process could take from 12 hours to months. For example, oil spilled under multi-year ice early in the winter may take most the growth season to become encapsulated. What this means is that while there are situations where the oil spill will be quickly hidden from "view" by new ice growth under first-year ice (Nov to March), there are also many scenarios in the Beaufort where deploying a system within 48-72 hours of a spill may give ample time to locate and map the distribution of oil under the ice in detail – for example late in the season in April or at any time with high concentrations of old ice in the vicinity of the spill.

4.3 Unmanned air vehicles (UAV's)

The field of UAV development is rapidly evolving with Predator drones and Global Hawks in the news on a daily basis. There are a number of smaller, more economical UAVs with potential to carry sensors that would be useful for offshore spill surveillance – e.g. tracking FLIR camera systems. Statoil recently commissioned an extensive study of current technology in this area to identify suitable platforms and assess capabilities in a marine oil development environment (SiMiCon 2008 – released to the JIP for internal use)

The current non-military use of UAV's in connection with vessels and Arctic applications is at a research level with for example:

- Alaska (Shell, ConocoPhillips), and
- Svalbard (NORUT)

Summary recommendations from the Statoil study are:

Fixed wing

- Fixed wing vehicles are in operation on ships and in the Arctic (landing is a problem)
- Fixed wing is the best choice for long range, land-based, arctic applications
- Use Fix wing UAV can be used for application testing (sensors and autonomy)

Helicopter

– Helicopters are the long term solution to short range, maritime, arctic applications.
– Need to contribute to helicopter testing and development of maritime landing system

For Maritime and arctic applications - need to

– Test and adapt existing systems to maritime and arctic environment s
– Improve efficiency through development of automatic detection (autonomy)
– Develop operational and maintenance procedures
– Gain experience through realistic field testing

Overall conclusions:

– UAVs can be used for oil slick monitoring and ice management
– VTOL UAVs will be important for future maritime applications
– UAV operations must be adapted to civilian users and arctic environment
– Regulations for UAV operations will be in place in few years
– UAV Testing is accepted in Norway

Regulations regarding UAV has just been introduced in Sweden, and Norway will follow late 2010. Although flying within Line Of Sight (LOS) is not heavily regulated, approvals to operate beyond LOS (BLOS) will be very strictly enforced with requirements similar to operation of a manned aircraft with approved pilot certification and courses etc. Due to the low density population, it is quite easy to get permission by the CAA in Norway to perform UAV flights BLOS, and during emergencies CAA has indicated that permission will be given with dedicated airspace allowing no other traffic.

4.4 Next-generation GPR for Oil Under Ice

Section 3.2 describes the capabilities and limitations of existing commercially available GPR systems in detecting oil in ice. A new JIP was initiated in December 2009 to build two new radar systems optimized in their design for the oil in ice problem (Dickins and Boise State 2010 – in process).

A long-term objective for the GPR development work over the past five years has always been the development of a reliable airborne system that can tolerate a wide range of ice properties (thickness, temperature, salinity). The previous experiences in Alaska and Svalbard showed that airborne detection through the full winter season will require the development of new hardware to achieve a reliability equal to existing ground-based surveys using off-the-shelf radar units. The new GPR’s to be designed and built in 2010 will incorporate a number of major technological improvements over currently available systems, including a more focused beam to greatly increase the signal to noise ratio. This improvement will allow more accurate detection of oil under a wider range of internal ice temperatures and potentially permit higher-altitude and higher-groundspeed measurements.

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