Remote Sensing for the Oil in Ice Joint Industry Program 2007-2009

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Abstract

This paper summarizes the different Oil in Ice Joint Industry Program (JIP) remote sensing activities carried out from 2007 to 2009, including: technology review and selection, airborne systems, Synthetic Aperture Radar (SAR) satellite imagery, trained dogs, and airborne Ground Penetrating Radar (GPR).

A key finding is that flexible combinations of sensors operating from a variety of platforms are required to cover a range of oil in ice scenarios.

Based on a combination of field data collected during the JIP and knowledge of sensor capabilities demonstrated in previous open water spills, the project concluded that the most useful remote sensing systems for spills in ice are expected to be: Forward Looking Infrared (FLIR) for oil on the surface in a broad range of ice concentrations, Side-Looking Airborne Radar (SLAR) and/or SAR for slicks on the water in very open ice covers, trained dogs on solid ice, and GPR for oil under snow or trapped in the ice.

Detecting isolated oil patches among closely packed floes (>6/10) is a major challenge with any current remote sensing system, especially during periods of darkness, low clouds or fog. The most effective solution to this problem is to deploy closely spaced GPS tracking buoys to follow the ice and the oil.

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

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 the remote sensing project (P5) within the Oil-in-Ice Joint Industry Programme (JIP) 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 particular ice regimes encountered in the 2008 and 2009 offshore field experiments.
- Draw conclusions and make recommendations as to sensors most likely to be effective in a variety of oil and ice situations.

The project focused on proven, commercially available systems and technologies. Research and development of new systems was outside the scope.

2 State of Knowledge and Initial Technology Review/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 in Canada 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, 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 undersurface with an Autonomous Underwater Vehicle (AUV). Statoil sponsored an initial evaluation of Unmanned Air Vehicles (UAVs) in the Arctic offshore surveillance role (2008 unpublished).

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

1. To provide a baseline summary of the current state of knowledge in remote sensing technology for Arctic pollution surveillance.
2. To short-list the most likely candidate sensors and systems for possible testing in 2008 and 2009 based on their expected capabilities in a variety of ice environments.

2.1 Selected Technologies for Field Evaluation

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

1. Airborne (utilizing operational pollution surveillance aircraft with integrated multispectral sensors including: UV/IR, FLIR, and SAR/SLAR)
2. All weather Satellite Systems – principally involving Synthetic Aperture Radar (SAR)
3. Dogs for surface oil detection
4. Ground Penetrating Radar (GPR) for low level airborne oil on ice detection

In addition, ship-borne sensors of opportunity such as such as Miros and Rutter oil spill setection systems utilizing raw data from navigation radars, and hand-held infrared cameras would be tested if the opportunity arose in the field experiments.

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.

A series of reports, internal and contractor-generated, covered all field and analytical remote sensing activities between 2007 and 2009.

The following sections contain highlights from selected activities activities, referenced to individual project reports.

3 GPR Testing for Oil on Ice Detection

3.1 Background

Since the earliest mainly inconclusive attempts to detect oil in ice in the 1970’s and early 80’s (e.g. Butt et al., 1981), 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).

Commercially available GPR previously tested over an experimental under ice spill at Svea 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 during that test (Dickins et al. 2006). See Figure 1.

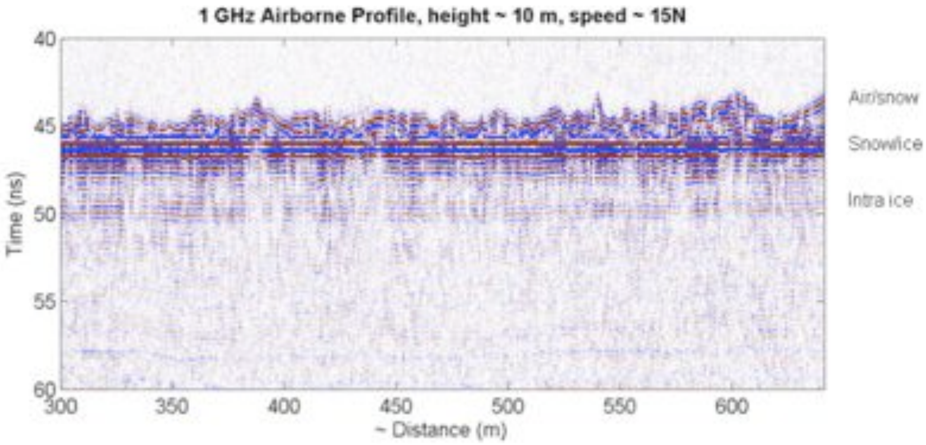


Figure 1. Airborne GPR profile of the snow surface on ice acquired March 2006. (Dickins et al., 2006/08; Bradford et al., 2010).

Numerical modelling subsequently confirmed that GPR is sensitive to the presence of oil in the snow pack over a broad range of snow densities and oil types. In order to test the GPR 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. 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. 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 and enhancing the prospects for detection with GPR. Sea ice on the other hand has much higher electrical conductivity (> 10^{-2} S/m) that 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 Methodology

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 wind pack 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 2). The oil flowed smoothly and formed a relatively uniform layer. Following the GPR surveys, 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.

Figure 2. Photograph of Sintef personnel pouring oil into the spill containment area for the oil-under -snow field experiment.

Air temperatures during the experiment reached a high of ~ -13°C. 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 3). Since the oil was highly viscous, there was very little mixing of the snow cover and oil, resulting in a distinct boundary at the snow/oil interface.

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 4) and flown across the test cells (Figure 3) at altitudes of 5, 10, 15, and 20 m and speeds of 2.6, 5.1, 7.7, and 10.3 m/s.

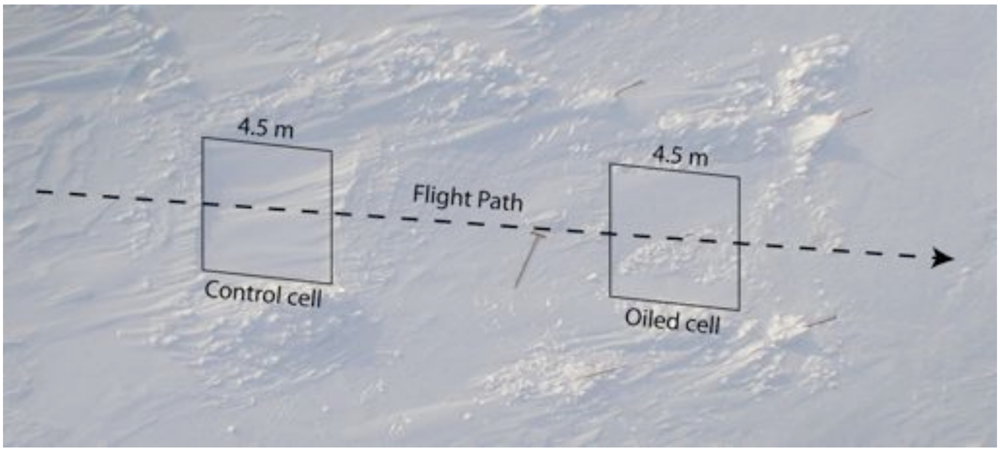


Figure 3. Overhead photograph of the snow covered test cells and helicopter flight path.

Figure 4. Photograph showing the 1000 MHz shielded antennas suspended from the cargo hook of the helicopter.

3.3 Results

With an oil thickness of 2 cm, the radar performance simulation 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 showed a substantial decrease in reflection strength over the oiled cell. 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 5).

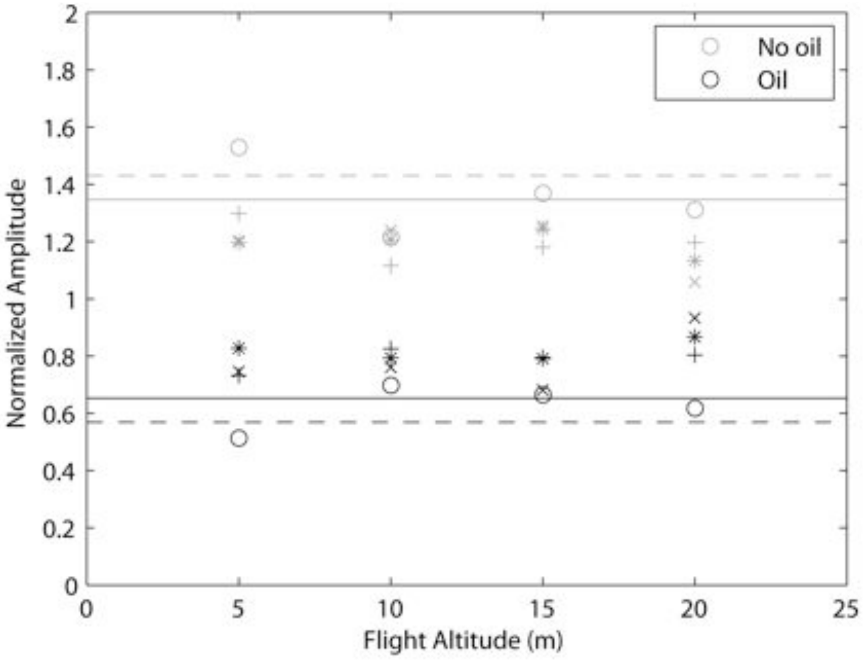


Figure 5. Summary of airborne radar results at speeds of 2.6 m/s (o), 5.1 m/s (+), 7.7 m/s(*), and 10.3 m/s (x). Solid and dashed lines show the predicted amplitudes from numerical modelling using wind blown (low density) and undisturbed snow (high density) properties respectively. In all cases the amplitude of the snow-ice interface in the oiled cell is significantly lower than that in the control cell. Source: Bradford et al., 2010.

The numerical and field results (Bradford et al., 2010) 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 melt water 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.

4 Dog Training and Testing

A common feature with any remote sensing methods 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.

4.1 Phase 1 Testing in Trondheim

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. Pictures from this video are included here as Fig. 6.

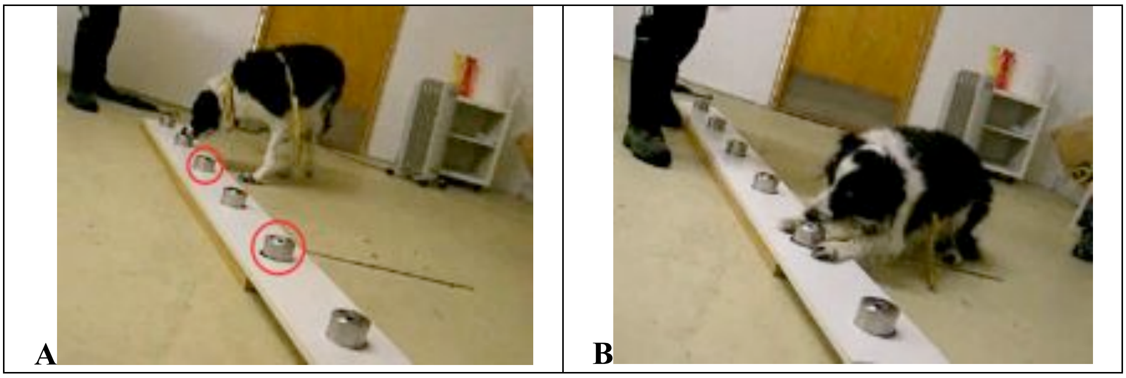


Figure 6. Blind testing of dogs during Phase 1: Pictures from enclosed video. Two of the six boxes contain oil vapour (**A**) and are very clearly detected by one of Turid Buvik's dogs "Jippi" (**B**).

4.2 Phase 2 Testing on Svalbard

The objective in the second project phase was to further develop a new method of detecting 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). The different elements of the Phase 2 testing are summarized below.

Transportation: 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 7).

Figure 7. 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.

Working outside in cold and windy conditions - air temperatures down to -20°C and a wind chill of -40°C - even furry dogs needed an insulated crate and some kind of warming suit after several hours and between training sessions.

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 (Fig. 2), and 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 8).

The dogs were equipped with two different GPS positioning devices, a Trackstick and a Garmin 220 tracking device (Figure 9) 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, to study each individual track in relation to oil and wind at the debriefing afterwards, and to derive parameters such distance, and average search speeds.

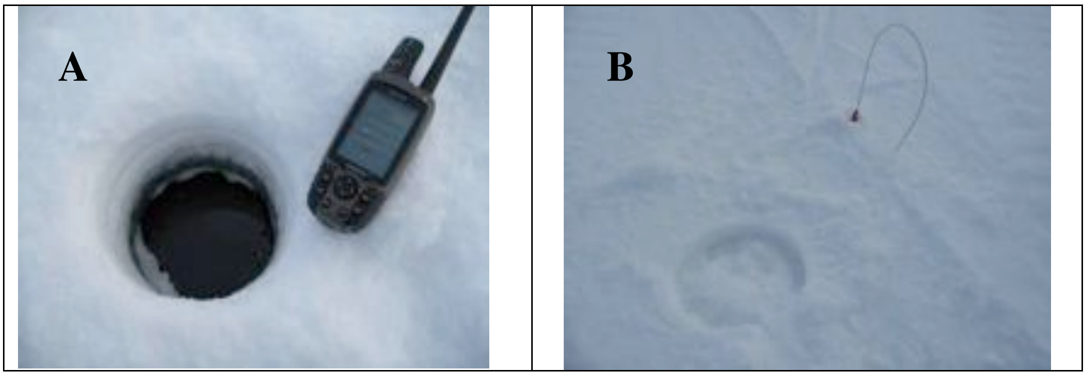


Figure 8. Small training oil spills used for the field training. A: 400 ml of weathered Troll crude (200°C+) in a 30cm hole in the first year ice. B: The hole covered with snow and ice chips.

Figure 9. 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 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 maximum distance during this training from releasing the dog to the spill was measured as approximately 5 km, with no indication of this being the maximum detecting distance. Time limitations prohibited further testing to determine the ultimate detection limits.

Overall Findings: 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 228) 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. More challenging snow or rougher ice conditions could make scooter transport more difficult and create a possible need for helicopter transport. Helicopter training was not included in these tests, but there is no reason why dogs could not travel to an offshore spill in pack ice by helicopter.

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.

The dogs showed an important 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:

- 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).
- Determine the dimensions of larger oil spills by indicating the borders of clusters of smaller oil spills (10 meter spacing).

- 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).

5 Airborne Remote Sensing Systems

The remote sensing project worked closely with the authorities and national surveillance programs to secure the participation of aircraft in both of the offshore field experiments, 2008 and 2009. From the outset, both sets of spills were expected to present major challenges for remote sensing in terms of the very small expected spill areas - in 2008 related to the limited volume, and in 2009 related to the anticipated higher ice concentrations that would contain the oil as localized patches. Regardless of the uncertain probability of actually "seeing" the oil, the participation of aircraft in the JIP 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 working with actual spills in an Arctic offshore environment.

5.1 Background

Multispectral airborne remote sensing supplemented by visual observations made 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 little is known about the capabilities of modern airborne systems in ice-covered environments. Historical examples where aerial documentation and remote sensing was applied to 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. Airborne surveillance of the 2002 Prestige tanker spill involved one to two flights per day for ten weeks by aircraft from six nations. The data delivered by these flights proved to be a key element in response operation, guiding offshore operations and increasing recovery efficiency (Peigné, 2007).

An example of the current generation of surveillance aircraft, the Swedish Dash 8 Q300 MSA, is shown in Fig. 10. This aircraft was employed in the 2009 offshore field experiment.

Airborne sensors such as UV/IR and SLAR are expected to 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 begins to significantly modify 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 thick patches rather than spreading as 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, IR and ALFS are all seriously affected by the presence of clouds or fog near the surface.

Figure 10. Swedish Q300 aircraft representative of the state of the art in maritime airborne pollution surveillance. Systems with similar capabilities are operated by member countries of the Copenhagen, HELCOM and Bonn agreements, as well as Canada. Source: Swedish Space Corporation

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). Eventually, the lack of readily available operational systems (one only operational in Europe, one in Canada) made it impossible to test the ALFS during the offshore JIP experiments. At this stage, the LFS should be considered a potentially useful sensor in the future for oil on the surface of solid ice and slush or on the water between floes under Visual Meteorological Conditions (VMC). Major drawbacks against its operational use are cost and limited availability.

5.2 2008 Airborne Remote Sensing Program

The 2008 spill was viewed as a valuable opportunity to test the procedures and coordination required to carry out the more extensive and complex experiment planned for 2009 and to collect data on the relative merits of different sensors, both airborne and satellite within the known limitations of working with the very small spills being planned for the first-year. In addition to the restrictions on spill volume, the 2008 spill presented the additional challenge of only being present on the surface 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 such a transient event represented an extreme operational worst case.

The only significant 2008 remote-sensing target available consisted of a 0.7 m^3 crude oil spill in very open drift ice (up to 4/10) with large openings between the floes (Figure 11). From the outset it was recognized that this slick represented a marginal target for the aircraft and a very low probability target for the satellite.

Figure 11. Large uncontained spill intended as the airborne remote sensing target in 2008. Photo: D. Dickins (from helicopter)

Norway provided their dedicated pollution surveillance aircraft, a Fairchild Merlin LN-SFT to survey 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 from Longyearbyen to the spill site, the aircraft was called away on an emergency request to assist with an accidental spill at one of the offshore platforms near Bergen. 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 demonstrated the uncertainty of working with operational aircraft in an experimental mode where the aircraft can be called away on short notice if a real emergency develops – this was always the understanding and a pre-condition of participation by the Norwegian Coastal Administration (Dickins and Andersen, 2010).

5.3 2009 Airborne Program

The spill volumes planned for 2009 were up to 10 times larger than the main spill in 2008 but the proposed ice conditions in the 5-7/10 range were expected to provide enough confinement in the worst case to produce a slick area potentially far less 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 on the day of the overflight that were only a fraction of the uncontained slick in 2008 shown above in Fig. 11.

In 2009 the primary remote sensing aircraft was the state of the art Swedish Dash 8 Q300 placed in service in 2008 with the sensor suite illustrated in Fig. 10. The specialized Norwegian surveillance aircraft LN-SFT used in the 2008 offshore field experiment was lost in a tragic accident in June of that year. Its temporary replacement LN-HTS made available for the 2009 experiment has very limited remote sensing capabilities consisting of an MSS6000 SLAR and hand-held photo/video.

Constraints imposed by weather and an overlapping marine emergency involving a grounded freighter on Bear Island, meant that the Swedish aircraft had time for only one flight to the spill site before the crew duty cycle expired. The “large” 7 m^3 spill took place in the morning of May 15. The aircraft made a series of high-level passes over the test site above the mist and low cloud during a 40-minute period 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. 12 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. Even after several days of being left within the ice pack, the oil had spread to cover patches no more than a few tens of meters. At the time of the Swedish overflight, the oil spill covered an area of no more than a hundred square meters. The oil was entirely trapped in thick layers between the closely packed floes, leaving no possibility of being able to detect the slick with SAR or SLAR imagery, dependent on a clear contrast between a floating slick and the surrounding water surface.

The persistent low cloud ceiling of 150-200 m prevented the flight crew from establishing visual contact with the spill. The sophisticated Electro-optical Infrared Camera System (Wescam MX-15) that could potentially 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, 2009) 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 achievable in low-level surveillance under VMC.

Figure 12. P1#2**,** 7 m^3 oil release May 15 at 0854. The oil is being pumped through the hose lying on the ice surface. Photo: Jan Nilsen.

In the 2009 experiment, the Swedish aircraft was forced to operate in a truly remote manner 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. Figure 13 shows an example of this imagery, which is normally used as a wide swath screening tool for large slicks at sea. Ground resolution on the SLAR is in the order of 30 x 60 m. The full 2009 airborne program is reviewed in Dickins and Andersen (2010).

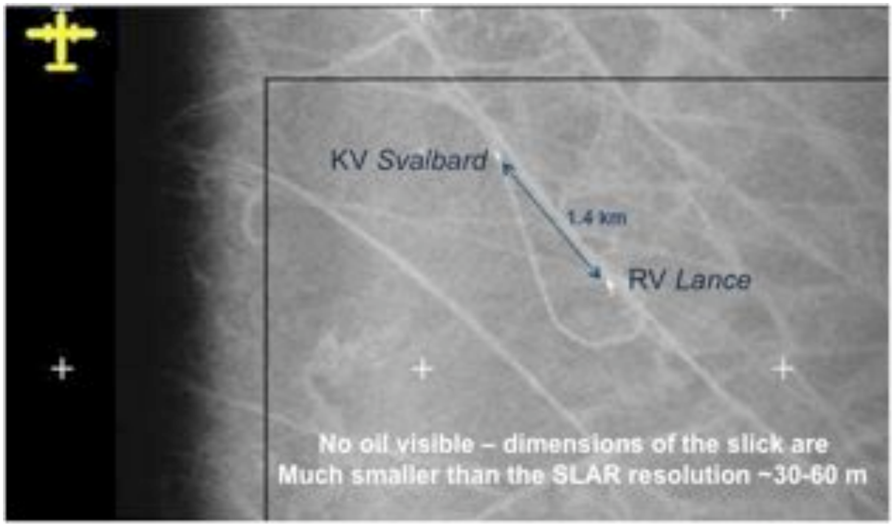


Figure 13. Enlarged right-hand segment from airborne SLAR imagery showing the two vessels and tracks left in the ice (within inset box). Aircraft is tracking NNW. KV *Svalbard* is slightly (~1.4 km) to the NW of *Lance*. Ice concentrations are 8 to 9+/10. Openings within the ice cover are smaller than the SLAR resolution. Source: Swedish Coast Guard

6 Satellites

Satellite-based SAR can offer wide area surveillance coverage day and night, independent of cloud cover and weather conditions. 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 useful surface resolutions in the order of 25 m. 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 covering an Arctic spill site from different satellites. 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 et al. 2003). Extensive use was made of SAR imagery during the *Prestige* tanker spill off Spain in 2002 (Palenzuel, et al., 2006; Peigné, 2007). 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).

While the capabilities of SAR satellites 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 question also applies to SAR/SLAR sensors routinely installed on dedicated surveillance aircraft.

6.1 Background and 2008 Experience

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 is caused by Bragg scattering through 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 darker signatures than the surrounding water without oil.

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. 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 spill lasting a few tens of minutes (Fig. 11). The timing of the having the aircraft and satellite overhead within the brief period when the uncontained slick was allowed to spread prior to herder application was extremely tight. In practice, the field crew exactly coordinated the simultaneous oil release with the satellite pass exactly. Unfortunately, the processing facility failed to acquire the high-resolution RADARSAT 2 image previously scheduled for that day, and the only chance to match imagery with an actual oil slick in 2008 was lost.

Figure 14 demonstrates 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. 15 and 17.

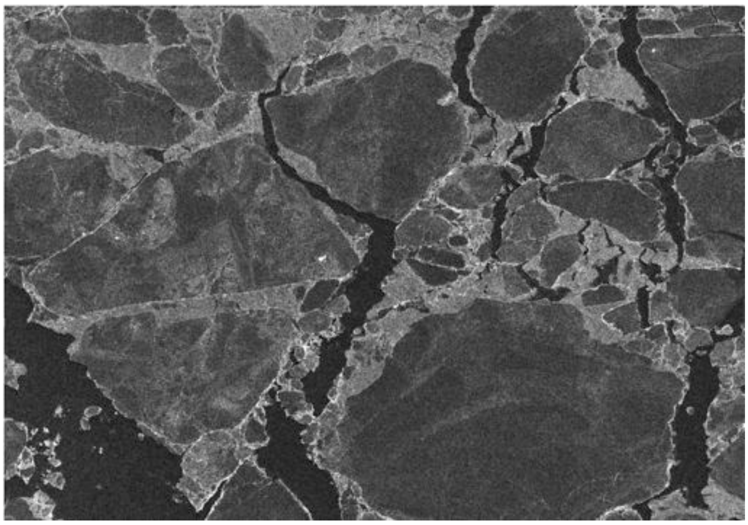


Figure 14: Subset enlargement from a Cosmo-SkyMed image acquired in the vicinity of the site of the 2008 offshore field experiment on May 22, 2008 – pixel spacing 5 m. Note the high level of detail with three main surface: open water (very dark), large ice floes (dark grey) and small ice floes with consistently rough edges in high concentration (light grey). The large floe sizes in this picture are in the order of a few hundred meters. © CopyRight 2008 Agenzia Spaziale Italiana

6.2 2009 Offshore Field Experiment: Image acquisition

Twenty-six images from three SAR satellite systems were acquired to monitor the 2009 oil in ice experiment – Table 1. With the relatively small amount of oil planned for release, the 2009 satellite acquisition program focused on achieving a balance between the highest possible pixel resolution to increase the chances of spill detection, while also maintaining sufficient aerial coverage to account for uncertainties in the final location of the experiment. Dual-polarization image modes were acquired from Radarsat-2 to determine whether or not this could improve the distinction between oil and open water in calm conditions.

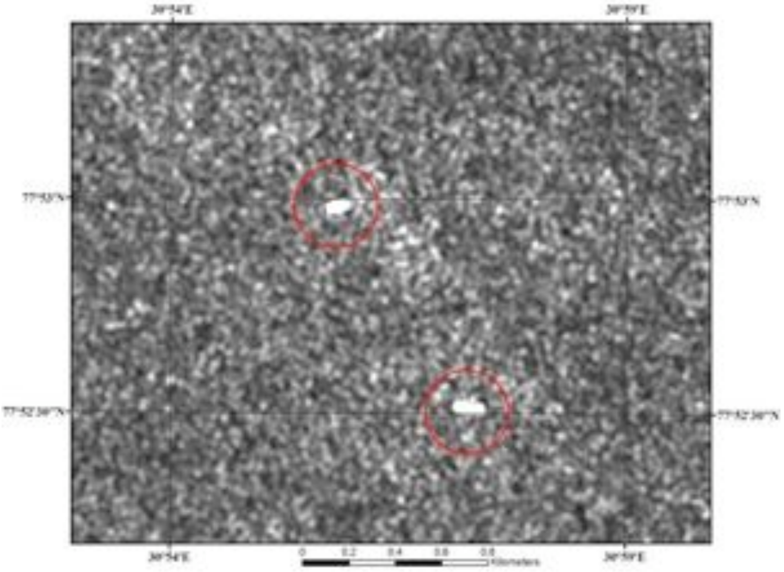
The composition of the ice regimes between 2008 and 2009 were very different. The 2008 experimental area was characterized by many well-defined medium floes (100-500 m) and leads about 75 km in from the ice edge in a mix of open to close drift ice (predominantly 6-7/10). In 2009, the main experimental 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 to the technical specifications of the individual sensors. Further details of the 2009 satellite acquisition program are provided in Babiker et al., (2010).

Table 1: 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	

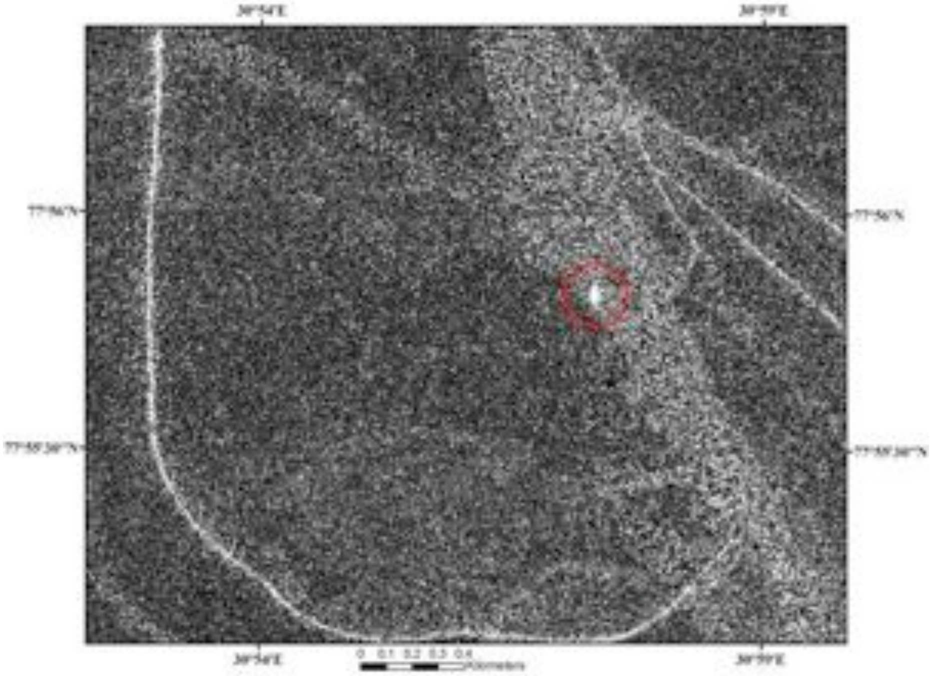


RADARSAT-1 Data and Products © MacDONALD, DETWILER AND ASSOCIATES LTD., 2009 – All Rights Reserved/Processed KSAT 20009

Figure 15. RADARSAT-1 image, date 20090514, time 15:18:59. The image shows the two vessels, RV *Lance* – bright return to the north and KV *Svalbard* – bright return to the south. The ice edge is about 14 kilometres further south, outside the image frame. The ice is very close pack (80-90% concentration). 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 Fig. 16).

Photos: D. Dickins

Figure 16. Photos taken from KV *Svalbard* 20 minutes after the satellite pass shown in Figure 15. RV *Lance* visible in background.



COSMO-SkyMed™ Product – ©ASI 2009 processed under licence from ASI – Agenzia Spaziale Italiana. All rights reserved. Distributed by e-GEOS

Figure 17: Cosmo-Sky-Med image, date 20090515; time 16:12:45 – 8 hours after oil release (Fig. 12). The image shows RV *Lance* – bright return – and the tracks of the ships from the past few days. No oil is visible as the spill is confined to small patches tens of meters or less trapped between floes and in narrow leads.

7 Conclusions and Recommendations

A key finding of the oil in ice JIP remote sensing project is that a flexible combination of sensors operating from aircraft, helicopters, vessels, satellites and the ice surface is required to cover a range of oil in ice scenarios. Factors such as the composition of the pack ice, visibility and ceiling, duration of daylight, ice drift rates and type of oil release (e.g. subsurface or surface) will dictate the likely effectiveness and capability to detect oil in any given spill situation.

SLAR and SAR represent the only truly all-weather sensors independent of daylight and cloud. All other sensors are constrained by both clouds/fog and darkness (UV and visual spectrum imagery), simply clouds and fog (e.g., IR, laser fluorosensor, passive microwave).

Detecting isolated oil patches among close pack ice (>6/10) is a major challenge with any current remote sensing system. The most effective solution to this problem is to deploy GPS tracking buoys at regular intervals to follow the oil moving with the ice.

The JIP experience confirmed the initial findings of the screening study while refining our knowledge of the practical limitations and capabilities of different systems under conditions of marginal flying weather and closely confined spills in close pack/drift ice conditions. Some specific conclusions and recommendations are provided here as a direct outcome of both the JIP program as well as the accumulated knowledge base of oil behaviour in different types of ice conditions and experience with different sensors over spills in open water.

a. GPR in surface or airborne modes, 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. Current limitations relate to its performance in warm saline ice and/or rough rubble and ridging. Ongoing developments are expected to lead to more capable airborne GPR systems optimized for the oil-in-ice problem by 2011.
b. 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.
c. Some form of 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.
d. Given the limitations of cloud cover and darkness, visible satellite sensors (e.g. Quickbird) cannot be relied on in an emergency to provide reliable oil spill coverage.
e. The latest generation of SAR satellites such as CosmoSKYMed, TeraSAR-X and RADARSAT 2 are can resolve some 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).

f. During freeze-up in fall and early winter, any detection of oil among ice with SAR/SLAR airborne or satellite 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.

g. 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.

h. 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.

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