ARCTIC RESPONSE TECHNOLOGY
OIL SPILL PREPAREDNESS

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CAPABILITIES FOR DETECTION OF OIL SPILLS UNDER SEA ICE FROM AUTONOMOUS UNDERWATER VEHICLES

FINAL REPORT 5.2

Report from Joint Industry Programme on oil spill detection and mapping in low visibility and ice: focus on undersea remote sensing

ABOUT THE JIP

Over the past four decades, the oil and gas industry has made significant advances in being able to detect, contain and clean up spills in Arctic environments. To further build on existing research, increase understanding of potential impacts of oil on the Arctic marine environment, and improve the technologies and methodologies for oil spill response, in January 2012, the international oil and gas industry launched a collaborative four-year effort – the **Arctic Oil Spill Response Technology Joint Industry Programme (JIP)**.

Over the course of the programme, the JIP will carry out a series of advanced research projects on six key areas: dispersants, environmental effects, trajectory modeling, remote sensing, mechanical recovery and in-situ burning. Expert technical working groups for each project are populated by the top researchers from each of the member companies.

JIP MEMBERS

The JIP is managed under the auspices of the International Association of Oil and Gas Producers (OGP) and is supported by nine international oil and gas companies – BP, Chevron, ConocoPhillips, Eni, ExxonMobil, North Caspian Operating Company (NCOC), Shell, Statoil, and Total – making it the largest pan-industry programme dedicated to this area of research and development.

EXECUTIVE SUMMARY

Ice-covered waters present a complex and challenging environment for remote detection of oil. Given the renewed interest in both hydrocarbon exploration and shipping in the Arctic, and recognizing previous significant investment in remote technologies, there remains a need to continue to research and develop solutions to aid oil spill response operations in the Arctic. This report summarizes the existing and emerging oil spill remote sensing and mapping technologies that have the capability to detect and map an oil spill in ice covered seas from below the surface using unmanned underwater vehicles (UUVs) and provides recommendations for future development.

Existing Capabilities:

To-date, the vast majority of remote sensing techniques developed for oil detection in ice-covered waters have focused on airborne or on-ice systems. All these techniques rely on the ability to effectively "see" through the ice and its snow cover to detect oil trapped beneath the ice. While some of these methods have been moderately successful in detecting oil in ice covered seas, sensors mounted on unmanned underwater vehicles (UUVs) hold the potential to overcome some of the constraints encountered with airborne or surface based methods, such as the need to sense through the ice and snow, and the logistical challenges in broken and young ice conditions.

UUVs have been successfully operating in ice-covered waters and are now a viable technology for under sea ice operations. UUVs, and especially autonomous underwater vehicles (AUVs), have the dual advantages of being deployable in a range of ice and weather conditions, and importantly their sensor payloads will have a direct view of oil trapped beneath the ice. The direct view of oil under the ice provided by UUVs means that a variety of existing sensor technologies (including cameras, sonars, and radiometers) that have been used extensively on UUVs can potentially be readily adapted to remote detection of oil under sea ice. Detection of oil encapsulated within the ice may also be possible with some sensors mounted on UUVs, and possibly more efficiently than with surface and airborne remote sensing methods.

Emerging Technologies for advancing detection from below the ice:

This document focuses on sensors and platforms that address these challenges below the bottom of the ice, i.e., from within the water column and looking up at the ice bottom. This is an almost entirely new approach to oil spill detection. As such, this report provides a review of the existing UUV capabilities and sensor technologies that are most promising for adaptation to this problem, and provides recommendations for future development and testing. This report is divided into six inter-linked chapters and its layout is as follows:

Chapters 1-3: *An overview of the operating environment along with a review of the relevant literature, research and technologies relating to oil spill remote sensing and mapping technologies by mobile-ROV, AUV-based, and fixed platforms.*

Chapter 4: *An assessment of the opportunities to better detect oil by correlating multiple sensor measurements through advanced processing techniques.*

Chapter 5: *A detection and needs analysis to identify various strategies for oil detection and mapping under various ice regimes and oil spill scenarios.*

Chapter 6: *A synthesis and summary including recommendations of technologies that would benefit from further research and development.*

Key Recommendations

To move towards development of an operational UUV platform for remote oil detection and mapping applications, testing, evaluation, and development of both a sensor suite, and UUV technology are required. Camera, sonar, laser fluorometer and radiometer systems are the most promising sensors for oil detection using UUVs. The advantages and limitations of these sensors under different sea ice and oil spill scenarios needs to be established for each sensor through controlled and repeatable laboratory experiments focussing on sensor signal response both for oil under, and encapsulated, within ice. Further development of sensor technology to transition potential sensors to AUV platforms is also needed. While routine AUV operations in ice are now possible, there is an opportunity to further advance capabilities with respect to (1) vehicle launch and recovery, (2) navigation in complex ice conditions, and (3) mission strategies and data telemetry so that transition of research-level AUV technology to easy-to-use operational platforms can be most effective. Dedicated oil-spill field trials should be performed once an appropriate sensor suite is incorporated into an operational AUV platform.

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CHAPTER 1. INTRODUCTION: SEA ICE AND OIL SPILLS

The potential wealth of oil and gas resources in Arctic waters, combined with rapidly changing ice conditions, are expected to increase the areal extent of the Arctic ocean where oil exploration and marine transportation systems are feasible. Any escalation in human activity in the ice-covered waters will increase the potential for an oil spill. Consequently, there is a pressing need to continue to develop improved methods of oil spill detection and response strategies in ice-covered waters. With the advent of autonomous vehicles capable of routine deployment under sea ice a new approach for detection and mapping of oils spills from the ice underside is now possible. This chapter briefly reviews the factors driving increased interest in the Arctic, relevant sea ice conditions and the nature of oil interaction with sea ice, and the motivation for exploring Autonomous Underwater Vehicle (AUV) based methods for remote sensing of oil from beneath the ice.

1.1 The changing Arctic

The Arctic is rapidly changing, possibly faster than any other region on earth and possibly faster than at any other time during the Earth's recent history. Recent Arctic warming has occurred at twice the rate of the rest of the planet (IPCC, 2007). This warming has been accompanied by dramatic changes in sea ice; annual average ice extent has declined by about 15% (Francis et al., 2005), a reduction in perennial (multiyear) ice **(**Kwok, 2007), variations in ice dynamics (Gascard et al., 2008) and a decline by some 40% in the thickness of sea ice (Rothrock et al., 1999) with an associated reduction of 73% in the frequency of deep ridges (Wadhams and Davis, 2001).

One manifestation of these changes is the alteration to the timing and length of the Arctic sea ice melt season i.e. the ice is melting earlier and freezing later, with the summer season being extended by as much as two months in some regions (Stammerjohn et al., 2012). The scale and speed of summer Arctic sea ice retreat has been remarkable, with minimum ice extent in 2012 being 50% below the 1979-2000 average. Some predictions suggest a near complete disappearance of summer sea ice may occur by 2040 or earlier (e.g. Holland et al., 2006).

These changes in the ice-free season are most dramatic over large expanses of the coastal offshore region, where it is estimated that up to 30% of the world's undiscovered gas and 13% of the world's undiscovered oil may lie (Gautier et al., 2009). The continuing reduction of the summer Arctic sea ice has also extended the Arctic navigation season and opened more of the Arctic to maritime traffic. The North-west Passage (via Canada) and the Northern Sea Route (via Russia) may soon become increasingly viable options for routine commercial traffic. In 2012, the first crossing of the Northern Sea Route by a liquefied natural gas tanker during the ice season was completed, accompanied by nuclear icebreakers.

The expected increase in oil production and transportation in the Arctic is not solely driven by climate change, but also by myriad other factors including increasing oil and mineral prices (AMSA, 2009), improved extraction technology (lowering the cost of extraction), and pressure to develop reserves in national waters to increase energy security. Commercial investment in the Arctic could reach $100bn or more in the coming decade, with oil and gas, mining and the shipping industries being the largest drivers (Lloyds, 2012)

With the combination of these factors - Arctic climate change, increased economic viability of resource extraction, increased shipping and ship-based tourism, energy security and territorial issues - human activity in the ice-covered waters of the Arctic will increase significantly in the years to come. Developing effective means of detection and response strategies for oil spills in sea ice-covered waters will form an important part of measures to mitigate the risks and potential consequences of such a spill as these activities increase.

1.2 Sea ice

Sea ice occurs in a wide variety of forms due to the varied thermodynamic and dynamic forces that control its growth, evolution, and decay. This results in a complex, highly heterogeneous environment that varies on scales of less than a meter to hundreds of kilometres. This variability has implications for how oil is distributed and interacts with this environment, and the logistics of oil spill response strategies – including AUV missions. This section briefly describes the basic types and characteristics of sea ice found in the Arctic that are relevant for oil spills and oil spill response and defines the sea ice terminology that is used throughout the report.

Sea ice can occur in a variety of forms – each of which may interact differently with oil. Initial freezing of the ocean surface occurs through the formation of loose crystals known as **frazil ice**. These can form “slicks” at the surface known as **grease ice**, which has a matte-like appearance, similar to the effect of oil on the ocean surface. Frazil can also be herded into clumps or long streaks by the wind. In calm seas, a thin consolidated sheet, known as **nilas**, will form, and further growth continues vertically downward. Nilas is often dark in appearance, as it transmits light well. This changes to grey as it thickens to more than about 15 cm and its transparency decreases. Even though the initial ice sheet may appear level, there are invariably small thickness variations due to heterogeneity in ice properties and freezing rates, and frequent rafting of the ice due to ice dynamics.

In the presence of waves and swell, frazil will consolidate to form circular pans up to a few meters across, known as **pancake ice**. Pancakes have rounded bottoms and upturned edges, so that when these consolidate into a continuous ice sheet, the ice sheet will have significant spatial heterogeneity in thickness and ice properties. Further thickening will then occur by freezing of seawater on the underside of the ice.

An important property of sea ice is that it is not pure ice – as it grows, brine is entrapped in small pockets. These form a porous network that evolves over time as the ice thickens and ages. If the ice is sufficiently warm, this network can interconnect, forming pathways by which fluid can flow through the ice. In winter, these pathways occur in the form of brine drainage channels, through which dense brine can flow out of the ice. In summer, these pathways form conduits through which fresh melt water (i.e. snow melt on the ice surface) can flow through into the ocean below. This internal structure can form a pathway for oil trapped beneath the ice to enter into the ice, even reaching to the surface (Martin, 1979). The process of oil migration through brine channels has important implications for detection at certain times of year and was observed and documented in a number of laboratory and field experiments dating back to the 1970’s. Recent research on this oil transport mechanism occurred during a spill under fast ice on Svalbard in 2006 and small-scale tank tests in Ottawa (Dickins et al., 2008; Buist et al., 2009). For more details on sea ice properties, see Petrich and Eicken (2009).

The Arctic is a dynamic environment. As winds and currents push ice floes against one another, the level ice will deform. When the ice is thin, floes may raft over one another. This is common for nilas and pancake ice. Both thin and relatively thick ice may also form ridges – long, linear-like features composed of small blocks of ice, piled both above the level ice surface and below. Ridge sails may be as much as several meters and height, and keels may reach depths of 40 m or more in depth. Ridge sails tend to trap more snow, so that there is also considerable spatial variation in snow cover. In a more open pack (i.e. in summer), ice floes colliding together may not form a ridge, but can still break bits of floes off to form **brash ice**. This ice is common near the ice edge where the action of waves can break up the ice into successively smaller floes. In winter months brash ice can freeze together to form rubble fields with highly variable ice thickness. Even for level ice, there are small-scale spatial variations in ice thickness due to changes in the thermodynamic growth rate brought about by spatial variations in snow depth (Wadhams and Martin, 1990). All these morphological variations lead to a high spatial variability in ice thickness and properties that will affect how oil would spread beneath the ice, interact with the ice, and complicate the interpretation of sensor data targeted at detecting oil in the sea ice zone.

If predictions are correct, then most of the oil reserves are to be found offshore, in less than 500 meters water depth (Gautier, et al., 2009). For most areas of the Arctic this covers the seasonal ice zone, although it can also include regions with substantial perennial ice. The ice conditions within this zone vary upon season, from open water in summer to close-pack in winter. Ice types in this region can vary across a broad range of forms, from new ice (frazil, nilas and pancake), to a first year ice sheet through to multiyear ice types. Both first year and multiyear ice can also have significant morphological variability, ranging from undeformed, level ice to heavily deformed (ridged) ice. Generally speaking we can divide this region into four zones (not all necessarily being present): fast ice, drifting pack, the shear zone and a marginal ice zone (MIZ). Each class are described below.

<u>Drifting pack:</u> The majority of sea ice within the Arctic is mobile i.e. it moves under the influence of wind, currents, and ice stress. Drifting pack can be further divided into **first year ice** (FY) and multiyear ice (MY). Generally, FY ice formed at the start of the winter is 1-2 m thick by the beginning of the following melt season. FY ice that survives the summer melt then becomes known as **multiyear ice** (MY), or perennial ice. MY year ice can be many years old and is generally thick (2-5 meters is typical) and can be heavily deformed. The morphology of the underside of MY ice is generally more rugged than FY ice as a result of the differential melt/growth rates throughout the seasons (Wadhams, 1985). FY ice is more saline than MY ice. It has been speculated that MY ice has a larger holding capacity for oil than FY ice due to its deformed nature, although this has not been confirmed. MY ice is generally located north of Greenland and Ellesmere Island (Canada) as well as over the deep basins. It is also found in varying quantities in the exit routes for ice leaving the Arctic Ocean i.e. Fram Strait or the Nares Strait/Canadian archipelago system. In some years, high concentrations of multi-year ice can drift in to the Beaufort Sea and along the Chukchi Sea coast as well as along the Russian Northern Sea Route.

<u>Fast ice (floating and grounded):</u> Fast ice is usually a seasonal sea ice cover that is in contact with the shore, but is immobilised due to the geometry of the coastline or by anchoring points such as small islands or grounded sea ice ridges and icebergs. Fast ice is not mobile and therefore is often in an undeformed state, although there are irregular undulations on the bottom of the ice due to snow cover variations. These natural undulations in the under-ice topography can provide effective catchments to contain any spilled oil (Barnes et al., 1979). Fast ice may stretch many tens of kilometres seaward, e.g. the fast ice barrier in NE Greenland, known as the Norske Øer Ice Barrier stretches almost 100 km off shore. Fast ice can be heavily deformed

as ice in the shear zone consolidates onto the existing fast ice, or as ice broken by dynamic events refreezes.

Flaw lead or shear zone: The flaw lead or shear zone system is the demarcation zone between the fast ice and the drifting pack. Because the drifting pack is influenced by a number of competing forces the ice cover within the flaw lead or shear zone is continuously developing. For example when the pack moves away from the fast ice a lead system (open water) develops; when the drifting pack moves towards the fast ice deformation of the ice cover occurs, usually in the form of ridge building events. These ridges, consisting of ice blocks and rubble, may become grounded (known as Stamukhi). Stamukhi provide additional anchoring points for the land-based fast ice, extending the fast ice zone and/or making it more stable as well as sheltering it from the pack ice beyond. The underside topography of the flaw lead – shear zone system is poorly known, and therefore its potential oil holding capacity and how an oil spill will flow under this ice type is also unknown. However, as this zone is heavily deformed, the ice underside is presumably highly irregular. Clearance between the seabed and the ice will also be highly variable, but may be as little as a few meters (or indeed, nil where the ridges are grounded). This presents challenges for AUV operations in this region.

Marginal ice zone*:* The marginal ice zone (MIZ) is not an ice type but a region of sea ice between the open water and continuous pack ice (Wadhams, 1986). This region is influenced by the proximity to the open ocean and as a result it can have properties quite different to the interior pack. Wave and wind induced break-up leaves the ice as a mixture of broken floes and brash. During ice advance in winter, new ice such as frazil and pancake ice are common in the MIZ. The ice within the MIZ is extremely mobile and because of this the ice concentration, i.e. the amount of open water surrounding the floes, is constantly varying. A classic MIZ (where ice conditions are dominated by the presence of ocean swell) has been historically uncommon in the Arctic Ocean because of the limited fetch and relatively calm seas. However, the increased northerly retreat of the ice cover, increased fetch, and increased storminess may make MIZs more prevalent and extensive throughout the high Arctic.

Icebergs: Icebergs originate from glaciers and thus are of non-maritime origin. Most icebergs originate in regions south of the Arctic Ocean i.e. the Greenland ice cap, but other calving areas include the glaciers of Spitsbergen, Franz Josef Land and Novaya Zemlya. They are rarely encountered within the Arctic Ocean. In some ways their rarity makes them more dangerous to shipping and fixed assets. Icebergs are more common in the Baffin Bay and the Labrador Sea regions.

1.3 Sea ice and oil

The distribution of oil in ice-covered waters presents a number of challenges to detection and clean-up efforts. Depending on the season, the surrounding sea ice conditions and the nature of an accident, spilled oil could be found on, under, or in the waters surrounding the sea ice. While a spill could happen at any time of the year of the sea ice cycle most Arctic marine activities at present are concentrated around the summer months. Depending on the location the summer may be dominated by a period of open water (e.g. Beaufort Sea), or broken pack (e.g. NE Greenland) and icebergs (e.g. W Greenland). Even regions that are generally ice free in summer may occasionally experience extended periods of drift ice, including both multi-year and first-year ice. If an open-water spill is not located and cleaned before freeze-up, then it will become incorporated into the ice and drift with it.

The sea ice conditions found in the broken pack of the marginal ice zone could be more challenging for detection as oil may be located under the ice, within the ice, on the surface of the ice, or within the waters surrounding the sea ice. Given the dynamic nature of ice within the MIZ, all of these are likely to occur together to varying degrees and at various times.

The MIZ is particularly challenging as each individual floe has a different surface and sub-surface shape and each floe will move differentially to each other. The result is an ice field whose concentration is continuously changing as a function of the ever-shifting winds and currents. Floes may come together squeezing the oil between them, or drift apart allowing to oil to spread out over the sea surface (where it will be herded by the wind). Modelling studies by Venkatesh et al., (1990) suggested that for low sea ice concentrations (less than 30%) oil behaved as in open water, and for ice concentrations higher than 30% the oil moved with the ice.

When oil is released in the water column, it may rise towards the surface in a conical shaped plume (if lighter than the surrounding seawater). The rising oil tends to be unstable, and typically breaks in to small spherical particles of about 1 cm in diameter or less, although this varies greatly depending on oil type and origination depth (Norcor, 1975). Upon reaching the underside of the ice, and if in significant quantities under the ice, the oil will preferentially flow towards regions of thinner ice, accumulating in interconnected depressions under the ice as it spreads (Fingas and Hollebone, 2003, Wilkinson et al., 2007a). Experiments performed by deliberately spilling oil underneath sea ice have determined that oil is highly mobile and spreads along the bottom of an ice sheet as a gravity driven flow (Wadhams, 1976, and figure 1.1). The rate and direction at which oil spreads under ice is determined by a combination of factors, but it is the under-ice topography that is fundamental in determining both the volume of oil that can be held by sea ice (its oil pooling capacity) and the direction of flow.

The pooling behaviour of oil under ice is an important distinction with oil slicks in open water and consideration in designing a detection strategy. For a spill under fast ice, or high volumes of oil spilled under drifting ice, oil can pool to fill depressions many centimetres or more in thickness. In contrast, open water slicks may be only a few microns in thickness. For blowouts at depth under drifting fast ice, the oil may spread very thinly over large areas, although how oil might flow or pool under the ice in such situations is unknown.

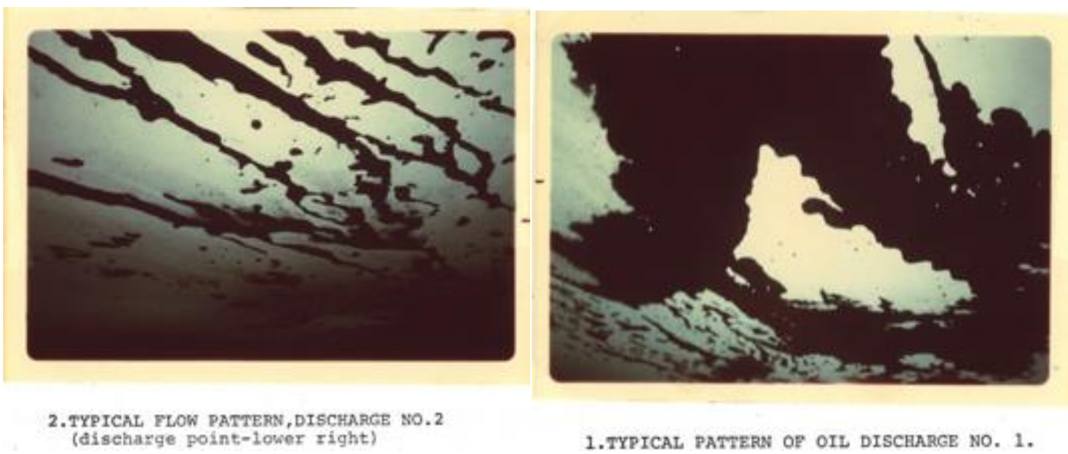


Figure 1.1 *Oil flow under sea ice forming rivulets in the Beaufort Sea (left). Substantial oil flow can occur around an area of thicker ice, with thick oil pooling in the depressions around the thicker ice (right). (Source: NORCOR oil under ice recovery tests Beaufort Sea, May 1975).*

Encapsulated oil: If a spill occurs during a time when the ice is growing then sea ice will form a lip around the perimeter of the oil before eventually encapsulating the oil within the ice matrix (NORCOR, 1975) forming what is known as an oil sandwich (figure 1.2). Once encased in the sea ice there is little opportunity for the oil to naturally weather. Field and laboratory tests reveal that encapsulated oil is released in the spring/summer melt period by either vertical migration of oil through the ice and its brine channel system, or through the ablation/melt of the ice surface downwards (Fingas and Hollebone, 2003). Upon reaching the surface the oil will substantially reduce the albedo of the snow and ice surface. Being dark the oil will absorb solar radiation and cause localized accelerated melting on the ice surface (Lewis, 1976).

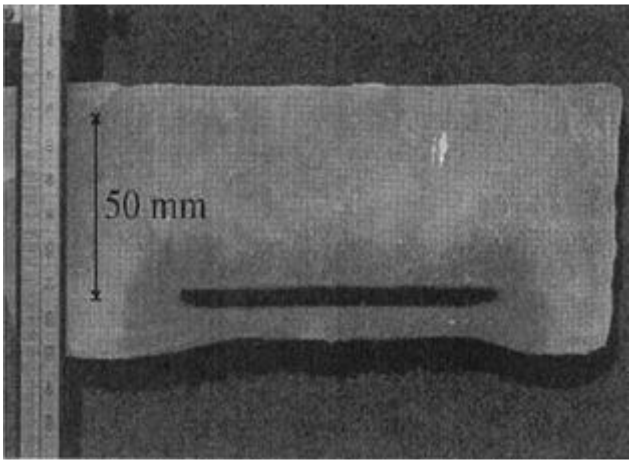


Figure 1.2. *Laboratory experiment showing the cross section of an oil-ice sandwich (Izumiyama et al., 2004)*

1.4 Detection of oil under sea ice from below

While oil spills under an ice cover spread much slower, occupy a smaller area than an open ocean spill, and are slower to weather, they do present complex challenges to the technologies to detect, monitor and recover the oil spilled in the ice-covered seas.

Detection of oil spills by sensors that can cover large areas quickly and accurately are preferable. For open water spills this is achievable with satellite or airborne sensors, and results suggest that many of these techniques are expected to work for oil spill detection in very open drift ice, i.e. up to 3/10ths concentration. In heavier ice concentrations the sensor performance and detection capability limitations are unknown. As the concentration of ice increases the likelihood of oil being located under or within a sea ice cover also increases.

Despite some advances over the past few decades, researchers have been struggling to design a system that can remotely detect oil under sea ice (PEW, 2010). No operational system or service is presently available to remotely detect the presence of oil under sea ice. The limitations of the techniques associated with the remote detection oil within sea ice have been reviewed in a number of status reports e.g. EPPR, 1998; AMAP, 1998; Dickins and Buist, 1999; Dickins *et al.,* 2000; USARC, 2004, S.L. Ross *et al.,* 2010, Dickins *et al.,* 2010.

Most currently applied sensing methods are either flown above or coupled to the snow/ice surface, which requires that the sensor must ‘see’ through the sea ice and any overlying snow cover to infer the presence or absence of oil. Air, snow, and sea ice have very different physical properties that change on different temporal and spatial scales. Both snow and sea ice are particularly challenging to ‘see through’ due to a high degree of heterogeneity. For example sea ice salinity, density, thickness, morphology and surface properties are extremely heterogeneous both temporally and spatially.

Many of the proposed surface-based systems are entirely impractical for young ice or the conditions found within the marginal ice zone – broken and scattered floes, melting ice, and highly dynamic conditions. MIZ ice conditions are most likely to be encountered during oil exploration and commercial shipping activities in the summer months. Airborne systems can operate independent of ice conditions but they have strict safety related procedures when operating over sea ice and in low visibility, which minimises their operating window. Sea ice presents severe technical, logistical and safety difficulties for the detection of oil located under the sea ice from above.

Detection of oil from below using an appropriately instrumented underwater vehicle, on the other hand, avoids many of the difficulties experienced by surface and airborne techniques. These include:

(a) *Independence from sea-ice conditions*: Ice thickness, roughness, and other physical properties do not impede the progress or successful outcome of a survey conducted in the water below an ice cover.

(b) *Proximity to the oil:* Some types of AUV/ROV can get closer to the oil-water interface than any other non-invasive technique. For some sensor types this may allow a higher probability of successful detection.

(c) *Independence from atmospheric conditions:* The water conditions under the ice are usually quiescent and turbulence free irrespective of the weather conditions above the ice.

(d) *Measurable and stable ocean properties:* Aside from a thin surface melt layer in summer and a deepening of the mixed layer in winter the upper ocean properties do not change dramatically over an annual cycle.

(e) *Unimpeded view of the oil:* Perhaps most importantly, for oil below the ice, there is a direct view of the oil from the vehicle. This may enable the use of sensors routinely used on AUVs, yet largely untried for detection of oil from above the ice, to be used.

The detection of oil spills from under the ice is probably the least studied technological sector. This has been due to most oil spill detection studies being concerned with open water and not ice-covered seas, where an underwater approach has not been necessary. While the detection of oil from below may seem an obvious solution, it is a developing field and therefore there is a need to understand the advantages, limitations and challenges that still need to be overcome. These challenges include:

(a) Logistical support on the ice or from a vessel for AUV deployment and recovery.

(b) Challenges with deployment and recovery through small openings.

(c) Navigational challenges under a complex ice cover and potentially shallow water.

(d) Potential challenges in rapid response, as detection from below may become much more difficult as the oil becomes encapsulated in a growing ice sheet.

A single sensor that is able to detect oil under ice in different seasons, all sea ice types, as well as oil encapsulated in the sea ice itself, may not be possible. A multi-sensor approach may be necessary. This report summarises the existing and emerging oil spill remote sensing and mapping technologies that have the capability to detect and map oil spill in ice covered seas in Chapters 2 and 3. The strengths and weaknesses of each sensor are evaluated, along with multi-sensor approaches in Chapter 4. These sensors and suite of sensors are objectively ranked and the detection ability of the reviewed technologies based upon selection criteria and the logistics available in Chapter 5. Finally, in Chapter 6 we provide specific recommendations of those (best) technologies that would benefit from further research, development and testing.

CHAPTER 2. UNMANNED VEHICLES AS PLATFORMS FOR DETECTION OF OIL UNDER SEA ICE

2.1 Introduction

The last 50 years have seen a proliferation of deep submergence vehicles for academic, naval and commercial applications. Since their inception these vehicles have evolved to fill niches corresponding to routine survey, manipulation, and sampling tasks underwater (figure 2.1.1)

Figure 2.1.1 *Manned Submersibles and Remotely Operated Vehicles are heavily used in open ocean work but have seen limited use in under-ice applications.*

Underwater vehicles may be classified into three distinct classes. Manned submersibles, often called Human Occupied Vehicles (HOVs) are the classical bathyspheres that are used to transport a few occupants to the depths of the sea. Perhaps the most well-known example of this class of vehicle is DSV Alvin operated by the Woods Hole Oceanographic Institution. Most vehicles in this class are dedicated to scientific diving and require considerable infrastructure including typically a dedicated ship and myriad controls required with certifying systems that ensure the safety of all on-board.

Remotely Operated Vehicles (ROVs) are vehicles that are unmanned and operated with the help of a tether that connects them to operators working on a mother ship on the surface. These are by far the largest set of underwater vehicles and are used for a wide variety of applications including search and rescue teams of small boats in rivers, scientific users in the documentation and exploration of the seafloor and mid water column and for complex manipulative and survey tasks in the offshore sector. The market for such vehicles is highly segmented with a broad spectrum of products that include systems with of varying sizes, capabilities, and depth ratings with price ranges from five thousand to five million dollars. We note that the technologies associated with towed vehicles, i.e. a body that is towed behind with no other means of propulsion, are generally classified as ROV technology.

Autonomous Underwater Vehicles (AUVs) are unmanned, untethered robotic vehicles that are preprogramed assets that comprise a maturing technology. The absence of a tether makes them easier to deploy and recover and extends the range of the vehicle, but limits the real-time data feed based on the capabilities of acoustic modem systems that are carried on many AUVs. Untethered vehicles carry their own power supply. The length of AUV missions and the sensor payload is limited by the size of the power supply.

We note that these distinctions regarding underwater vehicles are somewhat arbitrary. Likewise there are several hybrid systems that crossover between ROVs and AUVs and will be the subject of elaboration further on in this study.

2.2 Autonomous Underwater Vehicles

For those who study the ocean, AUVs provide unique capabilities to explore what can be an extremely forbidding environment. Free of a physical surface tether, AUVs are able to perform surveys without human intervention, and many kilometres from a surface vessel (figure 2.1.2).

Figure 2.1.2 *The Autosub AUV (left), a large (4m) torpedo shaped AUV and the smaller (1.5m) Jaguar AUV, a hover capable multihull design. Both have been used extensively for under-ice mapping missions*

AUVs enable scientists from across the oceanographic disciplines to answer questions about the health of our nation's fisheries (Clarke et al., 2009), or learn the secrets of ancient ship and airplane wrecks. AUVs have operated in environments as diverse as lively Puerto Rican coral reefs (Armstrong et al., 2006), the world's longest aqueduct (Stokey et al., 2005), hydrothermal vents along the mid-oceanic ridges (Yoerger et al., 2007), and the Arctic seafloor (Sohn et al., 2008). This independence from a surface ship is a significant asset in polar environments, where surface movement of any sort is challenging and slow work. AUVs have proven to be particularly effective tools for under-ice research since they can range freely for great distances under the ice.

The Odyssey class AUVs were deployed through a hole in the ice in the Arctic in 1994 (Bellingham et al., 1994). In 1996, the Theseus AUV laid cable for an under-ice acoustic array over a distance of several hundred kilometers and then returned to its launch location (Thorleifson et al., 1997). More recently, the Autosub AUV flew a number of under ice missions in both polar oceans, including a 50 km mission beneath Antarctica's Fimbul Ice Shelf before being lost on a subsequent mission at that site (Perkins, 2006). This loss led to improvements in under-ice navigation strategies, and Autosub-3 has since successfully completed missions of similar length under the complex terrain of the Pine Island Bay glacier (Jenkins et al., 2010). Other projects include drift-ice studies (Wadhams et al., 2003), AUV and glider deployments under-ice (Lee et al., 2009). Our own efforts in this regard include the AGAVE expedition to the Gakkel Ridge (Sohn et al., 2008), and sea ice studies in both western (2010) and eastern Antarctica (2012) (Williams et al., submitted).

While the earliest of these missions involved skirting the edges of ice floes, autonomous vehicles now venture farther and farther under ice from their launch point as scientists and engineers seek to understand previously difficult to access or inaccessible under-ice environments. These technologies should translate to providing a platform that is suitable for oil spill detection under-ice.

As opposed to AUVs, ROVs and towed vehicles have far greater constraints in terms of working under-ice. Only small ROVs have been deployed for work under-ice and these have been limited by tether length to ranges of several hundred meters at most. One option in this regard is the role of hybrid ROV-AUV systems that are essentially AUVs connected to surface operators through a disposable bare fibre that serves to provide real-time feedback and sensing. These systems are being developed for under-ice work and have the potential of providing significant capabilities for under-ice oil spill detection and recovery. In the succeeding sections as we talk about the issues associated with the use of AUVs under-ice, these issues are also applicable to the new generation of hybrid ROV-AUVs that we expect to emerge in the next few years.

The fundamental issues that govern the use of AUVs under-ice include size, shape, requirements to survey seafloor versus the underside of ice, requirements for seafloor survey, pack ice or landfast ice, navigation under-ice, and the concepts of mapping in a dynamic environment. We now look at each of these issues in turn.

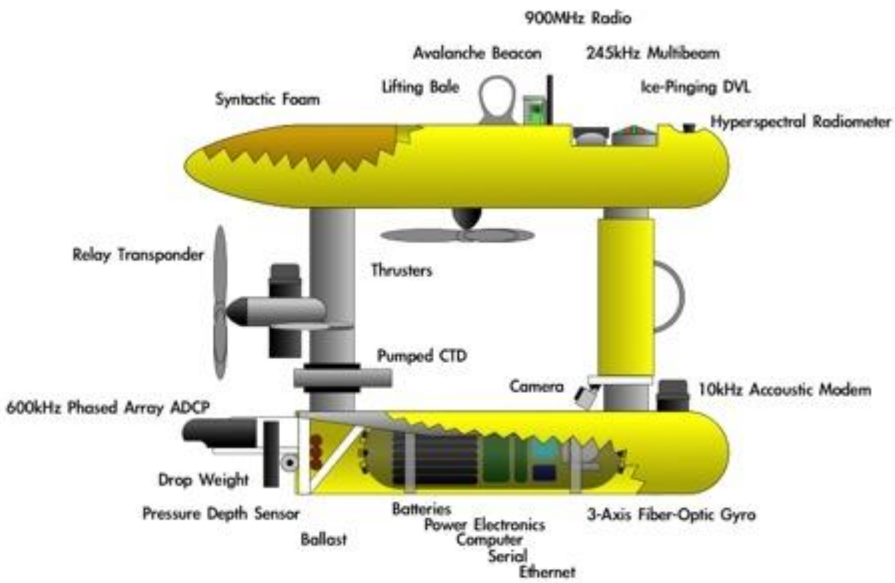


Figure 2.2.1 *The Jaguar AUV, one of the SeaBed class of vehicles developed at WHOI, configured for under-ice mapping. This configuration required the multibeam, ADCP and other sensors to face up towards the ice as opposed to looking down on the seafloor (courtesy P. Kimball).*

Large vs. small AUVs: The size of the vehicle is directly related to issues such as endurance. Within the constraints of existing systems, larger vehicles easily benefit from far greater endurance (range) than their smaller counterparts as they enjoy far greater battery capacity. However this range endurance is paid for with far greater complexity in terms of launch and recovery, and for issues such as transportation, and the overall system costs associated with acquisition and operations. Large AUVs are most suited for deployment and recovery in large open water areas or outside the ice edge for long missions into the pack. In comparison one could argue that the smaller AUVs are far easier to deploy and can easily support most of the existing technologies (from a navigation, computing and telemetry standpoint) and sensors (environmental, acoustic and optical). Because of the more limited range, smaller AUVs are sensible choices for deployments targeted at specific locations.

Torpedo vs. Hover capable shapes: The evolution of AUVs was to a large part originally dictated by naval considerations that required torpedo shaped vehicles. Such a shape is optimal for reducing drag as the AUV transits through the water column. However, this shape is not always optimal for working in rugged and harsh environments that one might see close to the underside of sea-ice. Torpedo shaped vehicles require flow over their control surfaces in order to maintain control. They cannot slow down, come to a halt, or back up as might be required for working close to rugged terrain such multi-year ice ridges or icebergs. Further recovery through a hole in the ice is easier to achieve with vehicles that are capable of moving slowly and coming to a stop (figure 2.2.1).

2.3 Acoustic communications

The bandwidth associated with state-of-the-art acoustic modems is limited by the environment to at best several hundred bits per second. This communication constraint ensures that the vast majority of data is not available until the vehicle has surfaced at the completion of the mission. If AUVs were able to communicate acquired survey data to surface operators, it would allow human operators to adaptively modify and optimize missions on the fly. Advances in acoustic communications are occurring, for example underwater specific compression schemes allow more data to be sent within the same bandwidth limitations. These were demonstrated during an environmental survey of the 2010 Deepwater Horizon oil spill by the Sentry AUV (Camilli et al., 2010). During that mission, individual readings from a mass spectrometer mounted on the AUV were transmitted to the surface ship in real-time. This limited, highly subsampled view of the data led to site selection and survey design, and a far more effective survey.

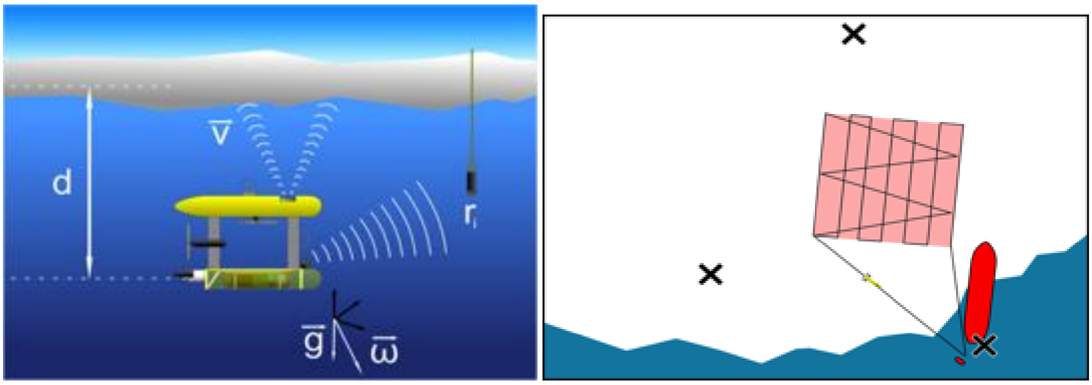


Figure 2.3.1 *Navigation for AUVs under ice typically involves inertial navigation systems coupled with transponders moored on the ice*

2.4 Navigation and mapping under-ice

A few researchers have discussed the design and performance of AUV navigation systems for polar latitudes. The navigation systems typically involve inertial navigation systems (which determine position from changes in vehicle velocity) and bottom-tracking Doppler velocity logs (which detect the vehicle velocity relative to the ice) augmented by acoustic transponders placed on the seafloor or moored in the ice. Over a long mission, Doppler velocity logs and acoustic transponders generally provide more precise positioning. On the other hand, placing of acoustic transponders within the ice may be logistically difficult, and maintaining a good Doppler velocity log is more difficult in broken ice conditions.

The fundamental challenge for sea ice AUV operations is that motion of the pack introduces a dynamic component to the mapping problem. While transponders fixed in the ice may move with the inertial frame associated with the ice under consideration, the AUV itself must drive with a true north heading reference that lies in an earth referenced frame that is independent of ice motion. While simple translational motions of the ice are relatively easy to deal with, the ice pack often undergoes significant rotational motion during the mapping exercise. As shown in the figure 2.4.1, even a small rotational rate can influence the overall mapping accuracy and consistency. The solution to dealing with the rotational motion is to instrument the surface of the ice with GPS receivers so that the motion may be compensated in post processing to arrive at a consistent map of the environment.

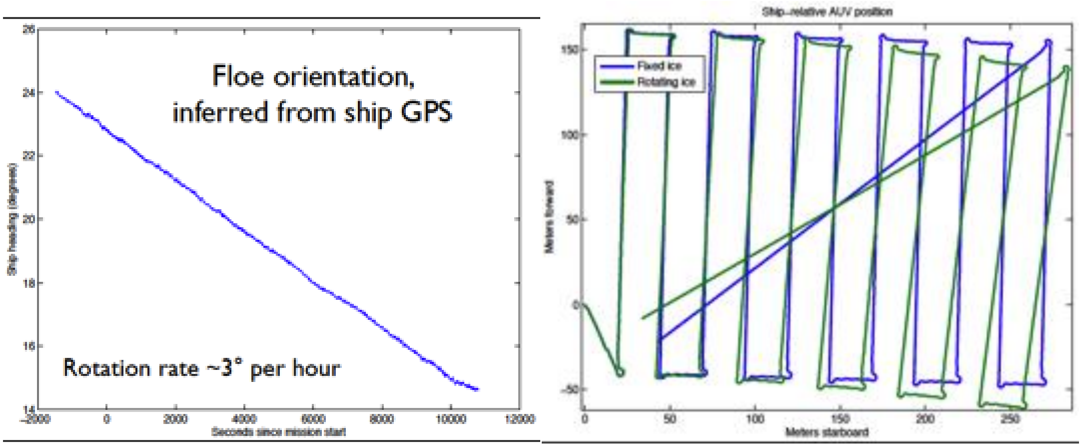


Figure 2.4.1 *The rotation of the pack ice can introduce significant errors in mapping the underside of sea ice. The right panel shows the correction to a "lawn-mower" survey under an ice floe that was applied to correct for floe rotation determined from GPS on a ship adjacent to the floe (left panel).*

2.5 Fixed Platforms

An alternative to UUVs for under ice detection is the use of fixed platforms, either on the ocean bottom or moored to the ice floe. Such platforms are attractive from the standpoint of their long history of use for other ice and oceanographic applications and the ability to monitor specific locations, like choke points, over a long period of time (months to years). In many, but not all cases, they offer simplicity of deployment and reduced cost (both in terms of platform and deployment logistics) over UUVs. However, they obtain data only at a single point and must be deployed by a vessel or on the ice, so offer little or no practical advantage for deployment in response to an oil spill. We are not aware of any efforts to use such platforms to detect oil under sea ice, but potential advantages and limitations of possible applications are briefly described here.

Standard oceanographic moorings can be deployed on the ocean floor with sensors looking up at the ice underside. These include upward-looking sonars, (Strass and Fahrbach, 1998), and current meters (Fukumachi et al., 2011). One advantage of bottom-moored instruments is that they can collect data continuously for months to years. A network of such moorings could monitor for potential spills in areas most likely for a spill to occur – such as in regions of intensive drilling activity.

However, bottom moored platforms suffer from a number of key weaknesses. They can only monitor at a single location; to monitor oil spills over wide areas would potentially require deployment of a large number of sensors. In areas of shallow water, such as are found on the Beaufort Sea shelf, ice scour of the bottom is widespread (Reimnitz et. al., 1978). Moored platforms are at a high risk of damage from deep keels from drifting sea ice in water up to about 40 m depth or from icebergs in deeper waters. Even in deeper water there is a high risk of damage for moored sensor which requires close proximity to the ice (i.e. less than ~ 30 m). Sensors deployed long-term to monitor for potential oil spills would require some means to telemeter the data to shore. For moorings beneath the ice, this is only possible through either a physical data link along the ocean floor, or through an acoustic telemetry network. Both systems would be also subject to potential damage from ice scour, and would be logistically difficult and expensive to maintain over larger areas or large sensor networks.

Moored platforms deployed as an oil spill response (as opposed to a long-term monitoring system) would require similar logistical support for deployment as UUVs, but would lack the spatial capability of the latter, and would still require a means of data telemetry.

Another possibility for long-term monitoring is ice-tethered platforms. These have seen recent widespread use in the Arctic to monitor the atmosphere and ice drift (Rigor, 2004), ice processes and properties (Richter-Menge et al., 2006) and oceanographic conditions beneath the ice (Krishfield et al., 2008). These platforms drift with the ice, so are not a good choice for long-term monitoring at a specific location (except on fast ice), and are subject to possible loss due to ice deformation. One advantage of ice-tethered platforms over bottom moorings is that telemetry of data is easily and inexpensively achieved using the Iridium or Argos satellite networks. As with bottom-moored instruments, ice-tethered platforms generally have limited spatial extent.

There is limited advantage of ice-tethered platforms for deployment in response to an oil spill, as the logistics required are similar to drilling through the ice (i.e. personnel must have access to the ice), except for sensors that might be deployed to detect undersea plumes or oil dispersed in the water column. Smaller air-droppable or ship deployed satellite transmitting GPS buoys deployed on an oil-contaminated floe can be used to track the floe until clean-up is possible.

Given these challenges, it is unlikely that fixed platforms can provide an efficient, effective solution for oil spill detection in ice-covered waters – particularly in the Arctic shelf seas. One potential application is their use for long-term monitoring of an area post-spill (either stationary or drifting with the oil and ice) to monitor the fate and dispersal of the oil, or for tracking purposes.

2.6 Summary

By the early 1960s US nuclear submarines had travelled over 50,000 km under the sea ice of the Arctic Ocean. At this time Dr. Waldo Lyon, the founder of the US Arctic Submarine Laboratory, stated that *'The Arctic Ocean has become the private sea of the submariner, who is free to move in any direction and at any speed under the ice covering the sea'.* AUVs have now matured to the point that this is no longer true. Advances in AUV and acoustic telemetry technology have rendered routine, operational use of AUVs in sea ice covered waters a possibility. While AUVs currently do not have the range or speed of nuclear submarines they do have many of the advantages the Dr Lyon advocated for submarine use under the Arctic sea ice, i.e., freedom from surface constraints. These benefits can be applied to the use of these vehicles as platforms to carry sensors that can detect oil under sea ice. The next chapter summarises these sensors.

CHAPTER 3. SENSOR TECHNOLOGY

A variety of techniques have been developed and tested over the last several decades for remote sensing of oil in open water – chiefly from airborne platforms. Some of these technologies are suitable for transition to use on AUVs, while other simple technologies (e.g. camera systems) may be more useful on AUVs than they are in many cases in open water. Still others have seen little to no use for oil detection but have a long history of use on AUVs for other applications and likely can be readily adapted for use in detecting oil. We will focus primarily on three promising sensor technologies – sonar, laser fluorescence, and camera systems. Other systems that may be useful either for oil detection capabilities (i.e. radiometers), or as auxiliary sensors that provide useful relevant information and should be included in a complete AUV-based sensor suite are also briefly described. In this section, each sensor technology is described with a focus on those aspects relevant for under ice work, and primarily with respect to detection of an oil slick pooled beneath the ice.

3.1 SONAR

Sonar is one of the most attractive candidate systems for detection of oil under sea ice from an autonomous vehicle. Above-ice acoustic techniques have received some attention for detection of oil spills, but results were not encouraging with the exception of Canadian trials in the 1980's utilizing transducers coupled to the ice surface (Jones et al., 1986). This is not an attractive solution for area surveys in moving pack ice. However, acoustic detection is a natural choice for an underwater platform that avoids the complexity of transmitting signals through a highly variable ice cover. The same platform offers the potential to be able to map oil under a variety of ice conditions, including the possibility of determining the thickness of the oil spill and detecting ice-encapsulated oil. A variety of sonars have been used successfully on underwater platforms for a variety of applications, including the mapping of the underside of sea ice (Wilkinson et al., 2007b). Recent work on underwater oil detection has shown that acoustic techniques can successfully detect oil in the water column, subsea, and under ice (Wilkinson et al., in prep). The choice of an appropriate sonar system will be determined by the acoustic characteristic of the system and target, which will depend somewhat on oil and ice conditions. Only very preliminary testing of underwater acoustics for oil detection under ice has been performed, so determination of an appropriate system, or systems, most suitable for deployment on an AUV platform merits much broader testing and development.

3.1.1 Background

The advent of the nuclear-powered submarines in the mid-1950s enabled under sea ice operations to be routinely performed in the Arctic Ocean, irrespective of ice conditions, weather or season without the need to surface. For operational safety there was a need to continuously identify areas of thin ice or open water above the submarine should there be a need to surface quickly. Sonars were used for this purpose, which has led to much interest in the use of a variety of sonar systems for studies of sea ice thickness distribution. A summary of advancement of upward-looking sonar technologies can be found in Wilkinson et al., (2007b).

3.1.2 Theory of oil detection under sea ice by sonar

Active sonars work by transmitting an acoustic pulse into the water and detects echoes from targets in the water. Targets can be material interfaces (such as the ocean bottom, ocean surface, or ice underside), objects of various sizes in the water column, boundaries between water of different density, or even different layers within subsea sediment. In the ideal case of a signal from a pencil beam sonar incident perpendicular to a flat sea ice surface, the strength of the returned pulse is determined by the difference in acoustic impedance between the two media:

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$$

Where R is the proportion of energy reflected, and n_1 and n_2 are the acoustic impedences of sea ice and water, respectively. Sea ice is a strong reflector of sound because of the acoustic impedance contrast between seawater and the ice bottom (Langelben and Pounder, 1970, and Table 3.1), although in the case of young sea ice with a porous growth layer on the bottom, the reflectivity is reduced (Stanton et al., 1986). From this table we can see that sea ice is a good reflector of sound propagating up from below because of the large contrast in acoustic impedance between seawater and ice. The values in Table 3.1 suggest that about 15% of the energy is reflected from a clean ice bottom, while 1-2% is reflected from an oil/water interface, with the remaining energy transmitted across the oil.

Note that there is an even stronger reflection across an oil/ice interface, so given that most of the acoustic energy will be transmitted across the oil, a strong return should also be evident from the oil/ice interface. By identifying the reflection from each of these interfaces as the first rise in the time series of returned acoustic energy, it is possible to obtain a time series of distance to each interface, and thus a time series of the thickness of the layer of oil can be formed as the difference between those two distinct distance measurements.

Material	**Impedance (**10^6 kg m^{-2} s^{-1}**)**
Air (P = 1 bar, T= 20 °C)	4 x 10^{-4}
Ice	3.5
Seawater (S=35, T=-1.5 °C)	1.48
Petroleum	1.07
Crude oil	1.3

Table 3.1 *Typical acoustic impedances for materials encountered in the experiment (Jones, 2010; Langelben and Pounder, 1970).*

Of particular importance is that a significant portion of the acoustic energy will be transmitted into the ice, raising the possibility that different strata within the ice, i.e. oil encapsulated within the ice, might be detectable, although this will depend on attenuation and scattering of the acoustic signal within the ice.

In practice, the interpretation of the signal may not so straightforward. The ice underside is invariably rough, with thickness variations occurring at a number of scales from small-scale roughness on the order of centimetres for smooth level ice, to variations up to several meters that can occur over distances of as little as a meter (see section 3.6.2). Small-scale inhomogeneities, either at the interface or due to brine inclusions within the ice, will alter the reflectivity and scatter acoustic energy (Stanton et al., 1986) so that the returned signal will be determined by the interaction of the emitted pulse with a variety of surfaces and scatterers.

If there is significant penetration of the acoustic energy into the ice, there may also be multiple returns from within the ice itself. In addition, all sonars exhibit some finite beam spread, so the pulse will act over a finite area. Scattering depends strongly on the angle of incidence, so the signal will be a function of shape of the interface and will vary with the orientation of the sonar (which will always vary somewhat due to motion of the vehicle) there may be multiple returns (known as multipath) from a variety of scattering interfaces. Even pencil beam sonars with a beam spread of only 1 degree the horizontal resolution will be over 10 cm for most practical depth ranges for an AUV mission.

Acoustic scattering theory is well developed so that in principle, for a given scattering signature, a return from oil, or a thin layer of oil beneath sea ice could be positively identified and distinguished from a similar return from a clean ice surface. For real-time processing, this is impractical, and comparison of calibrated acoustic returns with look-up tables with known scattering signatures may be a more feasible approach. In practice, given the probability of strong returns from the oil/water interface and the oil/ice interface the most promising method of positive oil detection is the detection of the presence of both. The strength of this method is that it can also detect the thickness of the oil. This determines the choice of sonar by its ability to resolve closely spaced acoustic returns, although under a rough ice surface, the tendency of oil to pool in hollows under the ice to much greater thickness than in the open ocean lessens this constraint.

3.1.3 Sonar Systems

A wide variety of commercially available and research sonars exist for a wide variety of applications. The characteristics of a sonar system that determine its suitability for detection of oil include (1) the beam pattern (beamwidth, shape, and sidelobes), which, in part control the spatial resolution, (2) frequency, which determines the attenuation rate and hence the useful operational range, and to some degree also controls the pulse width, which determines range resolution for narrowband systems, (3) the bandwidth, which controls the range resolution for broadband systems, (4) scanning method, which determines the utility for acoustic imaging of the ice underside, and (5) the size and power consumption of the system, which limits practicality for integration in to an AUV system.

Sonar systems can be broadly classified into several types:

1. **Rangefinders** and **single-beam** narrowband **echosounder sonars** generally operate at a single frequency (although some models are somewhat tuneable, with some degradation in performance) and typically have narrow beams to minimize energy loss due to beam spread and achieve good spatial resolution. **Range finders** generally are single return systems – so provide the distance to the first significant reflector. **Profiling sonars** return the entire acoustic response, providing a backscatter profile through the water column and thus may be used to detect multiple interfaces or objects. Single beam sonars may mechanically scan, so that they can provide backscatter information from a variety of directions.

2. **Multibeam sonars** use multiple beams from a compact transducer array with simultaneous detection of all beam echoes by the receiver (known as electronic beam forming and detection). These are capable of providing a high-resolution swath map along the direction of travel of the vehicle. Detailed knowledge of how the sound speed varies with depth in the water column above the sonar is required because the ray paths from the oblique parts of the beam are usually not straight due to refraction from by the sound speed gradient, and ray path analysis may be needed to calculate the correct depth and location of soundings taken away from the vertical. Multibeam sonars may be configured as first return systems (e.g. for mapping the ice underside or seafloor), or can provide full backscatter information (e.g. the Reson Seabat system). The latter will require greater processing by the user. For some systems and applications, these are referred to as multibeam imaging sonars, or simply **imaging sonars.** These systems (for example, Blueview 2D and 3D imaging sonars) are commonly used where high-resolution, camera-like imagery. 2D systems are commonly used for inspection and obstacle avoidance applications on UUVs. 3D systems can produce point cloud data that can be used to construct a 3D representation of the target.

3. **Side-scan** sonars are used to map the seafloor and offer an alternative to multibeam sonars. Rather than detecting reflections along many individual beams, a single wide beam is used. The timing of the returned echo and its strength in the cross-track direction are used to construct an image of features on the seafloor. Basic sidescan systems cannot provide precise ranges to features, so are less practical than multibeam sonars for mapping the underside of ice floes. Variants of this system include **synthetic aperture** side-scan sonars that use multiple views of features in the along-track direction to produce images with improved resolution in that direction. **Interferometric sonars** are side-scan sonars that use phase information to determine the angle from which the returned signal arrives, and thus can provide more precise location information.

4. **Scientific Echosounders** are echosounders with high range resolution, large dynamic range, and the signal strength can be calibrated, allowing classification as well as detection. These can detect, classify, and quantify 1) small individual targets (e.g. fish), 2) volume scattering (e.g. scattering from zooplankton patches or microstructure), and 3) layer scattering (e.g. interfaces at which there are density and/or sound speed contrasts), based on the calibrated backscatter strength. Narrowband, multi-frequency scientific echosounders are routinely used to detect and quantify targets (individual or volume scattering). Broadband scientific echosounder systems and techniques are being developed to quantify targets in the water-column spanning a range of sizes, such as oil droplets, ocean microstructure, fish, bubbles, or zooplankton (e.g. Lavery et al., 2010).

5. **Sub-bottom profilers**. These use powerful, low frequency (<10 kHz) transducers that can penetrate into the seafloor to determine bottom stratigraphy. These may be narrow-band or broadband. These typically use very large transducers, often in dedicated towfish, so are generally impractical for small to medium sized UUVs. These generally have low spatial and vertical resolution. **Parametric sub-bottom profilers (**such as the Kongsberg TOPAS systems), use two relatively high frequency transducers. The non-linear interaction of the two beams produces a low frequency, broadband, narrow beam with no sidelobes. This

provides high spatial resolution and good range resolution. It also produces a low frequency beam (and thus good penetration) with a much smaller transducer than would be required for a standard low frequency system. This raises the possibility of using such systems on AUVs (e.g. the SEApara system currently under development). Despite these advantages, the range resolution of most existing systems is still relatively low (~10 cm).

Most of these, or the principle involved, may be useful to some degree in the development of a system for detecting oil under ice. Single beam echosounders are the most promising due to their ability to obtain high-resolution (in range and horizontal) multiple return information and determine oil thickness. Mapping and imaging sonars may be useful for characterising the ice underside (see Section 3.6.2). Characterization of backscatter would be useful in situations where the oil might be dispersed in the water column, such as for a well-head blowout or pipeline rupture. Adaptation of sub-bottom profiling techniques may be useful to detect encapsulated oil, although the strong attenuation of acoustic energy in ice will likely limit the depth at which encapsulated oil might be detected within the ice to no more than a few centimetres (Melling, 1998). At very low frequencies, this penetration might be improved, but at the expense of range resolution.

The frequency of a narrowband system limits both the practical range, range resolution, and the ability of the sonar to penetrate into the ice. The attenuation of sound in water and ice is a strong function of frequency. For the range requirements for AUV operation (up to 10-30 m) this may limit the practical choice of the highest frequency to about 1 MHz. The range resolution of a single frequency sonar is determined by the pulse width, which is partly limited by the frequency, although longer pulses transmit more power. For a sonar frequencies > 1 MHz, range resolution can be as low as a few mm, so that in practical applications oil slick thickness beneath ice can be determined. However the range is limited by both attenuation and transmitted power for short pulses. Most systems transmit longer pulses (and hence, more power) and have range resolution of about 1 cm (e.g. the Imagenex 881A at 675 kHz). There is then a trade-off between resolution and range. That limits useful narrowband frequencies to ~300-1000 kHz, which, in turn, limit the ability of the sonar to penetrate into the ice.

An alternative is to use broadband sonars that frequency modulate the pulse (known as “chirp”). Here the range resolution is determined by the inverse of the bandwidth, so that fine range resolution is achievable with lower frequencies, and hence a longer range and the potential to penetrate into the ice to detect encapsulated oil. Broadband systems additionally result in improved quantification of targets because of the ability to capitalize on the frequency response of the target. There are only a limited number of commercially available broadband systems, and all are fairly large with high power requirements. But recently a miniature, autonomous, and relatively low-power (compared to alternative active sonar systems) system was developed at Woods Hole Oceanographic Institution and successfully deployed on a REMUS-100 AUV for the detection and quantification of small organisms and internal waves in the ocean (Lavery et al., 2010). This system continues to be developed.

3.1.4 Trials of sonar systems for oil detection underwater and under ice

Upward-looking sonar (single beam, side-scan and multibeam) are routinely used on under-ice submarine and AUV operations (e.g. Wilkinson et al., 2007b). At present we are not aware of any upward looking sonar system that has been deployed on an underwater vehicle to directly detect oil under sea ice As with most techniques involved in the detection of oil under ice from below there is very little literature available on the use of sonar to detect oil under sea ice. What little work has been done on the use of acoustics to detect oil under ice from above has shown that oil can be detected (Jones et al., 1986). This technique exploited the fact that both compressive and shear waves can transmit through solid ice, but only the compressive wave will reflect from the oil/water boundary. As such, this technique cannot be used from an AUV. There have been some recent trials of the feasibility of detecting oil using sonar underwater to detect oil, both on the sea floor and in the water column.

Backscatter systems have recently been used to investigate the Deep Water Horizon oil spill. 18 and 32 kHz echosounders, and a 30 kHz multibeam sonar with water column capability were used to detect hydrocarbons in the water column in conjunction with fluorometers (De Robertis et al., 2011). Ongoing work at the Virginia Institute of Marine Science is being done to develop techniques to determine droplet size with acoustic techniques. Acoustic Doppler has also been used from an ROV to determine flow rate from the Macondo well (Camilli et al., 2011).

The Sonardyne Automatic Leak Detection Sonar (ALDS) is a recently developed system designed to detect oil and gas leaks in subsea pipelines. At the time of writing, it is not clear what principle of detection this system uses. In a semi-permanent installation, it is claimed that detection of volumes of less than 1 barrel per day are detectable at ranges of 500 m. The system is small enough that deployment from an ROV may be practical.

While the above techniques show promise for detection of oil in the water column, for oil trapped immediately beneath ice (or even within the ice), the principle of detection will be different due to the close proximity of the strongly reflecting ice underside. Tests have been carried out with a Reson Inc. 7125 SeaBat 400 kHz multibeam echosounder at the National Oil Spill Response Research & Renewable Energy Test Facility (Ohmsett) in Leonardo, New Jersey, to distinguish heavy oil on the seabed from sand or other bottom material (Hansen et al., 2009). With the system calibrated, the system first produces a topographic map from the seafloor, and then backscatter strength from signals below that boundary were compared to a reference angular response curve for black oil for positive identification. This technique might be transferable to oil under sea ice, where the topography will be of the ice and oil underside, and backscatter from the oil/water or ice/water interface can be used to positively distinguish oil from ice. One advantage of this instrument is the ability to obtain backscatter in the water column as well.

To our knowledge, the only experiment designed to test the ability of an AUV-mounted sonar to detect oil spilled beneath sea ice was carried out by the authors at the US Army Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, USA in January, 2012 (Wilkinson et al., in prep).

During this experiment oil was injected under sea ice and an upward looking sonar (Marine Electronics 11001 multireturn rangefinder at 1.1 MHz) and other instruments were deployed on a trolley system beneath the ice in which the oil was injected under. Results suggest that the sonar was able to document the exact time the oil flowed over the region insonified by the sonar (red dotted line in figure 3.1.1) and monitor the increase in oil thickness over time. Initially the slick was very thin (around 2 mm), however within a few tens of seconds it reached a thickness of about 10 mm. A second oil injection, about 90 minutes after the first, was introduced and this also was clearly seen by the sonar. The second spill deepened the oil-water interface by about a centimetre. By examining the variability in the acoustic signature it may be possible to detect the difference between oil that was flowing along the bottom of an ice cover and oil that was motionless.

The detection of oil under sea ice exploits the different acoustic impedances between oil, ice and seawater. These differences led to a distinctive signature of the acoustic signal returned from the seawater, crude oil, and sea ice interfaces. Although these laboratory observations were conducted for the simplest conditions (flat, unbroken ice in freezing conditions with a single frequency, uncalibrated sonar), the findings demonstrate that the acoustic detection from below of the layered structure (seawater-oil-ice) associated with an oil spill under sea ice is indeed possible.

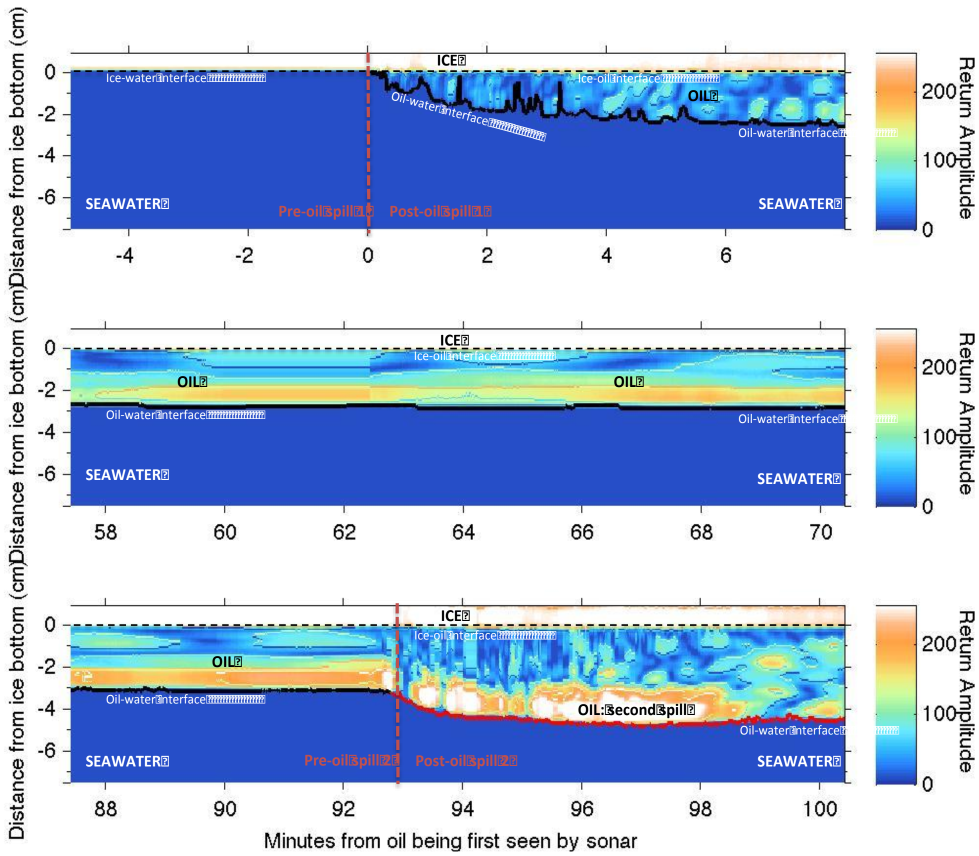


Figure 3.1.1. *Time series showing the return amplitude from the upward-looking sonar during its deployment under the sea ice and the resultant oil spill. Results show clear detection of both the oil layer and the ice underside. The return amplitude is color-coded with high amplitude returns being white and low amplitude returns in deep blue. The black dotted line is the ice bottom, while the solid black and red lines represent the oil-water interface. Flowing oil and thickening of the slick can be detected a few minutes after deployment (top), with a stable signature when the oil was immobile (centre), and a thickening again when the second spill reached the insonified region (bottom).*

3.1.5 Advantages, limitations, and summary

There are a number of advantages associated with the sonar technique. These include:

- Preliminary work under level ice suggests that, under ideal conditions, identification and determination of thickness of oil located under sea ice are unambiguous and relatively easy to interpret and require minimal processing of the acoustic data. This simplifies real-time identification as interpretation based solely on backscatter signature would require more intensive processing.

- Acoustic techniques are promising for detection of oil in all situations, including under continuous ice, open water, in the water column, on the sea floor, and potentially even encapsulated within the ice (although there are challenges and this has not been evaluated).
- There is a wide variety of 'off-the-shelf' systems developed for oceanographic applications as well as on-going development that is directly transferrable to oil detection under ice. There is potential to use the benefits of different system characteristics in tandem to improve oil detection.
- Many sonar systems have been adapted, and continue to be adapted, specifically for use on AUVs.
- The oil and shipping industry are familiar with the use of sonar technology.

There are no particular difficulties with this technique with respect to weather conditions or the season. Many sonar systems are currently too large for deployment on many AUV or ROV platforms, but there have also been many systems specifically designed for use on AUVs. Power requirements may be a limiting factor. Some potential issues that need to be addressed with further laboratory, field testing and development include:

- **Complexity of the ice morphology**. Backscattering from the complex ice/water interface and variations in the backscatter due to the interaction of the sonar beam pattern, morphology, and angle of incidence complicate the interpretation of the returned signal. For sonars with wider beam patterns (i.e. lower frequency) this will limit the effective vertical resolution as acoustic energy will be returned from features at different ranges.
- **Frequency and range resolution.** There is generally a trade-off between range resolution and attenuation. To achieve resolutions fine enough to determine the thickness of thin pools of oil (a few cm), frequencies in the MHz range may be necessary. Broadband systems obviate these issues. Some limited development of broadband systems compact enough for deployment on AUVs has been undertaken, although further development is required.
- **False positives.** There are a few circumstances that may produce oil detection false positives, such as where layered structures such as rafted ice with gaps, or under ice melt ponds might return an acoustic signature sufficiently like that of Figure 3.1.1 to produce a false positive identification for oil.
- **Ice encapsulation.** Ice is a strong reflector of acoustic energy and acoustic energy attenuates rapidly within ice. This strong attenuation may make it impractical to use sonar to detect oil that is encapsulated within the ice, especially deep within the ice. Low frequency broadband systems may be useful to detect oil newly encapsulated in ice due to their greater penetration versus higher frequency systems and improved range resolution over narrow-band systems.
- **Acoustic impedances variations.** Variations in acoustic impedance might occur due to interaction of the oil with the porous brine network in sea ice and encapsulation. For a calibrated system, this may be useful help detect the presence of slicks that are too thin to resolve the thickness from the multiple interfaces and that may have penetrated into the ice.

3.1.6 Recommendations for development of a sonar system

Based on experiments performed to date, and the capabilities of various sonar systems, further investigation and development should follow three key avenues: (1) determination of the appropriate sonar sensor, or sensor suite characteristics, (2) adaption of techniques for 3-D mapping of ice thickness to mapping of oil spills, and (3) evaluation of feasibility for detection of encapsulated oil and oil in a variety of ice conditions.

<u>Sonar system choice</u>: Laboratory testing of multiple sonar systems under realistic oil and ice conditions is required to determine the optimal choice of sonar characteristics, and in particular calibrated determination of the backscatter signal from oil slicks under ice, and testing of broadband systems. Ultimately, an operational system might include more than one sonar so that optimized solutions can be achieved for oil pooled beneath ice, in open water, and in the water column. Once the optimum system has been determined, further development for miniaturization and reduced power-consumption appropriate for extended use on an AUV will most likely need to be undertaken.

<u>3-D thickness mapping of oil spills</u> can be achieved through adaptation of techniques developed to map the ice underside using multibeam sonars (e.g. Wadhams et al., 2006). This could involve an adaptation of the techniques used at the Ohmsett test facility (www.ohmsett.com) of the Reson SeaBat system (Hansen et al., 2009) and make use of backscatter variations, or might make use multiple returns along individual beams to detect oil thickness.

<u>Encapsulated oil and variable ice conditions:</u> Testing of low to moderate frequency sonars and broadband systems is warranted to determine the penetration of the acoustic signal into ice and the resultant backscatter signal from encapsulated oil as a function of depth in the ice. While tests show much promise for acoustic detection of oil trapped beneath continuous, level ice cover a versatile system should be capable of detection under a variety of ice conditions, including in the vicinity of ridged ice and in brash and broken ice, where much of the oil may be present in the open water between floes. Potential variations in signal under conditions of growing or melting ice also need to be carried out.

3.2 Ultraviolet Fluorescence

3.2.1 UV Fluorescence from oil

When excited at ultraviolet (UV) wavelengths (or, alternatively, at longer wavelengths), oil is known to fluoresce across the visible spectrum with spectral responses that are may be distinguishable from that of other organic matter. Laser fluorosensors have been investigated for over four decades for their utility in detecting thin oil slicks on the ocean surface. These have focused primarily on airborne systems, with at least one system now used operationally. Among the attractive feature of this technique are that it can be done in day and night conditions, the thickness of the slick can be determined for very thin slicks (less than about 20 microns), it can detect oil on a variety of surfaces (including snow and ice), and uniquely among remote techniques, it can discriminate among difference types of oil. Laser fluorescence may potentially be a useful technique to help detect thin slicks under ice, hydrocarbons in the water column beneath ice, or even ice-encapsulated oil. It is almost entirely untried as a method of remote detection (i.e. for distances of several to tens of meters) for underwater sensors. Potential technological challenges to be overcome for deployment from an AUV or ROV include the need to develop small, low-power sensors, the effects of scattering and absorption of light within the water column between the sensor platform and the base of the ice (by both the water and any biological material or sediment), and the ability to discriminate the fluorescent signal from that of other fluorescing compounds (e.g. algal mats common on the bottom of summer sea ice), or the typically much brighter ambient light in the daytime.

A wide range of organic molecules, including oil and other hydrocarbons, exhibit strong fluorescent behavior when excited by ultraviolet light – i.e. they absorb light at one wavelength, and emit light at, typically, a longer wavelength. In principle, the characteristics of the emitted spectra of the substance can be used to identify, and quantify, its presence. This property has been used extensively in oceanography to determine concentrations of algae or dissolved organic matter (also known as CDOM, or Gelbstoff). Oil and other hydrocarbons exhibit characteristic spectra when excited in the UV (e.g. Hengstermann and Reuter, 1990, Patsayeva, 1995). Crude oil exhibits a broad peak between 400 and 550 nm, centered at about 480 nm when the excitation frequency is in the range 300-360 nm. Lighter oils tend to exhibit peaks at shorter wavelengths (Figure 3.2.1). Like many substances with complex, long chain molecules, the spectral response is broad, typically with some signal detectable across the full visible spectrum (except at energies higher than that of the excitation source, i.e. longer wavelengths). This property means that, in principle, oil fluorescence could be detected when excited with longer wavelengths – an advantage for undersea remote sensing – but at the expense of fluorescence intensity and reduced spectral response. The spectral response tends to vary depending on the excitation wavelength. This behavior can be exploited to discriminate oil from other fluorescing compounds.

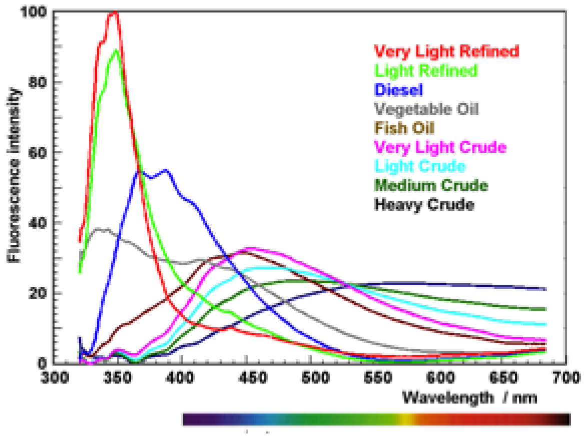


Figure 3.2.1 *Typical fluorescent spectra for various types of oil for an excitation at 308 nm (Source http://www.seos-project.eu)*

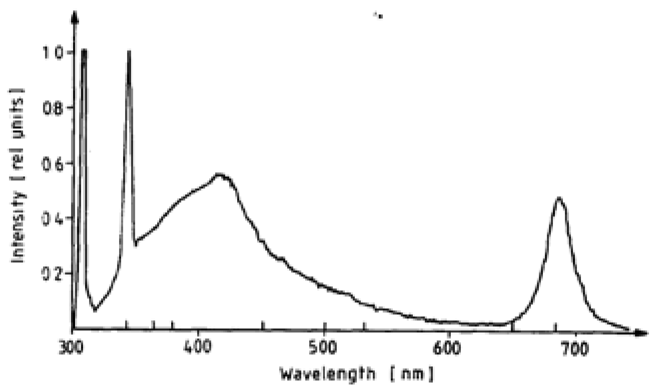


Figure 3.2.2 *Emission spectrum for natural seawater excited at 308 nm. Peaks at 308 and 344 nm are due to elastic scattering and Raman scattering. The broad peak centered at 420 nm is due to CDOM. The peak at 685 nm is due to chlorophyll-a emission (Source: Hengstermann and Reuter, 1995).*

The major complications for detecting oil, particularly for applications where oil is within the water column, is the presence of other organic matter which also fluoresces (CDOM and algae), and absorption or scattering of the source light by material suspended in the water column or by the water itself. The emission spectra of natural organic matter is somewhat distinct from that of oil (figure 3.2.2), and appears to be more affected by variation in the excitation wavelength than oil (Patsayeva, 1995) so that CDOM may in principle be distinguished from oil. The Raman scattering peak due to scattering of UV by water (figure 3.2.2) can also be useful for determining the thickness of very thin oil slicks by comparing the attenuation of the Raman peak through the oil slick with the Raman peak in oil free areas (e.g., Hengstermann and Reuter, 1990, Jha et al., 2008). For oil thicker than a few tens of microns, UV is completely absorbed by the oil, so this method of quantifying thickness is unlikely to be useful for surface slicks trapped beneath ice because, in most situations, the oil will tend to pool to much greater thicknesses as it is trapped by the irregularities in the ice thickness.

The variation in spectral response of oil to the excitation wavelength can be exploited to discriminate amongst different fluorescing compounds. In emission-excitation matrix spectroscopy, the emission spectra are detected for a range of excitation wavelengths, and a two-dimensional matrix of the response is produced (e.g. Muroski et al., 1996). A similar alternative technique known as total synchronous fluorescence (Patra and Mishra, 2002) can reduce the effects of Raman and Rayleigh scattering. Detection of the full-spectrum of emission intensity at a range of emission and excitation wavelengths may be impractical for a miniaturized AUV based system. An alternative to obtaining the full emission spectrum is to look at the ratio of emission at two or more wavelengths, similar to that used in optical techniques to detect phytoplankton in the ocean. This technique, known as fluorescence intensity ratio (FIR) is often useful for detection of low concentrations of oil as the ratio of the fluorescence intensity should not change with concentration. Due to the need to filter to improve the sensitivity, reliably discriminate oil from CDOM, and to be able to discriminate different classes of oil, techniques that use detection and excitation at different wavelengths may be preferred. This may be difficult to achieve with the power and payload limitations of an AUV.

Two additional techniques have been developed that take advantage of two additional properties of fluorescing oil. Time Resolved Fluorescence (TRF) is a technique that examines the temporal response of the fluorescence to discriminate different fluorescing compounds, as the rate of decay of fluorescence will vary for different compounds and with wavelength. As the decay time for oil fluorescence is very fast (tens of nanoseconds), the low signal strength for remote sensing application may make this technique less practical for an AUV-based application. Lastly, fluorescence polarization (FP) may be an effective technique for detection of oil under ice from an AUV. This exploits the fact that if excited by linearly polarized light, only those fluorophors aligned with the polarized light will fluoresce, so that at least some of the ambient light can be removed with a polarizing filter. The polarization depends on the viscosity of the substance, so that, for example, heavy oil will display more fluorescence polarization than other substances (such as DOM), so the confounding effect of biological material can also be mitigated. This technique then mitigates two key challenges for an AUV-based system under ice - the problem of ambient light saturating the detector, and the confounding effects of other organic matter beneath the ice.

3.2.2 Fluorometers

For oil dispersed in fine droplets in the water column, there are well-established commercial products originally developed for measuring chlorophyll and DOM (e.g. Turner designs C3 submersible fluorometer). These are inexpensive, compact, and can be readily integrated into an AUV/ROV platform (indeed fluorometers are routinely among the sensor payload on AUV/ROVs). These typically operate by detecting fluorescence in the water immediately adjacent to an optical sensor. This is useful for detection of very low concentrations of hydrocarbons (< 1-10 ppb). However, they cannot be easily adapted for remote measurement, so are not practical for detection of oil pooled under sea ice. They may be very useful for detection of oil near spill sites or in more turbulent waters where few other sensor may be effective at detecting low concentrations of oil dispersed in the water, or as an indicator of the possible presence of larger quantities of oil trapped beneath ice where positive determination can be made by other sensors in the vehicle payload.

Alternatively, fine droplets of oil in the water column can be detected using particle size analyzers (this is not a fluorescence technique). A Laser In-Situ Scattering and Transmissometer (LISST), The Sequoia LISST-100X measures size distribution of small particles in water using laser scattering and transmission over a wide range of particle sizes. These sensors have the advantage of determining the droplet size alongside the concentrations of oil in the water. These sensors were effective in determining droplet sizes of ~10-400 microns in dispersant tests at the Ohmsett facility (SL Ross, 2011) and sizes less than 70 microns at the Deepwater Horizon spill (Li et al., 2011).

Airborne laser fluorosensor systems have been described in a number of reviews (e.g. Brown and Fingas, 2003, Jha et al., 2008, SL Ross et al., 2010), so will not be discussed in detail here. A typical system consist of one or more commercially available UV lasers, in the 300-380 nm range, such as a XeCl (308 nm) or XeF excimer (351 nm) laser, nitrogen laser (337 nm). Some systems will also include a visible laser for optical excitation (e.g. 480 or 532 nm), which will induce fluorescence to a lesser degree than UV light. The fluorescence is generally received through a telescope connected to a photomultiplier and spectrum analyzer, a gated intensified diode-array detector, or with an intensified CCD camera. Existing airborne systems are far too large to be adapted for use on an AUV/ROV platform, and are very expensive ($300K-$2000K) (Jha et al., 2008). The need for extensive onboard processing to obtain real-time data also limits their adaptability for an AUV deployment. In ice covered-waters, an airborne system may still be the most practical in loose pack ice to be able to detect the oil found in open water.

Despite these challenges, there are several reasons that investigation of a laser fluorosensor for an AUV platform may be practical. If successful, such a sensor could detect oil in practically any concentration or ice conditions, including oil trapped beneath the ice, suspended in the water column, and potentially even encapsulated within the ice (where detection remains a challenge for all other sensors), and under continuous ice, brash, or loose pack. Although attenuation in the water column may be a major issue (see below), an AUV can operate within 10-20 m of the ice, or less, depending on ice conditions – much closer than airborne surveys, and so a smaller, more compact sensor may be practical.

3.2.3 UV fluorometers for underwater detection of oil

Little work has been done to develop a laser fluorosensor for underwater use, particularly for under ice. The primary challenge with an underwater system is the attenuation of UV light in the water column. To our knowledge, the only attempts to detect oil fluorescence through an ice cover from above was by Moir and Yetman (1993) and Dickins and Buist (1981). Using a 360 nm xenon lamp ultraviolet source coupled with a photo-diode detector system, Moir and Yetman (1993) were able to detect oil by induced fluorescence under fresh-water ice up to 1 m thick and sea ice up to 0.8 m thick. However, in the presence of a snow layer of a few millimetres thickness or more, no positive oil detection was possible. As sea ice is almost invariably snow-covered, the use of this method from above is not widely applicable. This result does suggest that detection of ice-encapsulated oil may be possible from below.

The primary issues with remote-detection fluorescent systems are that DOM and chlorophyll can attenuate the source and signal light, as well as confound the detection of oil (particularly for single-frequency excitation). Also, the UV source is attenuated and scattered by the water itself. Below about 400 nm, attenuation by the water becomes important, so that UV-lasers with significantly lower wavelength (e.g. 308 nm of some Xenon excimer lasers) are not a practical choice. Ambient light also becomes an issue in the daytime, although this is mitigated if operating under thick ice. Underwater laser fluorosensors have recently been investigated for biological studies. A ship-based system has been demonstrated for discrimination of live and dead coral at depths of up to 30 m (Sasano et al., 2012). A system is currently under development at the University of St. Andrews, UK, for detection of algae at the base of sea ice (T. Boyd, pers. comm).

Limited success with a laser line scan system to detect submerged oil was achieved in ice tank tests at Ohmsett (Hansen et al., 2009). These tests are the most directly comparable to the conditions that might be expected for an AUV-based system under sea ice. They mitigated against UV attenuation by using a 405 nm violet laser. While somewhat above the preferred wavelength to induce fluorescence, the availability of high-powered violet lasers and superior attenuation in water versus true UV lasers makes such a system preferable. The primary difficulty encountered by Hansen et al., (2009) was signal saturation due to solar radiance.

One solution to the issue of ambient light that was tested at the Ohmsett facility is to use fluorescence polarization (Hansen et al., 2009). Heavy oils containing higher molecular weight polynuclear aromatic hydrocarbons fractions exhibit strong fluorescence polarization, thus enabling discrimination from biological material. Tests at Ohmsett (Hansen et al., 2009) demonstrated that fluorescence polarization, using a 532 nm excitation wavelength, can effectively detect oil at a distance of a few meters with a reasonably compact system. Some issues with ambient light remained. The much-reduced solar radiance in the under-ice environment may be a distinct advantage over an open water environment, and in many instances, the search may necessarily be carried out in low light or darkness. Phase sensitive detection can provide excellent rejection of sunlight (Bello and Toomey, 2012). This system has recently been developed in a compact package suitable for integration into an AUV or ROV system.

3.2.4 Summary

In-situ detection of oil in the water column is well established with compact, commercially available fluorometers that can be easily integrated into an AUV system. Remote sensing of oil trapped beneath ice at distances of up to 10-20 m is more challenging, and will require design of a compact, low power system. The fluorescence polarization system developed by EIC laboratories (Hansen et al., 2009) had a length of 20 inches and weighed 16 pounds, which is approaching a size feasible for deployment on a variety of existing AUVs. In some cases where attenuation of light is high due to organic matter (such as is common in summer), laser fluorescence may not be practical. In other seasons, Arctic waters tend to be very clear and such a system may well be feasible. What tests of underwater systems have been carried out have demonstrated that detection of oil (or, equivalently, other organic material) is feasible at ranges of up to 30m, suggesting that attenuation of the source or signal in the water column may not be a limiting factor. The use of a modulated pulse and fluorescence polarization may aid discrimination of the signal from ambient light. The primary challenge may be in the development of an appropriate compact system (figure 3.2.1).

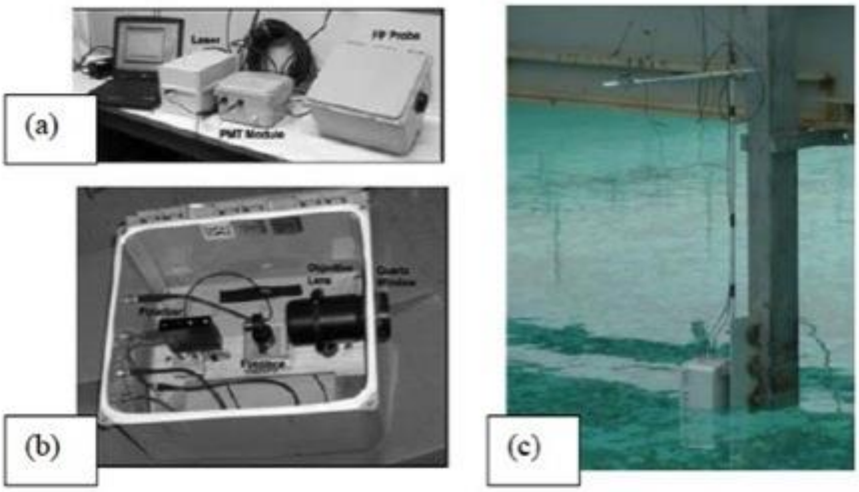


Figure 3.2.1. *An example of a recently tested prototype UV Fluorescence polarization system tested at the Ohmsett facility (from Hansen et al., 2009). This system was developed into a prototype system by EIC laboratories.*

It is expected that this method will be of most value for conditions in which small quantities or thin layers of oil are entrained into the porous basal layer of ice or in a brash ice environment where other techniques may be less effective. Given the potential of such a “universal” sensor to detect oil that is essentially independent of any ice or oil conditions, and as no testing of the sensitivity of such a system to the presence of oil has been attempted under ice, lab tests of existing prototype systems and/or simple test systems are warranted to better determine the feasibility of this method.

3.3 3.3 Camera systems

The most straightforward means of mapping oil distribution under ice from below is visually. This is because under ice, oil will pool too much greater thickness than on an open ocean surface, and there is a strong colour contrast between black oil and white ice. For good performance on AUVs under ice, a camera system should have a high dynamic range so that it can adjust to the wide variation in light levels likely to be encountered, and should be colour-calibrated. Based on recent under ice AUV missions charactering the underside of the ice with cameras is relatively straightforward and tank experiments have shown that the contrast between oil and ice is significant (Figure 3.3.1).

3.3.1 High dynamic range cameras and underwater lighting

The attenuation of visible light underwater at a particular wavelength may be modelled as a simple exponential function with an attenuation coefficient that is a function of absorption and scattering. However, this attenuation coefficient is a complex function of the wavelength. For each wavelength, the value of the attenuation coefficient depends on the depth and salinity of the water. Biological material or sediment in the water will significantly affect the absorption and scattering of the light.

In addition to the attenuation, the lighting pattern of a light source affects the spatial variations of the light on the ice underside. The light source is usually a single strobe for AUVs due to cost, size and power limitations. A combination of different light sources, such as halogen-gas light, incandescent light and strobes can be used to generate a more uniform lighting pattern for ROVs and manned submersibles but even so there is a strong dependence on altitude that affects such geometries, which leads to a non-uniform lighting pattern over the entire domain of application.

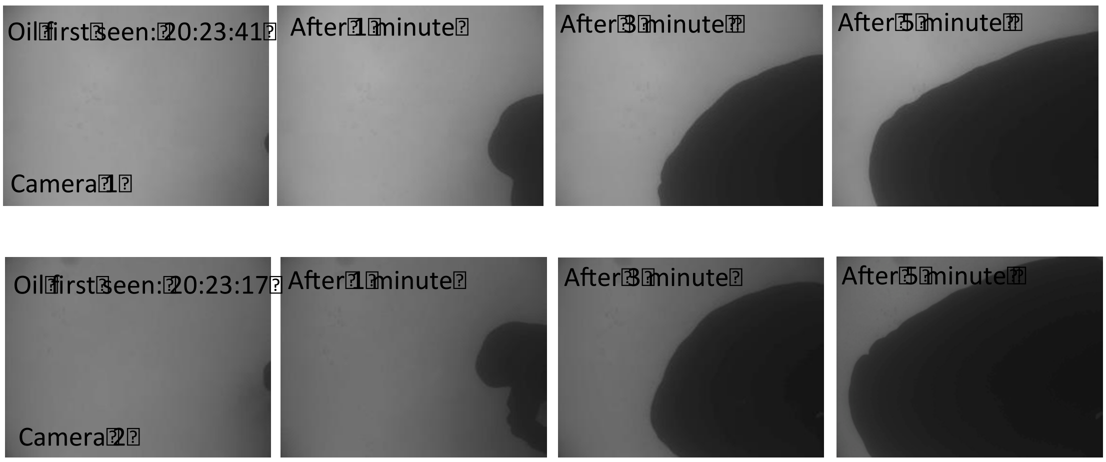


Figure 3.3.1. *Underwater photos showing the flow of oil under sea ice for CRREL trials described in section 3.1.4. The time-series is from two cameras mounted looking upwards. Field of view for each photograph is 0.5185m^2.*

High dynamic range cameras have been specifically built for underwater applications and are designed to work well in areas of extremely low contrast that is typical of underwater (and under ice) applications. These systems were originally devised for microscopic imaging applications that suffer from the same constraints, and have been adapted for underwater use. In combination with customized software, these camera systems can be used to correct the imagery for low contrast and lighting artefacts (figure 3.3.2).

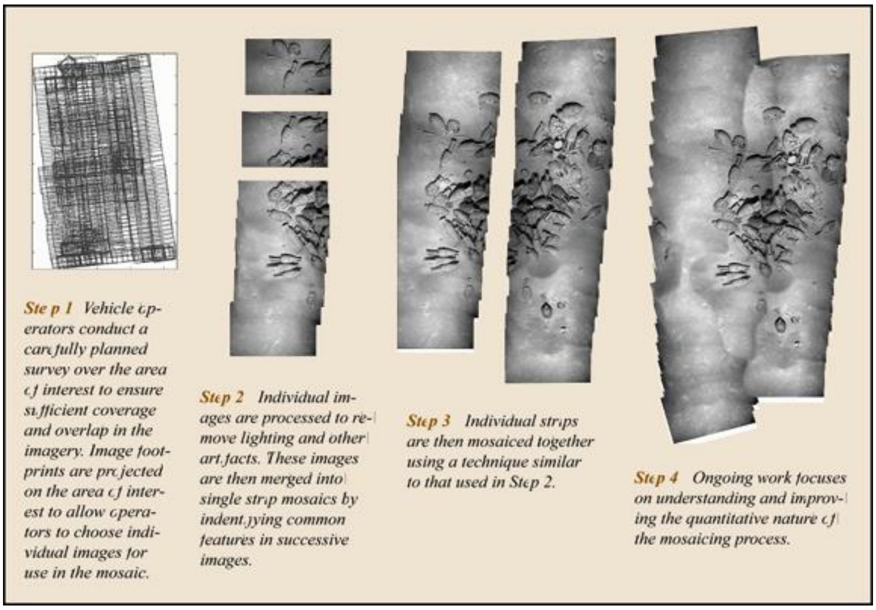


Figure 3.3.2 *The process of Photomosaicing. In this case, for a seafloor survey of artifacts from an ancient shipwreck.*

Figure 3.3.3 *Individual images collected underwater mosaicked into a composite to obtain a global perspective. 866 images obtained by cameras on an ROV were combined in this rendering of the RMS Titanic.*

3.3.2 Mosaicing

Due to attenuation and backscatter, the practical coverage of a single image is limited to a few square meters. At most, in combination with a strobe, these systems can provide imagery from a distance of up to seven meters in clear water. Sediment or biological material in the water column can obscure the target and further limit this range. To cover larger areas of interest, hundreds or thousands of images may be required. The rapid attenuation of the visible spectrum in water implies that a composite view of a large area (or photomosaic) can only be obtained by exploiting the redundancy in multiple overlapping images distributed over the scene. Although there has been considerable effort in this regard for land-based applications, the constraints on imaging underwater are different and are far more difficult to deal with. Mosaicing assumes that images come from an ideal camera (with compensated lens distortion) and that either the scene is planar or that camera is undergoing purely rotational motions. Under these assumptions the camera motion will not induce parallax and therefore no 3D effects are involved and the transformation between views can be correctly described by a 2D homography. These assumptions often do not hold in underwater applications since light attenuation (which limits the range to target) and backscatter (which affects image quality) rule out the traditional land-based approach of acquiring distant, nearly orthographic imagery. Underwater mosaics of scenes exhibiting significant 3D structure usually contain significant distortions. In contrast to mosaicing, the information from multiple underwater views can also be used to extract structure and motion estimates using ideas from structure from motion (SFM) and photogrammetry. An example mosaic, of the RMS Titanic is shown in Figure 3.3.3. Mosaicing has seen widespread use in underwater applications. However, there is currently no commercial software capable of mosaicing large numbers of images spatially distributed over a large area underwater.

3.3.3 Use of camera systems for detection of oil under ice

Oil identification is straightforward in relatively level ice due to the high contrast between oil and ice – both in natural and artificial light. In a heavily deformed or a broken ice cover, this distinction will be less clear due to the attenuation of light through the ice. In this case additional information will be useful to positively detect oil, such as the colour information in the imagery. Use of a multibeam sonar for ice thickness information (section 3.6.2) will be useful to distinguish contrast changes due to changes in ice thickness from changes in the presence of oil.

The advantages of an optical (camera) system include:

- they are a well-established AUV/ROV survey technology, including under-ice,
- they can provide a complete two-dimensional map of oil extent,
- standard techniques area available to provide imagery in low-light and full-darkness conditions i.e. deep sea,
- appropriate image processing techniques and software are widely available, and the contrast between ice and oil simplifies the classification problem, and
- classification and oil detection could be quickly and easily verified by a human operator.

The primary limitations include:

- power requirements of a strobe that will be required under thick ice,
- in turbid or low-clarity water, imagery could be obscured,
- need for high-bandwidth telemetry or on-board processing of imagery

3.4 Radiometers and multispectral measurements

An alternative to camera systems is to use multispectral sensors. These sensors broadly fall under the class of radiometers – sensors that collect light in several discrete spectral bands. Broadly speaking, this also includes digital colour cameras, which have three bands. Most multispectral sensors have many more discrete wavelength bands, often including bands outside the visible spectrum (i.e. ultraviolet and near infrared). These include radiometers, which generally have a relatively modest number of bands (seven is typical for oceanographic radiometers), or hyperspectral instruments that can have hundreds of channels. Radiometers and hyperspectral sensors can be imaging systems, such as the systems used on airborne and satellite platforms. In oceanographic applications, radiometers are more commonly not imaging systems, but designed to measure, for example, the incident solar spectrum and its attenuation in the water column. These radiometers are small, compact devices that can easily be used on AUVs.

The basic principle of multispectral detection relies on the variance in reflectivity of a medium with wavelength. Differences in the spectral reflectance of various media can be exploited to discriminate various surface types. This has been widely used in airborne and satellite geophysical applications. For under ice applications, the situation is somewhat different, in that it is transmitted light rather than reflected solar radiation that is used. In this case, the differential attenuation of light in different wavelength bands can be used to account for light level changes under ice of varying thicknesses. While standard oceanographic radiometers cannot provide the spatial information of a camera system, they provide well-calibrated light (i.e. visual) information with a much lower data rate and so can be more easily relayed to an AUV operator in real time. These have been used in airborne oil detection applications (both visible and infrared), but the principle of their application for under ice detection of oil would be significantly different.

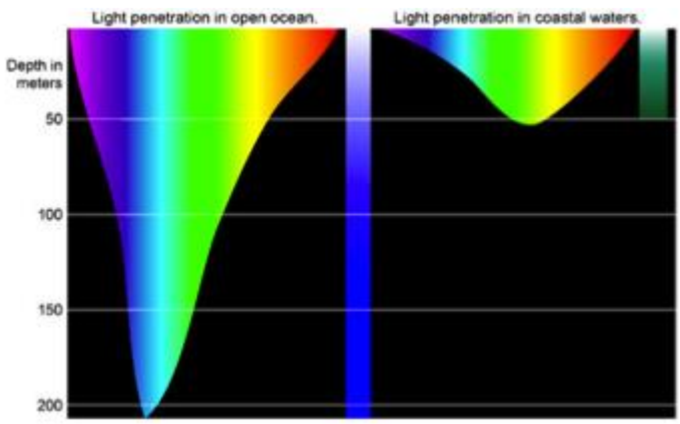
3.4.1 Light in the ocean and under sea ice

The transmission of sunlight through the ocean varies strongly with wavelength (figure 3.4.1). In seawater, both UV and infrared wavelengths are quickly attenuated by water (Wozniak and Dera, 2007). In the visible band (400-700 nm), transmission is much greater, although attenuation is still wavelength dependent. Long wavelengths (red) light are absorbed the most strongly, while transmission of green and blue is greatest. As a rough rule of thumb the intensity of visible light decreases by about an order of magnitude for every 75 m that you descend; very little light penetrates below 150m.

Light transmission varies strongly with water clarity. Coastal waters typically have transmissivities much less than in clear, open ocean waters due to increased abundance of biological matter and turbidity (sediment load). Arctic waters typically have a very high transmissivity, with few scatters being present in the water column. However, this changes with the season and region; spring phytoplankton blooms and/or sediment load from river inflow can significantly reduce transmissivity.

Sea ice will greatly reduce the amount of sunlight that reaches the ocean below. The optical properties of sea ice have received much attention due to the role of sunlight in sea ice thermodynamics (Perovich, 1996). Crystal size and orientation, presence/absence of brine pockets, ice type and thickness, presence/absence of micro-organisms, along with other factors all influence the absorption and scattering of light within sea ice. The highly heterogeneous nature of the snow and ice thickness distribution means that the light field beneath the ice will be highly spatially variable.

Colour	Frequency	Wavelength	Attenuation of light in seawater verses depth
violet	668–789 THz	380–450 nm	
blue	631–668 THz	450–475 nm	
cyan	606–630 THz	476–495 nm	
green	526–606 THz	495–570 nm	
yellow	508–526 THz	570–590 nm	
orange	484–508 THz	590–620 nm	
red	400–484 THz	620–750 nm	



http://oceanexplorer.noaa.gov/explorations/04deepscope/background/deeplight/media/diagram3.html

Figure 3.4.1. *The wavelengths and colours associated with the visible light spectrum. The figure on the right shows the attenuation of these colours as a function of depth, for open water and coastal seas.*

Spectral extinction coefficients for snow are more than an order of magnitude larger than for sea ice, and the albedo of snow can be almost twice as large as that for sea ice (Grenfell and Maykut, 1977). This is an important consideration as it is the snow depth that is a greater control on light penetration than the ice thickness. The situation becomes far more complex in the marginal ice zone, i.e. broken pack, where open water exists between floes. A number of other factors modulate the spectral transmission of light through ice, including cloud cover, aerosols, and sun elevation. As a result of these transient atmospheric processes the amount of solar radiation received at the ocean surface is temporally and spatially variable.

3.4.2 Theory of oil detection under sea ice by sunlight level variability

Airborne/satellite optical multi-spectral sensors have had good success in mapping the location of oil floating on water (see associated JIP report on Surface Remote Sensing). For example the Clark et al., (2010) use both the shape of near-infrared (NIR) absorption features and the variations in the spectral continuum due to organic compounds found in oil, to identify different oil chemistries, including its weathering state and thickness. However laboratory measurements showed that light in the NIR range penetrate only a few millimetres into oil-water emulsions (Clark et al., 2010). Because of the very strong absorption of near IR light by seawater, this technique will not be useful underwater. There are variations in spectral reflectance in the visible band that could, in principle be used to identify oil, but the reflectance is so low in the visible (Clark et al., 2010) that it is most-likely impractical given the low signal levels and the noise present due to scattering of ambient light in the ocean.

Under the ice, an alternative technique would be to monitor the spectral variations in light level transmitted through the ice to detect the presence of oil underneath, or possibly within, the ice. These types of measurements are routinely performed in the water column and more recently, under sea ice. Off-the-shelf radiometers have developed considerably over the past few years, with hyperspectral units now offering a large number of channels. Hyperspectral sensors are a class of multispectral sensor, primarily differing by the number of channels that the incident light is binned into. For instance, the Satlantic HyperOCR offers 136 channels in the 350-800 nm range. These systems can be mounted on a range of platforms, i.e., profilers/gliders, buoys, AUVs/ROVs. When performing optical readings in the ocean an independent upward-looking radiometer is often mounted at the surface to obtain the incoming light spectra.

Hyperspectral radiometers have recently been used on AUVs under ice to monitor spectral attenuation of light through the ice, with the aim to detect algae within the ice (e.g. Williams et al., submitted). The principle behind detection of oil would be similar, but simpler given the strong attenuation of light expected in oil. An AUV mission that moves from under clean ice to an ice cover contaminated with oil should see a change in the incoming light spectrum due to the scattering and absorption properties of oil at different wavelengths. These changes should be clearly seen by an upward-looking hyperspectral unit mounted on the AUV. However temporal and spatial variability associated with the scattering/absorption of light in snow, ice, and seawater mediums still remain and may cause interpretation difficulties.

3.4.3 Operational examples

There are very few examples of the scattering/absorption of light due to oil being present in sea ice. Adams (1975) monitored the controlled release of oil under sea ice in the Beaufort Sea Programme in 1974. Over time, ice grew around the oil, encapsulating it within the ice cover. In the following spring, when the sun returned, light-levels both under the spill and under sea ice away from spill were measured. In May and June, 1975 light levels in the 400-700 nm range underneath the encapsulated oil were approximately 50% lower than those under clean ice. Spectral attenuation information was not reported. Despite limited data, this suggests that this technique may provide a way to discriminate oil located anywhere within the light-path from the top of the snow through to the bottom of the ice.

Adams (1975) also performed some basic laboratory spectral light transmission experiments on Norman Well's crude. These experiments were run diluted in n-heptane and the transmittance of pure crude oil for a 1 cm path length was calculated from the spectral data. Results are summarised in table 3.4.1.

Oil effectively attenuated all light in the 300-600 nm range, but transmission was much higher at longer wavelengths. While these experiments were simple, these results indicate an effect on the spectral attenuation caused by an oil slick on the water or on, in or under sea ice. It may be possible to exploit these differences in order to detect the presence of oil contaminated sea ice. It would be advantageous to repeat these tests with modern radiometers to obtain more detailed information on the spectral attenuation of light due to oil. These results could then form the basis of a detection system using radiometers mounted on an underwater vehicles or platforms.

Visible Colour Range	**Wavelength (nm)**	**Percentage Light transmitted (%)**
Orange, yellow, green, cyan, blue, violet.	300 to 600 nm	0.3%
Red (620-750 nm)	650 nm	18%
Red (620-750 nm)	700 nm	83%
Red (620-750 nm)	750 nm	100%
N/A	800 nm	100%

Table 3.4.1 *Results of the transmittance of pure crude oil for a 1 cm path length was calculated from the spectral data. Based on data from Adams (1975).*

3.4.4 Summary

The detection of oil under sea ice exploits the scattering and absorbing characteristics of oil in the presence of solar radiation. Strong attenuation of visible light by oil should make contaminated areas easily distinguishable from clean areas (much like for photography). Spectral variability in attenuation may also aid identification, or even quantify small quantities of oil within or under sea ice. However given the limited literature available on this subject further experiments are needed.

Advantages

- This passive technique quantifies the changes in the light spectra from the snow surface through to the sensor's location in the water column. As a result this technique has the possibility of being able to detect the presence of oil irrespective of where it is located within the body of sea ice or snow.
- Standard 'off-the-shelf' technique that has been used for decades by the oceanographic community, with high-resolution hyperspectral units now available.
- Standard output that is familiar to a wide range of professionals.

Limitations

- Most visible light is strongly attenuated by oil. Spectral information may be of limited use, especially for thick oil. (Although discrimination between clean and contaminated areas should still be possible).

- Light attenuation through sea ice is a complex function of ice and snow thickness and properties. High spatial heterogeneity of ice conditions will complicate delineation of contaminated ice areas. Complementary information on ice thickness may be helpful.
- Light levels may be too low under thick snow, thick ice, and in periods of limited light or darkness.

3.5 Mass spectrometry

A promising new technology for detecting dispersed oil in the water column, even at very low concentrations, is real-time mass spectrometry. Mass spectrometry works by ionizing compounds to generate charged molecules, which are then characterized by measuring the charge to mass ratio as they are passed through electric and magnetic fields. By this means a variety of gases and chemical compounds can be readily identified, even if present in trace quantities. A handful of marine in-situ mass spectrometers have been developed. One that has been field-proven is the TETHered Yearlong Spectrometer (TETHYS) mass spectrometer developed at the Woods Hole Oceanographic Institution. This system uses a membrane inlet mass spectrometer capable of detecting a wide variety of hydrocarbons. The TETHYS system was used successfully in the Ohmsett test basin (Hansen et al., 2009) and was mounted on the SENTRY ROV to track the plume from the Deep Horizon Macondo well. It was able to track 10 independent chemical parameters within the plume in real time (Camilli, et al., 2010).

The system is not dependent on weather, ice, or light conditions. The primary advantage of such a system is it can positively identify a wide variety of hydrocarbons in trace amounts – below the threshold of detection of many other sensors. The primary limitation for detecting oil under sea ice is that it would require direct contact with the oil (or the presence of soluble chemicals released by the oil). This would be practical if there were a plume in the water column, or trace hydrocarbons were stirred to the depth of the vehicle in turbulent water. If this occurs, such a system might be a useful indicator of the presence of nearby oil slick above the vehicle as an aid to other sensors on board.

TETHYS has been used effectively from SENTRY, which is a relatively large ROV platform. It is currently relatively large for an AUV payload if a variety of other sensors will be on board, so its integration into a complete sensor suite for small to moderately sized platforms may need to be based on the relative capabilities of the complete sensor suite.

3.6 Auxiliary sensors

AUVs routinely carry a number of sensors for oceanographic missions that, while not necessarily useful for detection of oil, can provide information on the environment that may be useful auxiliary information for aiding oil spill response. If AUV payload space is available such sensors may provide valuable data on currents and under ice bathymetry. These data streams can be fed into under ice oil spill models to predict future evolution of the oil spill to enhance a reconnaissance efforts or aid in clean up and mitigation. The following instruments have all been used on AUVs and are off-the-shelf oceanographic instrumentation.

3.6.1 *Acoustic Doppler Current Profiler for multi-depth current measurements*

An Acoustic Doppler Current Profiler (ADCP) measures the direction and velocity of the water over a range of depths. It works by transmitting an acoustic signal at a constant frequency. As the sound propagates outwards through the water column it is reflected off suspended particles that are moving with the water. Due to the Doppler shift in the frequency of the returned acoustic signal the speed of the particle travelling with the water can be obtained. An ADCP is standard on many AUVs as it is used as an acoustic Doppler Velocity Log (DVL) to aid navigation. The current information from an ADCP is provided in a number of depth bins. These data can be assimilated directly into oil spill models.

3.6.2 *Multibeam sonar for 3-D under ice topography*

A multibeam sonar or swath echosounder is a sonar that is routinely used to obtain high-resolution, 3-dimensional (3-D) information of the seabed. It can be used in an upward-looking mode to obtain 3-D imagery of the underside of sea ice (figure 3.6.1).

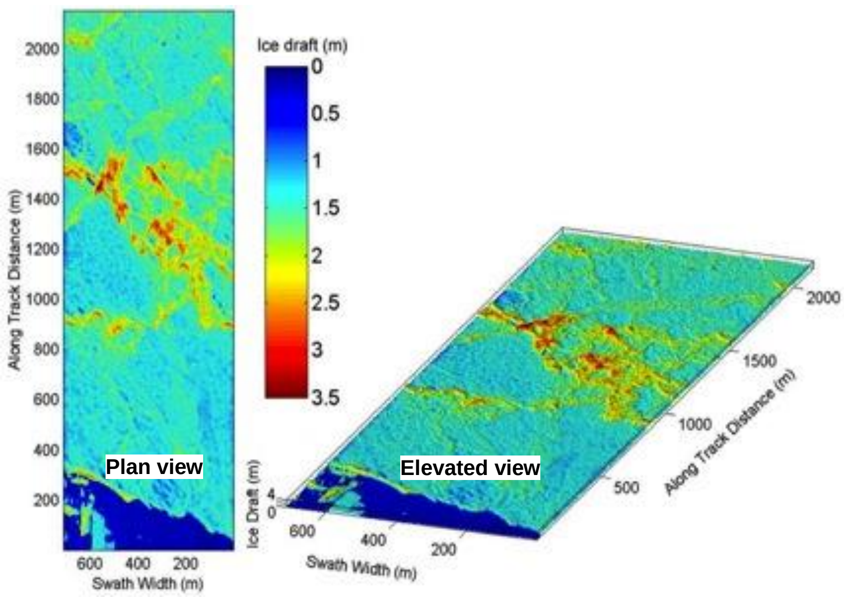


Fig 3.6.1 *3-D imagery of the underside of sea ice from an AUV with a multibeam sonar. The mosaic was constructed from 14 overlapping survey runs from software developed by Wilkinson. Under ice features (ridges) will have an impact on the flow of oil under the ice.*

In 2004 the Autosub-II AUV operating off NE Greenland, obtained the first successful multibeam sonar measurements under sea ice, showing in unprecedented detail the three-dimensional nature of the under-ice surface (Wadhams et al., 2006).

Since this time multibeam sonars have been used on a number of AUVs to image the underside of sea ice and floating glaciers. High-resolution under-ice oil spill models (e.g. Wilkinson et al., 2007a), can use the 3-D ice draft data to predict where oil may flow given the under-ice topography.

3.6.3 Turbulence probe for oil dispersal measurements

Compact turbulence probes have been recently developed to measure small-scale turbulence within the upper ocean from ocean gliders and AUVs. Upper ocean turbulence can redistribute small droplets away from the main slick and by doing so can reduce the volume of oil within the original slick, and potentially disperse oil droplets into the water column where they could be detected by in-situ sensors on the AUV. Turbulence data then can be assimilated into oil dispersion and weathering models.

3.7 Summary

Autonomous underwater vehicles (AUV) have matured to the point that they are now in routine use for oceanographic applications. Under sea ice, deployment and recovery logistics and navigation and telemetry are more complicated than in open water. Recent successes with a variety of vehicles under sea ice have shown that such operations can now be routinely undertaken.

Detecting and mapping of oil spilled beneath sea ice may now be more practical using an AUV, both because the vehicles afford access to the under ice environment, and because several sensor technologies that have been routinely used on AUVs hold much promise for oil detection and mapping applications, particularly cameras, sonar, and potentially, radiometer systems. Other sensors that have been shown to be useful for detecting oil in the water column have recently been demonstrated effective in both experimental and actual oil spill response applications on AUV platforms, including in situ mass spectrometry and UV fluorescence. Recent advances with laser fluorescence suggest that it could potentially be transitioned from an airborne detection application to an AUV-based solution. Finally, AUVs can carry a variety of auxiliary sensors for characterizing the under-ice environment in which oil has been spilled, providing information useful to formulating a response strategy.

As the detection of oil from below is a recent evolution of this challenging problem, there is little information on the detectability (and limitations) of oil under sea ice for each sensor described herein. Further laboratory and in situ testing of these sensors for this application is needed. In the next sections, AUV platforms and sensors will be investigated to determine appropriate strategies for responding to a spill under sea ice and the most appropriate choice of sensor suite, based on current understanding of capabilities, for a variety of spill scenarios.

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CHAPTER 4. CORRELATING MULTIPLE SENSOR MEASUREMENTS

Chapters 1 and 2 of this report discuss the possibility to directly sense oil under ice from below. This is an extremely attractive alternative as it avoids most of the difficulties inherent in surface-based techniques due to the barrier imposed by the ice cover when the oil is beneath the ice, and operations can be largely independent of ice and weather conditions. Chapter 3 outlined the various sensors that potentially could be used to detect oil beneath the ice and discussed the likely advantages and limitations of each primarily in terms of their general prospects for oil detection. In a real-world application, there are a number of factors, both environmental and logistical, that affect the ability of a particular sensor on a particular platform to make a positive detection. In this chapter we review the benefits and limitations of the most promising sensors that are available to detect and map oil in the ice covered waters and examine the multi-senor approach to oil detection.

The primary factors controlling the efficacy of any particular strategy for detecting oil under ice are the location of the oil (under ice, in ice, or within the water column), the ice properties, and upper ocean conditions. These factors will not only influence UUV operations, but they will determine the physical properties of the oil and may have a significant impact on the performance of a specific sensor to detect the oil.

However, given that a UUV payload can accommodate several sensors, a detection strategy need not be restricted to a single sensor. The vehicle payload should include a number of complementary sensors that will have different advantages under different conditions, and ideally, each with limitations that are offset by the capabilities of other sensors in the payload. Positive identification of oil could be improved through fusion of data from different sensors, either through interpretation of multiple data streams by a trained user or through formal data fusion processing techniques. While some sensor data may provide immediate identification of oil to a user on the surface through real-time telemetry, in other cases identification may require more processing (either from real-time data streams or post-mission processing).

For an AUV (as opposed to a tethered ROV or hybrid vehicle), there are additional issues to be considered for real-time data analysis. The primary issue for an un-tethered operation is the bandwidth required for telemetry of large volume data through an acoustic link to the operator on the surface. Telemetry of digital imagery or multibeam sonar data, for example, requires more advanced techniques than low-bandwidth data that might be output from a fluorescence system or single-beam sonar. A second consideration when analysing real-time data during an AUV mission is the ability to adapt the mission on-the-fly in response to a positive identification of oil – either by a user on the surface, or automatically by data processing on board the vehicle. A third consideration, not examined here, is the use of more than one AUV during a search campaign.

Within this chapter we evaluate sensor strategies for identification of oil located within/under sea ice and the rapid transmission of these data back to the user. We discuss detection issues with respect to particular ice conditions, oil conditions and search strategies. A more detailed analysis of specific scenarios is discussed in the following chapter, Chapter 5.

While the discussion in this Chapter is based on current understanding of sensors and AUV operations, as discussed in Chapter 3, one should always keep in mind that there have been very few trials of sensors for detecting oil under ice from below. Therefore, the performance of any particular sensor or sensors in many of the scenarios described here is uncertain until further, realistic tests are performed.

4.1 Sensor suites for remote and in situ detection

In Chapter 3 we reviewed the basic principles and previous relevant testing of sensors that have the potential to detect oil under sea ice from an AUV platform. For remote detection (i.e. detection some distance away from the oil) beneath or within the ice, these sensors included:

- Sonar
- Camera systems
- Laser fluorosensor
- Radiometers and multispectral systems

For in-situ detection (i.e. detecting oil or other hydrocarbons dispersed in the water column), three candidate sensors were identified as capable of detecting low concentrations of hydrocarbons:

- Laser In-Situ Scattering and Transmissometer (LISST)
- TETHYS mass spectrometer
- In-situ fluorometer

Each of these in-situ sensors requires direct contact between the sensor and the water containing oil. There is little difference in principle in the use of these sensors under ice or in open water, and each has been used to some degree successfully to detect hydrocarbons in open water spills. For in situ detection in the water column, the ice conditions do no come in to play. As our report focuses on remote-sensing techniques, we do not discuss these methods further here, and the reader is referred to the existing literature mentioned in the previous chapter.

Importantly two of the sensors identified as being capable of remote detection may also be useful for detection of hydrocarbons remotely in the water column (sonar and laser fluorosensor). An echosounder has been used to detect the presence of hydrocarbons at the Deepwater Horizon site (Li et al., 2011) and there is on-going research to determine droplet size from acoustic scattering. In the water column, a laser fluorosensor system would not necessarily offer any advantage over a standard in-situ fluorometer (with the latter most likely being easier to implement on an AUV), except for detection of a plume at some distance from the sensor head. However, the strong attenuation of UV in water will limit the range of such a system to a few tens of meters at best (Sasano et al., 2012). This range may be significantly less for an AUV payload as there are limitations to the physical size and power of the sensor). Longer excitation wavelengths may be more practical (at the expense of reduced spectral information). Further complications for remote sensing include biological material in the water column that may also fluoresce.

Sonar is the most-promising underwater remote technique that has the potential to detect hydrocarbons in the water column at distances greater than several tens of meters and indeed, the possibility to detect oil trapped beneath (or possibly within) sea ice at these ranges.

As the application of the technology for remote detection of hydrocarbons within the water column is in all respects similar for open water and under ice conditions, and this application is in a nascent stage, we do not discuss these applications further here. We concentrate on the remote sensing of oil immediately under, and within sea ice.

4.2 Sensor evaluation for remote detection of oil under sea ice

The efficacy of any of the four remote sensor systems listed above, or suite of sensors will depend on a variety of factors, including ice conditions and ice type, water clarity and properties, and distance from the target. The effectiveness of the complete system (i.e. platform and sensors) will also depend on vehicle navigation, performance and data telemetry. These are discussed in Sections 4.5 and 4.6. Logistical issues pertaining to vehicle deployment, recovery, and operation in different ice conditions is covered in Chapter 5.

Ice and ocean conditions will vary widely both spatially and temporally depending on the time of year. However, for the purposes of categorizing the likely behaviour of each sensor, we can identify several broad classes of ocean and ice conditions as follows.

4.2.1 Ocean conditions

Good visibility: Lack of ocean turbidity and thin sea ice with a limited snow cover will allow visibility in clear Arctic waters can exceed 50 meters, with e-folding depths of light transmittance of 10-15 meters (Smith, 1973).

Limited visibility or darkness: Thick snow cover and sea ice thickness will strongly attenuate sunlight (Perovich, 1998), although for an active light source, this is obviated. During the polar night complete darkness excludes the use of passive optical instruments, but may be an aid for active optics.

Turbid water: In summer, phytoplankton blooms can greatly reduce the visibility (Pegau, 2002). In coastal areas where there sediment due to river runoff, scattering from suspended sediment will further reduce visibility (e.g. Doxaran et al., 2012). Visibility can be 10 m or less in some cases.

Ocean stratification: Temperature and salinity stratification within the upper 10s of metres generally occurs during the summer months due to ice melt and fresh water capping the ocean surface, either amongst ice floes or beneath the ice. In winter the upper water column is generally well mixed. These changes in ocean properties are primarily a consideration for sonar (sound) systems.

4.2.2 Sea ice conditions

The variety of sea ice types and conditions will have implications for how oil is located amongst, and interacts with the ice cover (figure 4.2.1). This may have important implications for the efficacy of a particular sensor. Many of these ice types can also entrap, or encapsulate oil as it grows. Furthermore oil may percolate up through channels in the ice.

Young ice: This is the first stages of formation of an ice cover, and can represent unconsolidated frazil or grease ice, or nilas. In this case, oil will tend to become incorporated into the forming ice cover.

Consolidated level first year ice: This ranges from thin sea ice types such as grey and grey-white ice to thicker FY ice (up to 1.5-2 m). Oil will likely pool on the bottom of the ice, potentially spread relatively thinly in the case of very level ice.

Continuous level multiyear ice: Level Multiyear ice is generally in the range of 2 to 3 m, but invariably will have hollows where oil can pool.

Deformed ice: Ridged, rafted, and rubble ice will have significant bottom topography to trap oil.

Broken ice cover: An ice cover with open water areas, such as cracks and leads can trap oil between floes (Bobra and Fingas, 1986), so that there are areas where the oil is not covered by ice.

Marginal ice zone: The marginal ice zone (MIZ) could include a number of the ice types described above, and conditions (ice concentration, sea state) can vary greatly spatially and temporally. Here, we consider a MIZ where there is potential influence of waves, broken ice cover, brash, and frazil/pancake formation.

Algae: Algae grows on the bottom or within the ice in spring and summer. In the Arctic, the greatest concentrations are found on the ice underside, and can be many times the concentration in the water (Arrigo et al., 2010). This affects light penetration though the ice, but will also complicate optical methods such as cameras, and particularly fluorescence.

4.2.3 Sensor efficacy under varied conditions

Tables 4.1-4 summarize how the ocean and sea ice conditions are likely influence the detection of oil located both under the ice and within the ice for each sensor under consideration. For simplicity, we use a color-coded traffic light system to simplify the evaluation.

Green: Has been shown to detect oil under these, or similar conditions and/or there is a strong likelihood of success.

Yellow: Good experimental or theoretical basis, but with potential limitations that require testing to verify efficacy.

Orange: Is theoretically possible to detect oil under these conditions, but there are potential strong limitations and required testing has not yet been performed.

Red: Research or theory has shown that it is not possible or very unlikely to detect oil under these conditions.

It is important to note that for the candidate sensors listed above, there have been almost no tests to date for detection of oil under sea ice from below. To our knowledge, sonar has been tested only by Wilkinson et al., (in prep), as described in Chapter 3. Multispectral methods have seen very limited use (Adams, 1975). There have been some tests with both sonar and laser fluorescence (Hansen et al., 2009) that involved remote sensing of oil deposits through seawater that have relevance, although did not involve ice. Cameras have been used by Wilkinson et al., (in prep) and others. Otherwise, several of these systems have seen varied degrees of use under sea ice for applications without oil. There have been no directly relevant tests for encapsulated oil. Thus, there is very limited information yet available to evaluate the efficacy of any of these methods under complex, realistic conditions. As such, evaluations herein are necessarily speculative, and further experimental work is required for each to better understand their potential.

As indicated by Table 4.1-4, there are potential limitations for practically all sensors in most ice and ocean conditions. However, in almost all conditions, there is likely one or more sensors that potentially have a high chance of success (with the caveat that adequate testing and development has yet to be taken for any sensor). For the case of oil encapsulated in ice, there are added complications – particularly since one of the best sensors for oil located beneath ice (cameras), are unlikely to be particularly effective for encapsulated oil. However, none of these techniques have been tested in laboratory experiments, so the efficacies listed here are highly speculative, and may critically depend on where in the ice the oil is encapsulated. Below we briefly summarize potential limitations of each sensor under the variety of ice conditions likely to be encountered.

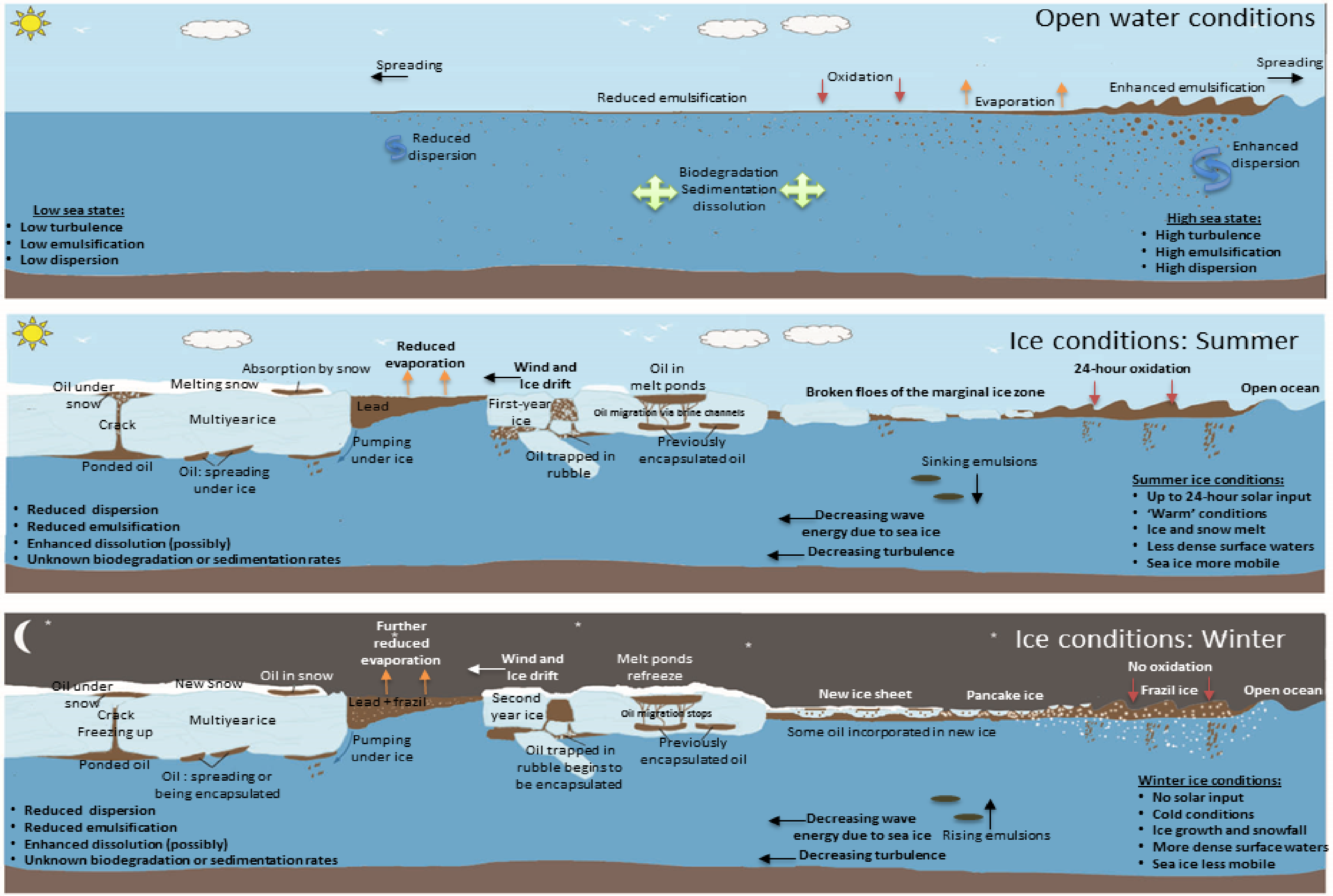


Figure 4.2.1 Sequence of the main oil-ice interaction and weathering processes in (top) open water conditions, (middle) ice conditions in summer and (bottom) ice conditions in winter (adapted from original figure by Bobra and Fingas, 1986). Different ice conditions and seasons will have varied implications for the detection of oil for different sensors.

Oil located under sea ice

	Good visibility	Limited visibility and darkness	Turbid water	Upper-ocean stratification
Sonar	**YES** (Wilkinson et al., in prep). Very thin slicks (if they can occur) may be difficult to detect	**YES** (Wilkinson et al., in prep). Very thin slicks may be difficult to detect	**YES** Extremely turbid water may introduce noise from large scatterers in some systems	**LIKELY** Possible complications due to sound speed variation. Validation is needed
Fluorescence	**LIKELY** Range may be limited (Hansen et al., 2009)	**YES** Range limited, but no ambient light noise (Hansen et al., 2009)	**POSSIBLY** Range may be limiting	**YES** (Hansen et al., 2009)
Cameras	**YES** (Wilkinson et al., in prep)	**YES**. Artificial light needed, limited range (Wilkinson et al., in prep)	**LIKELY** Limited range	**YES**
Multispectral Radiometers	**POSSIBLY** Very thin slicks may be detectable. (Adams, 1975)	**NO** Requires transmitted sunlight. Use of artificial light to detect spectral reflectance highly uncertain.	**POSSIBLY** Absorption/scattering in the water column will make interpretation difficult	**POSSIBLY** Adams (1975)

Table 4.1. *Evaluation matrix for Oil located under sea ice. Matrix shows the general ocean properties that are found in the upper Arctic Ocean (columns) and the sensors that show promise to detect oil from below (rows). Multispectral system efficacy is indicated for methods that discriminate oil based on spectral reflectance or transmittance, detection (including possible thickness detection). For detection of oil based on colour, multispectral methods are effectively the same as cameras.*

Oil located within sea ice

	Good visibility	Limited visibility and darkness	Turbid water	Upper-ocean stratification
Sonar	**POSSIBLY** Will depend on sonar characteristics and depth of oil	**POSSIBLY** Will depend on sonar characteristics and depth of oil	**POSSIBLY** Will depend on sonar characteristics and depth of oil	**POSSIBLY** Will depend on sonar characteristics and depth of oil
Fluorescence	**POSSIBLY** Scattering and absorption within the ice is potentially major issue	**POSSIBLY** Scattering and absorption within the ice is potentially major issue	**POSSIBLY** Scattering and absorption within the ice and water column is potentially major issue	**POSSIBLY** Scattering and absorption within the ice is potentially major issue
Cameras	**UNLIKELY** except where oil is at or near basal layer	**UNLIKELY** except where oil is at or near basal layer	**UNLIKELY** except where oil is at or near basal layer	**UNLIKELY** except where oil is at or near basal layer
Multispectral radiometers	**POSSIBLY** (Adams, 1975)	**NO** Highly unlikely even with artificial light due to scattering within the ice.	**POSSIBLY** Absorption/scattering in the water column will make interpretation difficult	**POSSIBLY** (Adams, 1975)

Table 4.2. *Evaluation matrix for Oil located <u>within</u> sea ice (encapsulated). Matrix shows the general ocean properties that are found in the upper Arctic Ocean (columns) and the sensors that show promise to detect oil from below (rows). In all cases, limitations will also include those limitations mentioned in Table 1. It is assumed that the oil is fully encapsulated with some clear ice beneath; in the case where the oil exists trapped with the porous network of the basal ice and can be clearly seen from below, the success of many of these systems will be similar to Table 1, with the possible exception of sonar which may then not have a clearly distinct layer to produce a strong acoustic return.*

Oil located under sea ice

	Young ice	Level FY ice	Level MY ice	Deformed ice	Ice with algal growth	MIZ	Open water in broken ice
Sonar	**POSSIBLY** Complicated by mixing of oil and ice, and possibly more processing	**YES** (Wilkinson et al., in prep)	**YES** May be easier than for FY ice due to less penetration in ice and thicker pooling	**YES** May be thick pools, but ice roughness adds complications	**YES**	**POSSIBLE** Complicated by waves, frazil crystals, and mixing of oil and ice	**LIKELY** Difficult for very thin slicks
Fluorescence	**LIKELY** Range may be limited in daylight (Hansen et al., 2009)	**LIKELY** Range may be limited in daylight (Hansen et al., 2009)	**LIKELY** Range may be limited in daylight (Hansen et al., 2009)	**POSSIBLE** AUV Range to avoid ridge keels may be limiting	**POSSIBLE** Thick algal mats may be difficult to distinguish from oil	**LIKELY** Range may be limited in daylight (Hansen et al., 2009)	**LIKELY** Range may be limited in daylight (Hansen et al., 2009)
Cameras	**POSSIBLY** Complicated by mixing of oil and ice	**YES** (Wilkinson et al., in prep)	**YES** (Wilkinson et al., in prep)	**YES** (Wilkinson et al., in prep)	**YES** Oil/ice distinction may be less clear	**LIKELY** Complicated by mixing of oil and ice	**YES** Very thin slicks may be difficult to see
Multispectral Radiometers	**POSSIBLY**	**POSSIBLY** (Adams, 1975)	**POSSIBLY** (Adams, 1975)	**UNLIKELY** Complicated by ice thickness variations	**POSSIBLY** Algae will affect spectral signature	**POSSIBLY** Complicated by mixing of oil and ice	**POSSIBLY** May be useful for thin slicks in large breaks

Table 4.3. *Evaluation matrix for Oil located under sea ice. Matrix shows general ice conditions found in the upper Arctic Ocean (columns) and the sensors that show promise to detect oil from below (rows). Efficacy is shown for favourable water conditions (e.g. good visibility). See Table 1 for effects of visibility. Multispectral system efficacy is indicated for methods that discriminate oil based on spectral reflectance or transmittance (including possible thickness detection). For detection of oil based on colour, multispectral methods are similar to cameras.*

Oil located within sea ice

	Young ice	Level FY ice	Level MY ice	Deformed ice	Ice with algal growth	MIZ
Sonar	**POSSIBLY** Would require identifiable change in scattering	**POSSIBLY** Will depend on sonar characteristics and depth of oil	**POSSIBLY** Will depend on sonar characteristics and depth of oil	**POSSIBLY** Will depend on sonar characteristics and depth of oil	**POSSIBLY** Will depend on sonar characteristics and depth of oil	**POSSIBLY** Will depend on ice types and oil detection success with these types
Fluorescence	**LIKELY** Oil will be near basal layer of thin ice	**POSSIBLY** Scattering and absorption within the ice may be a major issue	**POSSIBLY** Scattering and absorption within the ice may be a major issue	**POSSIBLY** Scattering and absorption within the ice may be a major issue	**POSSIBLY** Algal fluorescence will further complicate detection	**LIKELY** Oil will be near basal layer of thin ice **POSSIBLY** for other ice types
Cameras	**LIKELY** Should be visible in thin ice	**UNLIKELY** Except where oil is at or near basal layer.	**UNLIKELY** Except where oil is at or near basal layer	**UNLIKELY** Except where oil is at or near basal layer	**UNLIKELY** Except where oil is at or near basal layer	**LIKELY** Should be visible in thin ice. **UNLIKELY** for other ice types
Radiometers	**POSSIBLY** (Adams, 1975)	**POSSIBLY** (Adams, 1975)	**POSSIBLY** (Adams, 1975)	**POSSIBLY** Complicated by ice thickness variations	**POSSIBLY** Algae will complicate spectral signature	**UNLIKELY** Complicated by highly variable ice/sunlight conditions

Table 4.4. *Evaluation matrix for Oil located within sea ice. Matrix shows general ice conditions found in the upper Arctic Ocean (columns) and the sensors that show promise to detect oil from below (rows). Efficacy is shown for favourable water conditions (e.g. good visibility). See Table 1 for effects of visibility. Multispectral system efficacy is indicated for methods that discriminate oil based on spectral reflectance or transmittance (including possible thickness detection). For detection of oil based on colour, multispectral methods similar to cameras.*

4.2.4 Sonars

Sonar systems have the advantage of being effective independent of visibility conditions, and for AUV-mounted systems looking up at the ice, they are not particularly range limited except for higher frequency systems. Based on CRREL ice tanks tests described in Chapter 3 and Wilkinson et al., (in prep), oil should be detectable for layers as thin as a few centimetres or less when occurring in topographic irregularities at the base of the ice. For very thin layers, which might occur when dispersed oil accumulates at the base of very level ice it is currently unknown whether oil can be identified by its backscatter signature.

There are several cases where interpretation of sonar signals may be more complicated. In new ice conditions such as frazil or grease ice, oil is likely to spread thinly on the ocean surface, mixed among the ice crystals. In this case there is unlikely to be a distinction between oil and ice in backscattered signal and oil may be identifiable by a characteristic (and currently unknown) backscatter signature. In thin nilas, oil may percolate into the porous ice or rapidly be encapsulated. Because of the resultant ice/oil matrix, a distinct oil acoustic signature may be absent.

In a growing (freezing) MIZ, unconsolidated frazil crystals, patches of open water, and growing pancake ice will complicate the interpretation of acoustic backscatter. This is compounded by the presence of a wave field.

For complex ice morphology, such as around ridges, rubble fields, or the stamukhi zone, in principle sonar will be effective due to thick accumulations of oil on the ice underside. However, the complexity of the ice bottom, rafted blocks, gaps and voids, may complicate the clear interpretation of the backscatter signal.

Sonar detection of encapsulated oil has not been attempted, and its efficacy is unknown. In principal, however, relatively thick (several cm or more) layers of encapsulated oil may be identifiable very close to the ice underside (perhaps a few centimetres) with lower frequency sonars that can penetrate into the ice cover.

4.2.5 Laser Fluorometers

In contrast to sonars, laser fluorometers are more limited by conditions in the water column, including ambient light, turbidity, and range to target. It may perform well for very thin slicks, or where ice is interspersed with oil (frazil and new ice) and open water – conditions where sonar is less likely to be successful. For encapsulated ice, provided the oil is trapped near the base of the ice such that scattering by the ice is minimal, fluorescence may be effective. How fluorescence is affected by complex ice morphology is not known, although deep ridge keels may impose a practical limitation as safe AUV operation will enforce a minimum distance to the ice bottom that could potentially exceed the range of the UV laser, given the strong attenuation of UV in seawater. Visible light is attenuated less (especially in the blue and green wavelengths) and thus may be used for optical excitation, but these wavelengths will induce fluorescence to a lesser degree than UV light (see section 3.2). On the other hand, quantifying the changes in the returned signal (ice vs. oil) may provide some useful information regarding the presence or absence of oil within an ice cover (see section 3.4.3).

Fluorosensors are limited by ambient light (Hansen et al., 2009), which can be much stronger than the fluorescent signal, so they are actually more effective in the low light, dark conditions generally found under sea ice with a snow cover.

4.2.6 Cameras

Cameras should be effective in most cases under continuous ice cover due to the strong contrast between oil and ice. In situations where the oil may become mixed into the ice cover (frazil ice), or in open water, cameras may be less effective. In low light and darkness, a light source (i.e. strobe) is required, which limits the practical range. Due to scattering of light in the ice, the usefulness of camera systems to detect encapsulated oil may decline strongly with depth to the oil in the ice.

4.2.7 Multispectral radiometers

Traditional multispectral methods (e.g. Svejkovsky and Muskat, 2009) are unlikely to be effective given the complex ambient light environment under the ice, the strong attenuation of near infrared light, and in many (or most cases) the oil will not be thicker than the very thin slicks (<0.5 mm) that occur on the ocean surface. However the multispectral detection of transmitted light (Adams, 1975) may be possible if the absorption characteristics of the oil is different from that of the ice cover and water column. There may not be sufficient spectral variation in reflectance underwater for thicker oil deposits (> 1 mm) that can add information above and beyond the strong broadband absorbance of oil. However a hyperspectral sensor may provide the needed spectrum band granularity needed for separating spectral signals, although narrower wavelength bands have poorer signal to noise ratio. Many multispectral radiometers are small and have already been incorporated on AUVs and ROVs under ice (e.g. on the ICEBell and SIPEX II cruises, Williams et al., accepted).

4.3 A sensor suite payload

It is difficult to select a particular sensor suite without more extensive tests. However, as noted above, many of the sensors may be complementary. It would be advantageous to incorporate several of these sensors (and possibly some of the sensors that detect hydrocarbons in situ) in the vehicle payload. Before this is done there are several considerations that must be addressed:

4.3.1 Payload

The payload an AUV/ROV can hold is a function of the real estate available on the vehicle and the power available to run the sensors. Generally speaking the larger AUVs/ROVs have more payload and power options than smaller AUVs. For example the SeaBed Class AUVs used recently under sea ice in the Antarctic and Arctic (Williams et al., accepted) can accommodate a compact single beam sonar, camera, compact hyperspectral sensor (e.g. SATLantic Hyperspectal OCR), and other auxiliary sensors such as multibeam sonar, ADCP, and CTD (see Chapter 3.6). Laser fluorosensor systems - such as that tried in heavy oil tests at Ohmsett (Hansen et al., 2009) - are currently somewhat large for easy incorporation in this sensor suite. The Tethys mass spectrometer has been used on a large ROV (Camilli et al., 2011), but would take up significant space on moderate sized AUVs. One advantage of twin-hulled AUVs like the SeaBed class vehicles is the in situ sensors (LISST or fluorometer) could be carried on the lower hull without taking up space for upward-looking sensors on the upper hull.

A sensible system (until further tests are undertaken) might be to include a single beam sonar, camera, and compact laser fluorosensor system as the remote sensing suite. For mapping of the ice underside, it may be advantageous to include a multibeam sonar at the expense of a multispectral unit if space is an issue.

4.3.2 Timing stamps

It is important that all sensors located on a vehicle have the same timestamp and their data are geo-located. This makes the interpretation of co-incident data easier. This is an advantage of a large sensor suite on a single platform – multiple sensors can provide coincident and complementary data.

4.3.3 Interference

It is important to test multiple sensor options for interference or cross-talk between sensors. For example an ADCP may interfere with data streaming in from a sonar system if frequencies are similar. This is also true for multibeam and single beam sonars on the same platform. Laser fluorosensors will generally produce weak signals that are unlikely to cause interference with camera systems. Indeed, intensified CCD systems could be used to image the fluorescence (e.g. Sasano et al., 2012).

4.4 Sensor data fusion and processing techniques

With a suite of several sensors, data fusion will increase the chances of positive detection of oil. This fusion can simply be a trained user monitoring multiple data streams on the surface while the mission is underway, or it can involve formal data fusion techniques, either of the underway data, or in post-processing.

The simplest method of data fusion is to analyse multiple data streams in real-time. In this case, several scalar data sets can be transmitted in real-time to an operator. Simple time-series data can have very low data volume, such as fluorescence strength, multispectral reflectance or transmittance (which can simply be reduced camera imagery into average brightness in each colour channel) and multiple acoustic returns from a single-beam sonar. These may require some on-board processing – for example, sonar data might have acoustic backscatter strength threshold so that the interface (oil-water and oil-ice) positions only need to be transmitted to the user. In many cases, these data may be sufficient to identify oil and more detailed analysis or post-processing may not be required.

However, for a human user it is often easiest to identify oil with digital imagery (see figure 3.3.1). Higher volume data can also be telemetered to the surface using advanced data compression techniques and acoustic telemetry. These are discussed below.

4.4.1 Image classification and data fusion

Given the suite of sensor data that may be available from an AUV with a large sensor payload, there are a number of advanced processing techniques that might be useful to constrain estimates of oil location and volume.

When collocated data is available from multiple sources, a suite of standard advanced processing techniques can be used to discriminate regions of oil from regions without oil. The simplest of these is to use is an unsupervised classification scheme where the dimensionality of the data set (for example, airborne multispectral imagery can readily classify vegetation because of its strong reflectance in near IR) is used to create clusters of points in the image with similar spectral signatures. In simple terms, supervised classification works on similar principles, but a user identifies “training” regions or regions of interest with similar data values, and these are then used to automatically identify regions throughout the imagery. Somewhat more sophisticated techniques have been applied to the identification of oil over open water with airborne multispectral data (Svejkovsky and Muskat, 2007). Here, they used an artificial neural network to run a supervised classification.

In most cases where we expect the oil spill under ice to have thicknesses of greater than 1 mm, this method becomes less useful because the spectral reflectance curve flattens as the oil thickens (Svejkovsky and Muskat, 2006), and becomes black. This reduces to the simplest case of classification, where an image mosaic containing regions of oil and clean ice, could be classified by simple thresholding of the color-corrected mosaic (described in Chapter 3) in a single band.

But in our case, we can have multiple, distinct and collocated data streams. For instance, a multibeam sonar map will provide information on the vertical variation in ice thickness. In this case, we might expect large hollows to have oil pooled to greater thicknesses. Then, when the multibeam map is collocated with an image mosaic, it then provides a second dimension (ice draft or thickness) to the brightness map that may be used in a simple supervised classification scheme. By the same token, a system which used fluorescence imaging (e.g. Sasano et al., 2012) could also include a fluorescence channel to the image mosaic.

Processing of these multidimensional spatial data sets would need to occur post-mission, given the large data volume (although see below for advanced data compression and telemetry that could be used to provide high-volume data in real time). In real-time, it may be more efficacious to use low volume data sets. Encapsulated oil is a prime candidate as traditional imagery is unlikely to be particularly useful in this case. While the expected success of any of the one-dimensional datasets (e.g. radiometer, fluorescence, and single beam sonar) for this application is uncertain, by examining all three data streams together should greatly increase success. Again, however, no experimental tests of these systems have been tried, so it is somewhat premature to determine what processing and interpretation techniques might be useful.

There are also advanced techniques that could be applied to fuse data sets that have different dimensionality. An example is the oil slick thickness data set expected from single-beam sonar. This may be able to be used with the multibeam map to extrapolate from one-dimensional to two-dimensional thickness using kriging or similar data interpolation techniques. An alternative to this would be to use a multibeam echosounder – for example the SeaBat system used at Ohmsett to map heavy oil deposits (Hansen et al., 2009). In this system, the raw echosounder data is available for post-processing, so that beam-forming could be done after, as opposed to onboard. This may then allow multiple returns along each beam so that a map of both the oil-water and oil-ice interfaces could be produced. The downside is this system is much larger than compact multibeams like the Imagenex 837 DeltaT, which more readily fits on small AUVs.

4.5 Vehicle navigation and sampling strategies

There are two components to a successful AUV mission. Above we have discussed the sensor suite essential for the detection of oil under ice. The second component is the operation of the vehicle itself. This includes vehicle navigation, telemetry of data to the surface, and mission strategies. These concepts were briefly introduced in Chapter 2. In the following section, these issues are discussed in more detail.

4.5.1 AUV navigation

Most underwater vehicles carry a diverse suite of navigation sensors that together provide a redundant and often conflicting set of pose estimates. Underwater, a body can move through six degrees of freedom, and on most vehicles four of these six degrees of freedom are directly measurable: depth, roll, pitch, and heading. This is the case on manned submersibles and tethered remotely operated vehicles as well as on free-swimming AUVs. Onboard pose estimators often simply accept measured values as truth, or minimally filter measured values to smooth out noisy signals. Underwater localization is then reduced to estimating the remaining two degrees of freedom corresponding to horizontal position. There are several approaches commonly in use, described below in order of the amount of additional infrastructure required.

An underwater vehicle can be equipped with a velocity sensor. On any vehicle expected to work within a few hundred meters of the seafloor, the typical sensor will be a doppler velocity log (DVL), which measures 3-D velocity relative to the terrain. These sensors only work within range of the terrain, however, which is dependent on their operating frequency. For 1200 kHz systems, for example, the working range is about 40 meters. Lower-frequency units can achieve much greater range, at the expense of larger transducer sizes. When DVLs are out of range of hard terrain, velocity can usually still be measured relative to the water mass, but the AUV will not be able to detect the motion of the water itself as it moves through it. When a DVL is not available, velocity estimates can be derived from thruster speed or electrical current draw, or by integrating accelerometer measurements, but these are usually not the preferred methods because they are noisy. Regardless, once a 3-D velocity estimate has been determined a pose estimate can be derived by integrating the velocity estimate using the vehicle's attitude sensor to determine the direction of motion in the geo-referenced frame. The pose estimate will be relative to an arbitrary origin, but can be used for relative navigation. For navigation in an Earth-fixed frame, either velocity estimates must be available on the surface, where GPS can anchor the trajectory, or additional infrastructure is required.

External navigation infrastructure is often provided underwater by a network of acoustic beacons. The particular system used depends on the deployment context, but it is usually a long-baseline (LBL) or ultra-short baseline (USBL) network. In these networks, positions are computed based on the acoustic travel time of signals sent between the vehicle and a set of beacons. The beacons may be moored to the seafloor, attached to a surface buoy or ship, or deployed through sea ice, but they generally have a location known to the underwater vehicle. The vehicle localizes by interrogating the network, transmitting an acoustic signal. The beacon responds with its own acoustic signal, and the vehicle determines its range to the beacon by measuring the response time and multiplying by the speed of sound. In traditional LBL navigation, the robot interrogates all of the beacons in the network simultaneously, and if, after outlier rejection, at least two reasonable ranges can be determined, a fix is computed geometrically by intersecting the horizontal plane at the robot's depth with the two spheres induced by the ranges to the LBL beacons (Milne, 1983). If the ranges are in fact reasonable, then in a network with two beacons there will be two solutions, symmetric about the line between the beacons (called the *baseline),* and the ambiguity is resolved by laying out the network ahead of time to keep the vehicle to one side of the baseline at all times. A simple on-board pose estimator may take these fixes as truth, using high rate velocity-based pose updates as it moves, and resetting the integrated position based on acoustic fixes when they are available. The two methods can also be used together in a complementary filter (Whitcomb et al., 1999). There are several variations to LBL that are dictated by context. In the case of USBL, a 2-D bearing measurement (comprising azimuth and elevation) to the beacon can be made, though the use of a transducer array. A vehicle’s location can be estimated passively by listening to the interrogations and responses and then measuring the difference in travel times, yielding a hyperbolic solution (Jakuba et al., 2008). Finally, position fixes estimated on the surface (e.g. through acoustic devices too large to carry onboard a vehicle) can be combined with GPS measurements and then transmitted to an under- water vehicle, either via tether, or using an acoustic modem. Another approach is to compute ship-relative fixes underwater, and then add global context from GPS via an acoustic link (Eustice et al., 2007).

There has been increased interest recently in the idea of using underwater vehicles to map areas that are not fixed to the seafloor. Those concerned with security of ocean- going vessels would like to use robots to autonomously inspect hulls for sabotage, a challenging problem due to the general lack of distinguishing “terrain” on the side of a ship that could be used as a navigation landmark. Nonetheless, researchers have used SLAM (Simultaneous Localization and Mapping) techniques to map ship hulls using either multibeam (Walter et al., 2008), or using cameras (Kim et al., 2009). While neither of these studies explicitly allow for the ship to move, it is clearly a forthcoming step in the research.

More directly relevant to the work here is the recent use of AUVs to map moving icebergs and sea-ice. Icebergs present a very challenging and risky target for mapping, as they can be quite large, fast moving, and have significant draft. A good proof of concept of a solution to this problem is presented in Kimball and Rock (2011), in which the goal is to map the sides of a moving, rotating iceberg with multibeam while circumnavigating it. The approach therein augments the set of variables being estimated with the velocity (in translation and rotation) of the iceberg, so that deformations that might otherwise be introduced into the map to make it self-consistent are instead used to estimate iceberg motion. A significant accomplishment of their work is that the iceberg is not itself instrumented; all iceberg motion estimation must be derived from vehicle odometry and the consistency of the derived map, using only a prior model assuming approximately constant iceberg velocity. Our own work on mapping the underside of drifting ice floes makes use of measurements of DVL measurements with the DVL pointed up at the ice. We also consider moving floes with floe rotations and translations available from the ship moored to the floe (Williams et al., accepted). On Seabed-class AUVs, which use a fiber-optic gyro for attitude sensing, the dead reckoning error when using DVL is about 0.5% of distance travelled. This error is significantly reduced by the incorporation of constraints from the mapping sensor (in this case, the multibeam sonar) in a SLAM framework to the binning resolution of 0.25 to 0.5 meters. The absolute (floe-referenced) navigation error is dominated by the uncertainty in acoustic ranging, to about 1 to 2 meters, which can be reduced by matching features and draft estimates between the multibeam and surface-based data.

4.5.2 Underwater communication and data compression

A key capability for rapid oil spill search and detection with AUVs is the ability to transmit data in real time to the operator at the surface so that detection of oil can be made immediately and the vehicle mission can be modified while underway in response to detection.

Historically, telemetry from AUVs has been limited to basic vehicle state information interspersed with the occasional measurement from one or two simple sensors. This level of communication has proven adequate (if unsatisfying) when the only decision facing an operator is whether or not to abort the mission of a single vehicle. Missions, however, may now involve multiple vehicles working towards a loosely defined set of goals, in dangerous and unconstrained environments such as under ice. These goals, rather than being pre-programmed, may be based on complex analysis of “rich” data sources such as imagery. Architectures such as MOOs-IvP (Benjamin et al., 2010) and DAMN (Rosenblatt 1997, Rosenblatt et al., 2002) grant AUVs increasingly high-level autonomous control over mission execution and goal-setting, yet these advances have not been met with similar advances in AUV telemetry. Transmitting complex high-resolution data, such as photographs or sonar imagery, remain out of reach for all but a few special purpose communication systems.

The diversity of AUV missions, ranging from shallow water mine hunting to under-ice exploration, has led to most users “rolling their own” software solution for encoding and decoding messages. Many of these are based on the early CCL (Stokey et al., 2005) standard for acoustic communication, which provides a number of standard 256-bit encodings for individual samples of depth, latitude, bathymetry, altitude, salinity, and other data. CCL relies only upon quantization to provide compression and makes no use of the inherent correlation between successive samples from most instruments. In 1996, Eastwood et al., proposed predictive coding methods that could be used in concert with these methods to improve performance (Eastwood et al., 1996). Schneider and Schmidt (2010) have incorporated predictive coding into their recent work with DCCL, sending up a mean value followed by smaller, quantized, delta values.

For data that is highly correlated, transform codes allow much higher efficiency. Transitioning away from transmitting small numbers of samples has an additional benefit - compressing more (correlated) data at once increases the efficiency of transform compression methods.

Figure 4.5.1 shows the result of piecewise compressing a long series of reduction potential and temperature data. When the data was compressed a few samples at a time, the compression was much less efficient than when long sequences were compressed simultaneously. Transform compression methods typically follow a standard pattern. First, a source coder such as the Discrete Cosine Transform (DCT) or Discrete Wavelet Transform (DWT) exploits the inherent correlation within most data, and concentrates the energy of the signal into a sparse set of coefficients. Next, these coefficients are quantized and entropy encoded (Saha, 2000). Wavelet compression is described as being especially appropriate for functions that are “piecewise smooth away from discontinuities” (Donoho et al., 1998). There has been additional study suggesting that wavelet transform compression techniques are particularly applicable to underwater images, video, and acoustic imagery (Hoag and Ingle, 1994; Hoag et al., 1997, Goldschneider, 1997; Murphy et al., 2010) Eastwood et al., (2005) evaluated the performance of an early wavelet-based image compressor, EPIC, in 1996, but most recent work has focused on using high bandwidth acoustic tethers. The underwater community has investigated transmission of imagery and video data over acoustic tethers (Suzuki et al., 1992, Pelekanakis et al., 2003, Sayers et al., 2005) using transform compression algorithms such as JPEG, yet these solutions rely on artificially high throughput by positioning a surface ship directly above the AUV. This is impractical in many autonomous operations and impossible for those in polar environments.

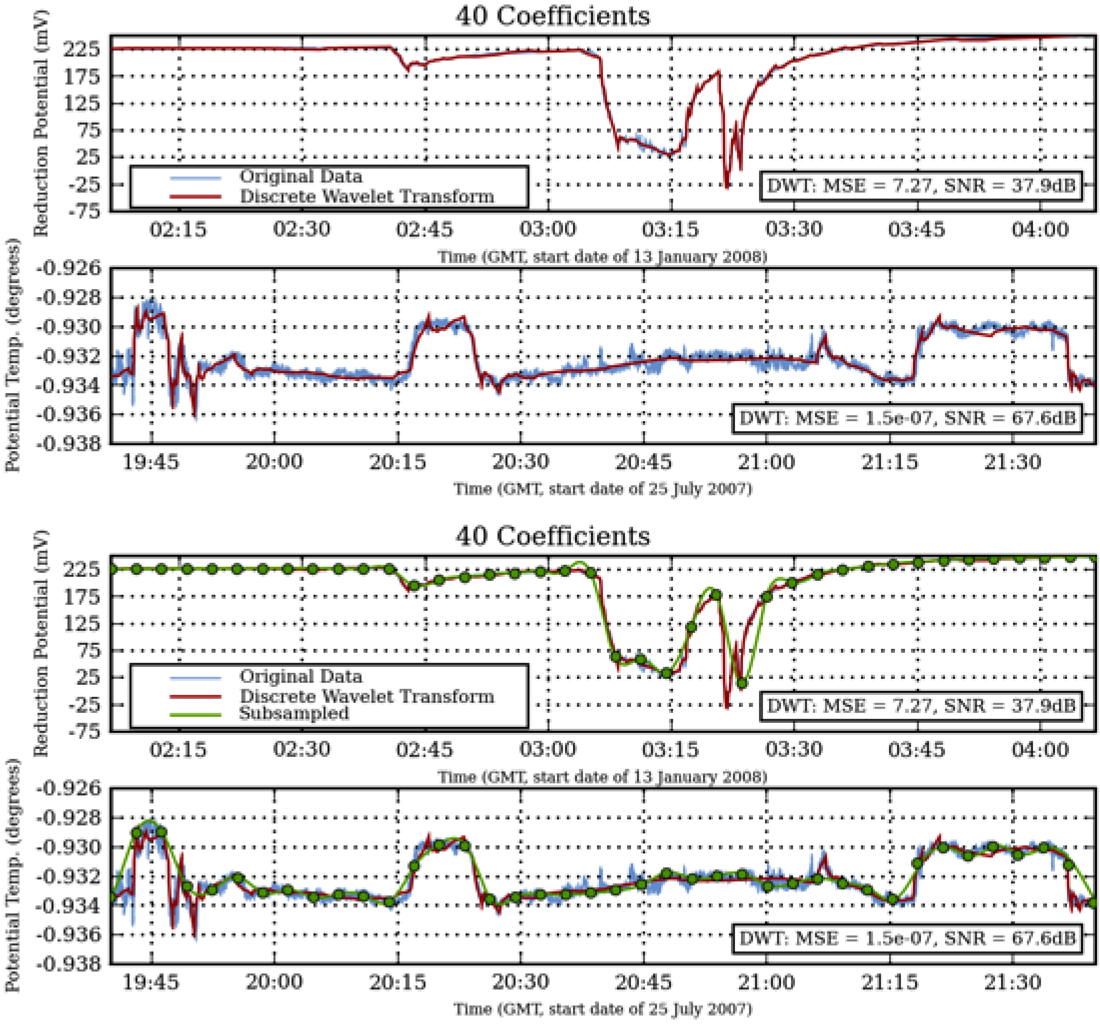


Figure 4.5.1. *Discrete Wavelet Transforms provide very high fidelity for scalar environmental data at extremely high compression ratios (top). In comparison to subsampled data it also ensures that important peaks in the data are not aliased (bottom).*

4.5.3 Resource Prioritization

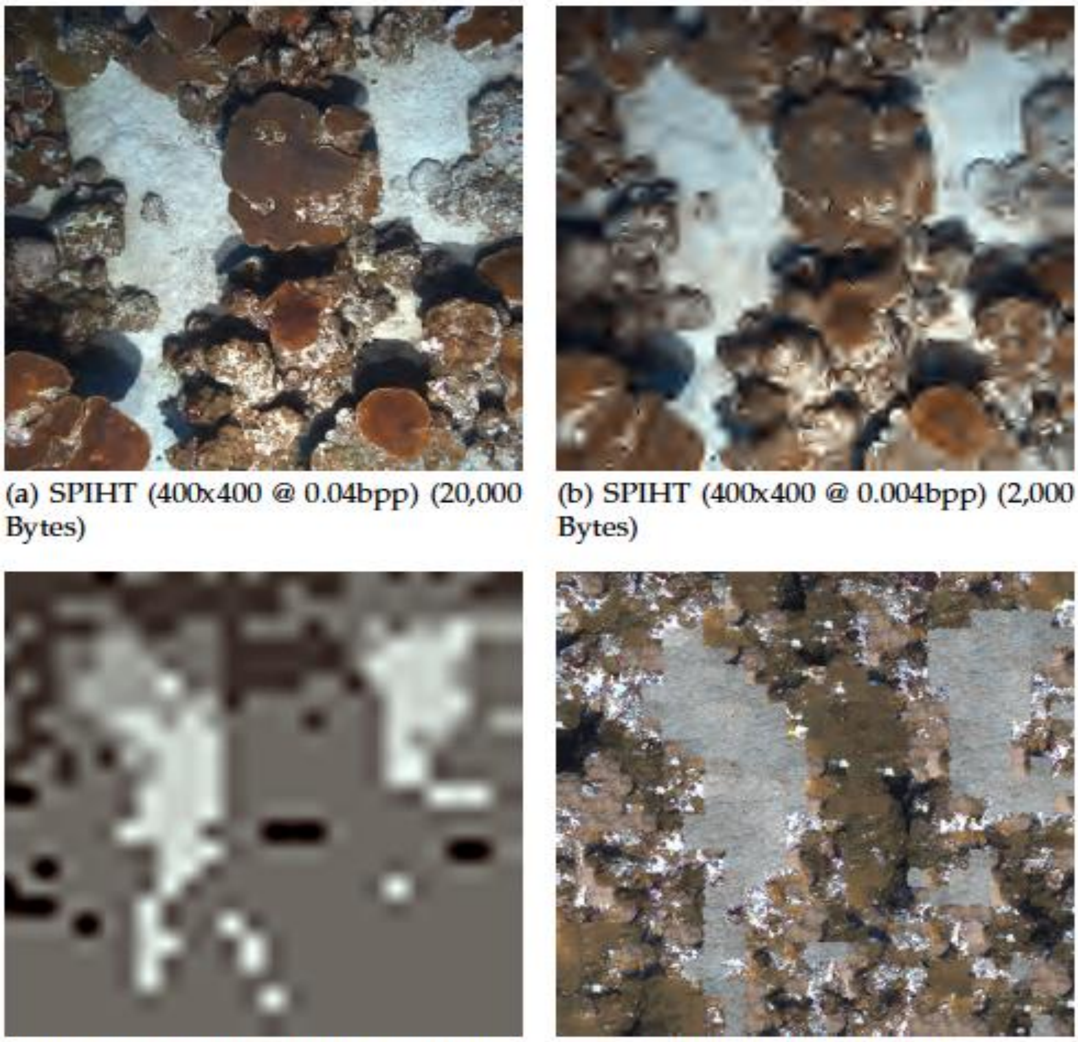
Over the course of a dive, a single AUV can easily collect millions of samples of scalar environmental data, ranging from temperature data to salinity, from measured methane concentrations to vehicle depth. The same vehicle may easily capture tens of thousands of photos, and sonar imagery. Modern AUV platforms generate orders of magnitude more data than could possibly be transmitted to the surface – the first task facing any telemetry system is to prioritize which data should be transmitted.

For vehicles with multiple sensors of interest, it is also necessary to multiplex the transmissions between those sensors. For example, coincident scalar data from single-beam sonar, radiometer, and laser fluorometer may be sent to the surface while underway. These steps can be quite simple, such as always sending the most recent resource registered by a single sensor. More complex missions may involve significant computation in this step, such as identifying oil through image analysis on-board a vehicle. Multiplexing approaches could range from a round robin scheduling-based approach, to priority queues, or computed metrics.

4.5.4 Progressively Encoded Compression

After identifying a resource for transmission to the surface, that resource must be compressed to maximize the throughput of the channel. Progressively coded compression methods – preferably fully embedded ones - transmit enough data to the surface to reconstruct a low-quality “preview” of each autonomously selected resource before moving onto a new resource. Due to the progressive nature of the encoding, each new piece of data received on the surface will allow an increasingly high-quality representation of the resource to be reconstructed. This serves two opposite, but equally important purposes. If the “preview” piques the operator’s interest, the operator can request more encoded data from that resource to refine the already-transmitted data with no wasted transmissions. Every byte sent up for the preview will be used as the basis for the higher-quality version. If, on the other hand, the resource is uninteresting, the operator may be able to determine that after only a few transmissions and avoid wasting further bandwidth to deliver a full preview. The success of wavelet-based analysis techniques in the underwater domain suggests the use of fully embedded coding methods that supported wavelet compression. The Embedded Zerotree Wavelet (EZW) (Shapiro, 1993) algorithm is one noted early example, which led to the more efficient Set Partitioning in Hierarchical Trees (SPIHT) (Said and Pearlman, 1996) coding method and others (Tian and Wells, 2001; Walker, 2000). These quantization and entropy coding methods can be coupled with the 1D, 2D, or multidimensional Discrete Wavelet Transform, allowing compression of both time-series scalar data and imagery using the same algorithm. Previously obtained data can even be analysed to determine the best wavelet for a given type of data, matching the compression to the underlying sensor.

However, we note that even with the highly efficient wavelet compression, we require multiple acoustic packets to transmit a single image to an operator as illustrated in Figure 4.5.2. While this may be acceptable in some scenarios, an alternative has recently been proposed that would allow transmission of an image through the transmission of a single packet as shown in Figure 4.5.3. Instead of compressing the imagery, it is segmented in-situ on the AUV into different classes. This segmented image is then subsampled, encoded and transmitted to the surface. A dictionary of classes on the surface is used to reconstruct representative imagery. The basic idea here is that the human operator may be prepared to sacrifice the details in the actual imagery for an accurate representation of the scene. We believe that such algorithms hold great promise for imagery of oil in an ice-covered environment.



(a) SPIHT (400x400 @ 0.04bpp) (20,000 Bytes)

(b) SPIHT (400x400 @ 0.004bpp) (2,000 Bytes)

(c) SPIHT (400x400 @ 0.0004bpp) (200 Bytes)

(d) Synthesized (116 Bytes)

***Figure 4.5.2**. Two dimensional imagery can be compressed with the same techniques as are used for scalar data. See figures (a) and (b). However, even these methods fail when compression ratios are extreme, figure(c). In-situ classification of the imagery and it subsequent reconstruction on the surface provides a mechanism for transmitting imagery within single 256 byte packets.*

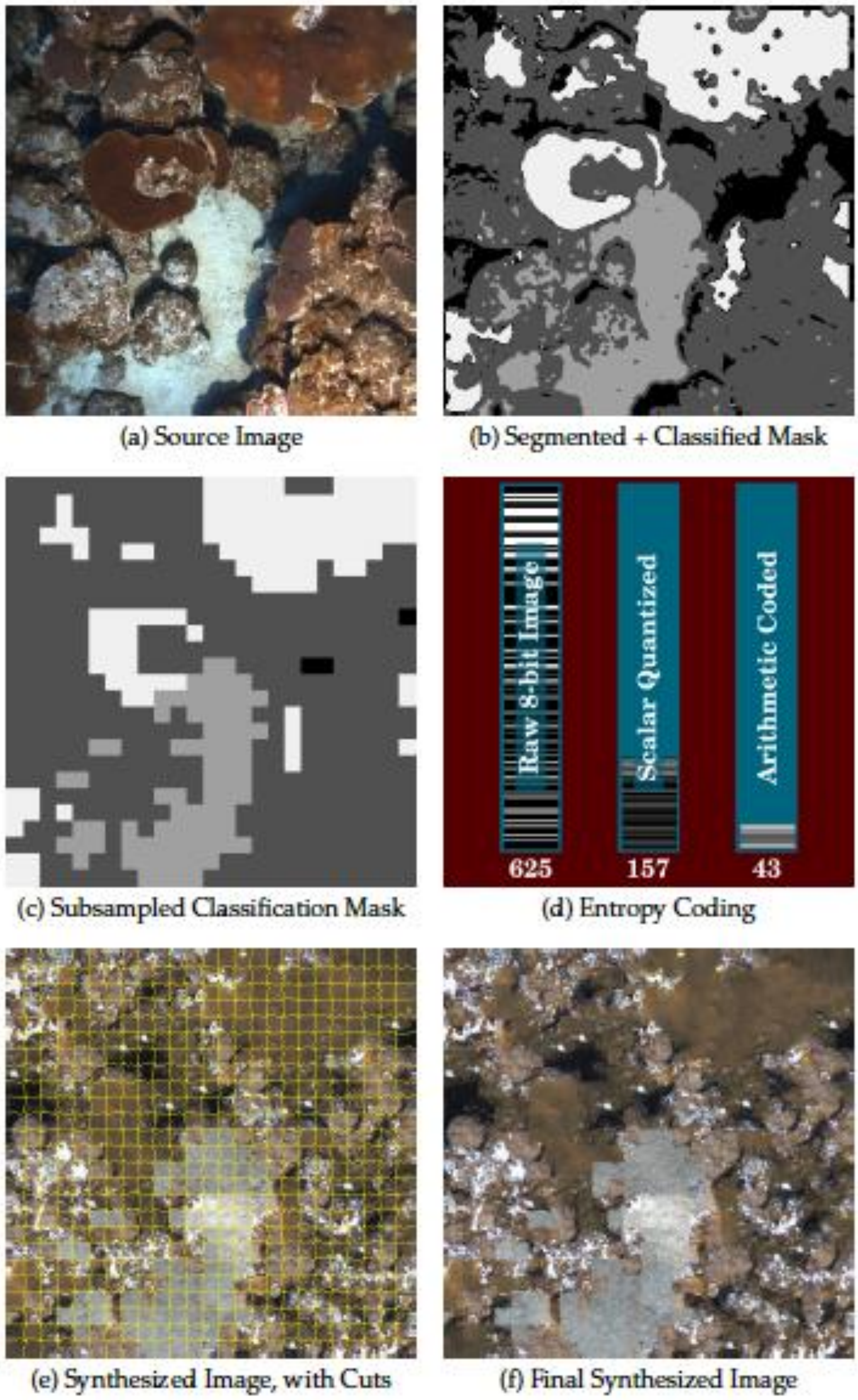


Figure 4.5.3*. Synthesizing images at extremely high compression ratios. The original image (a) is segmented into a predetermined set of classes (b) based on our expectations of the imagery. This segmented image may be subsampled (c) before being encoded (d) and transmitted to the surface where it is synthesized (e) and presented as an accurate representation of the scene.*

4.5.5 Adaptive sampling strategies

Given the capabilities outlined above for telemetry of sensor data during a mission, we can explore possible strategies for an oil spill search and detection scenario under sea ice. This will be explored in more detail in Chapter 5. Here, we point out two possibilities for a mission where the AUV is initially programmed for a coarse “lawn-mower” grid search strategy. This is precisely the mission strategy that has been used to map ice floes with multibeam sonar (Williams et al., accepted), except that in this case, the vehicle would cover a larger grid at the expense of complete mapping of the ice underside. This is a trade-off between the size of the search area and the degree of coverage. For example the swath width of a multibeam sonar is a function of the depth of the vehicle. Once oil is identified (by sensor data criteria still to be determined), this mission can be altered to provide more comprehensive coverage of the detected spill. In the simplest case, the search mission would be aborted, and a predefined smaller grid mapping mission would be completed prior to returning to the deployment hole (figure 4.5.4a).

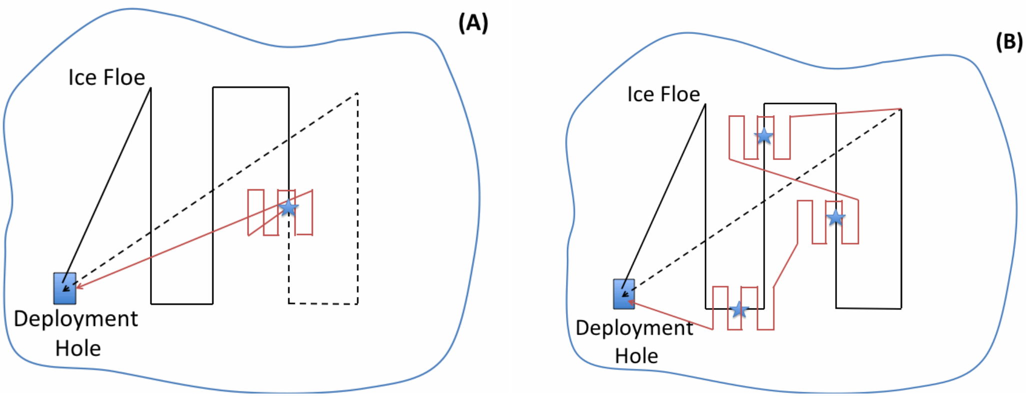


Figure 4.5.4. *Oil spill search mission strategies. Black solid lines indicate the initial search mission track that has been completed; dotted black lines indicate the portion of the mission that has not been completed. Red lines represent a mapping mission triggered by candidate oil spill locations identified by data obtained during the search mission. (A) Upon locating probable oil under the ice, a mapping mission is initiated, after which the search mission is aborted and the vehicle returns. (B) The search mission is completed; candidate spill locations are evaluated and the vehicle performs mapping missions at each prior to returning to the deployment location.*

A more complex mission would be to complete the original search mission, and identify key candidate oil locations. These locations could be identified either by the operator via real-time telemetered data and relayed to the vehicle, which would then compute a new mapping mission with each site mapped in turn (figure 4.5.4b). Alternatively, the sensor data could be processed on board and the locations determined automatically. Here, several levels of processing are possible. The vehicle could process data and determine the mission entirely autonomously, or some level of sensor data fusion could occur on board and a reduced data set sent to the user, or, selected unreduced data could be sent to the user. While a completely or partially autonomous mission is attractive due to the limited need for data telemetry, there may be risks associated with the vehicle identifying false positives, particularly given that real-world testing of scenarios with oil spilled under sea ice is not possible. The most prudent strategy would then involve significant volumes of telemetered data.

4.6 Summary

The main factors controlling the effectiveness of a particular sensor for detecting oil under ice are:

1. the location of the oil (e.g. under the ice, in ice, or in the water column),
2. the ice conditions (e.g. continuous, fast ice cover or broken, drifting pack, deformation, etc.),
3. the upper ocean conditions (e.g. turbidity, visibility stratification, etc.).
4. nature of the spill (e.g. blowout at depth under drifting pack, near surface spill under fast sea ice, etc.) and
5. the amount of oil split, its properties and thickness, and importantly the detection threshold of the particular sensor or sensors.

These factors will determine the physical properties (e.g. weathering rate, oil spill thickness) of the oil, which in turn may have a significant impact on the performance of a specific sensor to detect the oil. There are are a number of factors, both environmental and logistical, that affect the ability of a particular sensor on a particular platform to make a positive detection. The primary sensors that show promise for remote detection of oil under sea ice on an AUV platform are sonar, camera systems, laser fluorosensors, and multispectral radiometers. Each of these sensors has specific advantages and limitation for any given scenario (spill thickness, ice and ocean conditions) such that an AUV payload containing some or all of these sensors is desirable. At present, all these sensors can be accommodated together on small to moderate sized AUVs, with the possible exception of a laser fluorosensor (for which power requirements and size of existing prototypes are difficult to accommodate). Detection of oil will then be based on interpretation of these data streams in concert, either ad-hoc by an operator or with more sophisticated data fusion schemes. However, until further experimental tests of these systems are carried out, the most effective scheme for data interpretation is unclear. Sensor development, testing and validation must be a priority.

For an effective complete system, accurate navigation and telemetry of real-time data are highly desirable, if not essential. Modern AUVs with acoustic navigation are capable of very precise navigation under sea ice. The limited bandwidth available for acoustic transmission of data can be effectively mitigated through data compression techniques. These bandwidth issues generally do not apply to ROVs, for which higher data rates can be accommodated via the cabled tether.

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CHAPTER 5. DETECTION SCENARIOS AND NEEDS ANALYSIS

In Chapters 1-4 we discussed the basic operation of UUVs under sea ice, and the prospects for UUV operations under sea ice for the detection of oil spills. This included an assessment of the advantages and limitations of the most promising sensors that could be incorporated into a vehicle payload to detect oil under a variety of circumstances.

In an actual oil spill response, the success of a UUV mission will depend on a number of factors, including any logistical challenges with the operation and navigation of the AUV, the speed of deployment, and performance of the sensor payload under specific oils spill conditions (discussed in Chapter 4). In this chapter, we explore three oil spill scenarios and describe the operational details of a hypothetical mission to map the extent (and volume, if possible) of each. This also includes a discussion of an appropriate sensor payload for each particular case and the primary factors that are likely to affect the detectability of the spill.

As before, we concentrate primarily on AUVs because of their greater range capabilities, but we note that ROVs could play a role, particularly for small spills in difficult ice conditions and very shallow water. As hybrid ROV/AUVs develop in the future (i.e. ROVs with very long tethers and semi-autonomous operation) they will also play a role. There are a wide range of factors that will control the effectiveness of any particular choice of vehicle and payload, we focus this discussion primarily on the SeaBed class of AUVs that we have used successfully under sea ice in several regions (described in Chapter 2). Basic operations would be comparable for similar small to medium sized AUVs, such as the Remus 100 (e.g. Pluedemann et al., 2012) or larger AUV such as Autosub (Wadhams et al., 2006).

5.1 Spill release scenarios

Oil spill detection in the polar regions presents additional logistical and operational challenges above and beyond those present in other regions. These include the extreme environment, the remoteness, the total darkness and intense cold in winter and of course the presence of an often complex and dynamic sea ice cover. While an AUV-based detection and mapping strategy offers certain advantages (see Chapters 1-3) that mitigate many of the challenges of operating in this environment, these factors also present logistical challenges to AUV operations not present in less extreme and open water environments.

As described in Chapters 1 and 4, the nature of an oil spill, and hence, strategies for oil spill response, is shaped by the particular sea ice environment in which it has occurred. The wide variety of sea ice conditions that occur, varying seasonally and regionally (see Chapter 1) suggests that the most effective strategy for response will vary for every incident. As discussed in Chapter 2, AUV missions under the ice have the advantage of being largely independent of ice and weather conditions. Nevertheless, both the ice and weather conditions will affect logistical considerations involved in deployment and recovery of the vehicle, and will affect the effectiveness of any particular sensor on the vehicle.

Additionally, how a particular spill manifests within the sea ice will also depend on the nature of the spill, i.e. the depth and rate of release, the volume of oil, and the type of oil.

There are a range of possible incidents that may involve a large-scale spill or release of oil into ice-covered waters. Some examples include, but are not necessarily restricted, to:

1. <u>Pipeline rupture:</u> a sub-sea pipeline breach would produce a localized spill in shallow water, most likely under fast ice.

2. Sub-sea blow out: such a blow-out could occur at a variety of depths under varied ice conditions. How the oil spreads will depend on the nature of the resulting oil/gas plume, the water depth and the mobility of the ice.
3. Offshore platform or mobile offshore drilling unit: This could include oil spilled beneath the ice, or oil spilled onto the ice surface
4. Shipping accident: If an oil tanker carrying a cargo of crude oil cargo runs aground or its hull is compromised in ice covered waters, a relatively thick slick might occur. Depending where the hull is compromised involve oil release could occur close to the waterline in the broken ice track around the vessel or under the ice itself. If the vessel sinks then oil could be released from near the sea floor, which potentially could result in a more dispersed spill. Subsequent dispersal of the oil will depend on ice conditions, ice drift rates and ocean currents. This class of oil spill has the potential to occur in the most remote of Arctic locations, away from established infrastructure or other marine support.

We make no judgement here on the likelihood of any particular incident, logistical constraints etc., but these illustrate the range of spill conditions that could occur. It is not possible within the scope of this report to consider all the possible scenarios that could occur in every environmental condition, but based on the scenarios listed above and the range of ice conditions in which they occur, we can define three prospective scenarios that are illustrative of the range of challenges that might be encountered in any particular spill. These scenarios are

- Scenario 1: Pipeline breach within the fast ice zone (near shore)
- Scenario 2: Blowout under drifting pack zone (far shore)
- Scenario 3: Shipping accident within the Northwest Passage (remote).

These are not necessarily the most likely scenarios that could occur, but are included to best illustrate the range of challenges for both AUV operations and the effectiveness of the sensor payload. Nor are they intended to be a comprehensive assessment. Nevertheless, they demonstrate most of the issues likely to be encountered in any particular scenario, and the range of considerations that would need to be made when conducting oil spill detection operations.

5.2 Scenario 1: Pipeline breach within the fast ice zone (near shore)

Scenario 1 is a near shore pipeline breach, or similar discharge of oil, within the fast ice zone on the North Slope of Alaska (e.g. Prudhoe Bay) occurring during the period of total fast ice cover, perhaps February. It is assumed that an emergency system detected the occurrence of the spill and the pipeline was shutdown relatively quickly, resulting in a relatively small spill in the order 10,000 barrels or less. It is not known where under the fast ice the breach of the pipeline occurred.

5.2.1 Ice conditions

We assume a continuous, reasonably level, fast ice cover. In the Prudhoe Bay area, fast ice can be very level over large areas. However, there are irregular undulations on the bottom of the ice due to variations in ice growth due to the varying insulation provided by spatial variations in snow loading (Wadhams and Martin, 1990). In some areas, there may be significant amounts of deformed ice and grounded ridges (e.g. the Stamukhi zone, Reimnitz et al., 1978) where drifting pack interacts with the fast ice.

In very shallow regions, normally directly adjacent to the shoreline, the growing sea ice can reach a thickness where it is able to freeze to the seabed. This is known as bottom-fast ice. As the sea level rises and falls with the tides, there is differential motion between the bottom fast ice and the adjacent free-floating fast ice. The result of which are tidal cracks. Both AUV and ROV operations are impractical in this ice regime.

In this scenario it is assumed that the pipeline runs under relatively level fast ice, although the implications of heavily deformed ice in shallow water are touched on below, as this represents a significant potential hazard for AUV operations.

5.2.2 Oil dynamics

Oil, if more buoyant that the surrounding seawater, will rise through the water column breaking down into small droplets as it rises (Topham, 1975), although this process is depth dependent. At the underside of the fast ice most of these droplets will coalesce to form an oil slick. Because both the oil release point and the bottom of the fast ice are fixed the oil layer thickness builds up to form a slick which will then move outwards from the central region due to hydrostatic pressure differences. Laboratory and in situ testing under sea ice have shown that this thickness is range 0.5 to 1 cm (Dickins et al., 1975, Keevil and Ramseier, 1975).

Moving radially outwards, the oil will fill all available irregularities and preferentially flowing towards regions of thinner ice. This movement will either be dominated by the oil spreading out in narrow rivulets or filling up deeper and wider depressions (figure 5.1). When an individual depression is full, a rivulet of oil run will flow outward over the depression and into the next interconnected depression (Fingas and Hollebone, 2003, Wilkinson et al., 2007).

1.TYPICAL PATTERN OF OIL DISCHARGE NO. 1.

2.TYPICAL FLOW PATTERN,DISCHARGE NO.2
(discharge point-lower right)

Figure 5.1*. Oil forming small rivulets that move from one depression to the next. (left). Oil gathers in depressions to form under ice larger rivers. Also visible in the image are areas of thicker ice remaining as 'clean' islands surrounds by oil (right) (NORCOR, 1975)*

It is under-ice roughness the dominates an oil's behaviour, although the rate at which it is introduced, the viscosity of the oil, and the surface oil-ice-water interfacial tensions all play a role in determining the rate at which oil spreads under sea ice (Wadhams, 1976; Wadhams 1980; Malcolm, 1979, Wilkinson et al., 2007). The direction of the flow of oil will primarily be a function of the under-ice topography and oceanic currents. Individual sessile drops or slicks are quite difficult to move due to "sticking friction" between the drop and the skeletal layer at the ice/water interface (Lewis, 1976). Tests to quantify the movement of oil due to oceanic currents have shown that the minimum threshold current to move crude oil under smooth sea ice was in the order of 0.15 m/sec increasing to approximately 0.21 m/sec under slightly rougher ice (Cox and Schultz, 1980). Under ice currents are much lower than this in the Prudhoe Bay region, but can be greater in some fast ice zones such as off point Barrow (Shroyer, 2012). For this scenario is it assumed that currents are below this threshold. Ice thickness at the end of winter is typically 1.7-2.2 m (Wilkinson et al., 2007).

We assume an oil spill of approximately 10,000 barrels or 1500 m^3. Using the oil spreading model of Wilkinson et al., (2007), we might expect this to spread under level ice over an area of order 200m X 200m or less (Figure 5.2). As there is a finite amount of oil on the underside of the ice, and that February is still within the ice growth season it is likely that sea ice may form a lip around the perimeter of the oil pool, inhibiting the further horizontal motion of the oil. If the transfer of heat from the ocean/ atmosphere to the ice-oil-ocean interfaces is sufficient for ice growth, the ice will continue to grow beneath the oil pool eventually completely encapsulating the oil within the ice matrix (NORCOR, 1975). In situ experiments by Lewis (1976) showed that it took about a week for ice to start to grow beneath the oil spilled under 160 cm thick ice (March in the Beaufort Sea). Faster encapsulation rates, more like 24-48 hours, were seen during oil spill experiments performed in the winter of 1979/80 (pers. Comm., 2013). The encapsulation process would be quicker under thin ice, and may not happen at all under thicker ice.

In summary, the oil is likely to spread over a relatively limited area, its thickness will be variable depending on the under ice topography, and the spilled oil is likely to be encapsulated within the growing ice cover over a period as short as a few days.

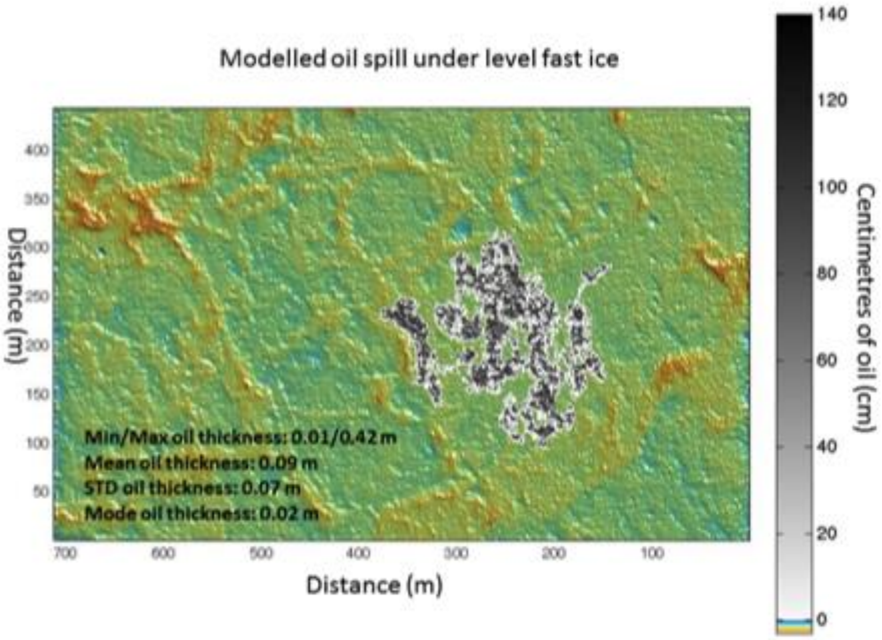

Figure 5.2. *Results from an under ice oil trajectory model run under real ice topography obtained from an upward looking multibeam sonar mounted on an autonomous underwater vehicle (courtesy: Wilkinson unpublished)*

5.2.3 Environmental conditions

Conditions in February on the northern Alaska coastline can be difficult and dangerous to work in. Temperatures at Prudhoe Bay are typically -10° to -20° F, but can drop to -40° F or lower. Winds are typically moderate, increasing the harshness of the environment. By mid-February, there are still only about eight hours of daylight – operations may need to be carried out in darkness. All these considerations will contribute to logistical challenges and safety of operating on the ice.

5.2.4 Response strategy and logistics

This scenario presents some of the most challenging logistics of the three scenarios presented here, primarily due to the extreme conditions, but also the need to operate on the ice (as opposed to from a vessel). This is mitigated by the proximity to infrastructure that could be kept at nearby facilities to support the spill response. It is most likely that AUV/ROV operations will originate and terminate from an ice-hole within a heated structure and therefore a small ice camp would most likely need to be established. It is beyond the scope of this report to go into detail regarding the establishment of an ice camp, however once established, AUV/ROV operations theory, could in principal progress independent of weather conditions and available sunlight. For safe operations the land-fast ice in the region of the ice camp should be level, stable and strong enough to safely accept the load stress delivered by the camp and associated operations.

At Prudhoe Bay, the water tends to be very shallow (< 5-10 m), and the ice may be grounded in places. This will limit the choice of vehicle. The dual-hulled SeaBed vehicle (see Chapter 2) will offer the manoeuvrability required to operate in shallow water conditions and for deployment and recovery through a small hole in the ice. On the other hand, a small, torpedo shaped vehicle that has adequate collision avoidance capability would be simpler to deploy. In this case, a system for recovery of the vehicle through a small hole in the ice would be necessary (e.g. Pluedemann et al., 2012). Very shallow water with complex ice conditions such as grounded ridges would present severe challenges to the safe navigation of the vehicle. Sophisticated collision avoidance routines have been developed for some vehicles under-ice (e.g. McPhail et al., 2009, albeit in deeper water), but further development and testing of vehicles is needed for reliable operation in these conditions. In such conditions, ROVs may be an appropriate solution, as these can be controlled by an operator at the surface to navigate around difficult terrain. Here, we assume sufficient clearance between the ice and seafloor to safely operate an AUV.

A sub-sea release of oil under a total ice cover remains one of the more difficult scenarios to detect with above, or on-ice remote sensing technologies. In this scenario the fact that the ice is fast, and the location of the pipeline is known (even if the breach point is not) will aid in determining the approximate location of the spill. On the other hand the static ice cover, combined with the relatively smooth nature of the ice over relatively large areas, provide additional benefits to spill detection. The response will then involve transport of the AUV/ROV to a prospective search location, either over the ice by truck or tracked vehicle, or landed by aircraft.

The basic deployment scenario on ice calls for the AUV to be transported to the site of interest, the setting up of a command structure which can be quite basic - comprising of laptops, basic electronics supplies, and navigation transponders. In addition there is a requirement for cutting and maintaining a hole in the ice through which the AUV/ROV can be deployed and recovered. Depending upon ice conditions, this infrastructure can be easily transported via snowmobiles to the area of interest. For the most rapid deployment where significant logistic support is difficult, a small, torpedo-shaped vehicle is recommended as it could be transported by snowmobile and sled.

Figure 5.3 Example of a 1.5m x 1.5m x 1.5m hole cut in sea ice. The process associated with cutting this hole, from the time the gear was offloaded on the ice (in this case from an icebreaker) until the hole was cut and secured lasted ~6 hours. It involved setting up the gantry frame, drilling an augur into the ice to lift the ice block, using a hot water cutter to cut through and then pulling out the ice plug to provide access to the hole.

After setting up the command structure, suitable locations would be scouted out in the vicinity, based on the requirements of area to be covered and the water depth, for the deployment of transponders. These can then be deployed using standard four inch drills with their positions calibrated using a hand held GPS.

With such infrastructure in place, vehicle operations can begin.

5.2.5 AUV navigation

Given that operating parameters, a non-moving ice cover in shallow water, it should be expected that AUV navigation would be excellent. In addition to standard long baseline navigation, dead reckoning associated with using a Doppler Velocity Log (DVL) integrated with a heading reference should give accuracies and precision of the order of a meter. A hover capable AUV and ROV can easily use such measurements to return to the hole in the ice for recovery. However, for the smaller torpedo shaped vehicles these navigation systems would be supplemented by an Ultra Short Baseline (USBL) system that would allow the vehicle to return via a homing behaviour. Under very shallow conditions there may be an issue with sound reverberation between the ice bottom and sea floor.

5.2.6 AUV Sensor payload

Chapters 3 and 4 discussed the merits and limitations of prospective sensors for remote detection of oil under sea ice on an AUV platform. Here, we briefly discuss the general issues affecting the choice of a sensor suite before discussing an appropriate choice for this specific scenario. The prospective sensors are:

- sonar
- camera systems (with strobe)
- laser fluorosensors, and
- multispectral radiometers (during daylight only).

Sonar and camera systems are mature technologies with a high probability of effectiveness in most scenarios. Radiometers may have some use, but as discussed in Chapter 4, until more extensive testing is performed, their advantage over camera systems is questionable. Until proven effective, we believe other sensors should be considered first if payload space is an issue, although compact multispectral systems are readily available. While laser fluorosensor systems may be an effective means to detect oil under sea ice, a system suitable for deployment on an AUV has not yet been tested. In these scenarios, we assume that a relatively compact system could be developed that could be deployed on an AUV. At present, compact prototype systems are under development (e.g., the EIC system tested at Ohmsett to detect submerged, heavy oil, Hansen et al., 2009) and may soon be practical for smaller torpedo-shaped vehicles such as the SeaBed 100 currently in development.

The most appropriate payload in this scenario will depend on the choice of vehicle. If logistic support is an issue and a small torpedo-shaped vehicle is the best option, then the sensor payload will be limited. In this case, the payload would include a sonar system and cameras. A laser fluorosensor might also be included if a compact enough system is possible.

For this scenario, we have assumed sufficient logistical support and water depth to deploy the larger Jaguar vehicle (see Chapter 2). In this case, the vehicle should support all sensors listed above. If a compact fluorosensor is not possible, one of the in situ detection sensors mentioned in Chapter 3 could also be considered (such as an in situ fluorometer or LISST sensor). And ADCP may also be useful to measure currents so that possible movement of the oil can be predicted.

5.2.7 AUV Mission

It is assumed that an aerial reconnaissance has been performed and no evidence of oil, or newly formed ice deformation features, can be seen along the track of the pipeline. Given the combination of shallow water and low currents the oil is likely to be located directly above the pipeline breach. The oil would then flow outwards from this point (Figure 5.2). Once a prospective search location is determined, the vehicle will need to be transported over the ice and a mobile AUV command centre erected (a tent or small structure to protect operators from the elements with generators for heat and to power). Navigation transponders could be deployed by snowmobile, although an advantage of operating under fast ice is the vehicle navigation can be determined by DVL lock on the ice underside (or, alternatively, on the ocean bottom). At the deployment location, a hole large enough to deploy and recover the vehicle would be cut into the ice (approx. 5’ X 8’) and the vehicle deployed using a hoist or chain lift. Recovery of the vehicle will be aided by the manoeuvrability of a hover-capable AUV, which the operator can bring close to the hole. If needed, recovery can be aided using a small ROV to grab the AUV and return it to the hole.

For this scenario a two-stage process could be performed.

<u>Stage 1- Identification of spill location</u>: An initial spill search scenario would first be performed to identify the general location of oil under the sea ice. This could be achieved through a simple AUV ‘out and back’ mission along the track of the pipeline. Low-volume data could be transmitted to the AUV operator in real time, but under fast-ice and low-mobility of the oil, this may not be a priority. Once the AUV returns to the deployment hole, data would be downloaded and, for example, the location-stamped photographs, in tandem with other sensors, can be examined at the deployment site to identify the location of the spill.

<u>Stage 2- Spill extent and thickness</u>: Once some of the spill is targeted, a second survey would be conducted to quantify the area and thickness (if possible) of the oil spill. Depending on the volume of oil spilt and the under ice topography it is unlikely that the extent of the oil would be quantified through an ‘out and back’ mission of Stage 1. The vehicle would be programmed to return to the target location where it would perform a focused mowing-the-lawn survey, with the centre of the survey area identified from positive oil detection at a location determined in Stage 1. Depending on the distance from the deployment hole the Stage 2 mission could be run out of the same hole, or the operation could be moved nearer to the contaminated ice and a new deployment hole cut in the ice. Data from the second survey will be used to quantify the extent, and if possible, the thickness of the oil on the ice bottom or encapsulated in the sea ice itself. It is possible that this survey could be performed with an ROV, although that depends on the extent of the oil spill.

5.2.8 Mission limitations and effectiveness

Operating under fast ice in shallow water can present one of the more challenging AUV operations because of the need for logistical support on the ice itself. As important as testing the AUV itself in this scenario is the need to develop an effective plan for rapid and safe delivery of the above ice support required for deployment, operation and recovery.

There are limitations to AUV missions under fast ice. These include:

- Shallow water. Some fast ice zones, particularly at Prudhoe Bay, water depths may impose operating constraints i.e. the water becomes too shallow for an AUV to successfully operate.
- Acoustics in shallow water. Given the shallow water depths acoustic transmission of data may be compromised as well as acoustic navigational aids i.e. DVL.
- Grounded ridge or deep keels: Collision avoidance sensors and associated software are needed for the AUV to successfully navigate around these objects and continue on mission. In the case of very shallow water and extensive grounded ridges, and ROV may be a more appropriate platform.

At this time of year under fast ice, water clarity is likely to be high. Therefore, detection and mapping of the spill is likely to be effective simply with a camera system, particularly under relatively level fast ice. Laser fluorescence may be most effective in this particular scenario, given the low light levels due to thick ice and low sun angle (or darkness). However frazil /platelet ice formation, and maybe anchor ice that has floated to the surface may detrimentally influence detection methods. For instance, frazil/platelet ice within the water column will provide more scatters, which in turn would have a real impact on sonar returns.

Determination of the oil thickness with sonar will be more challenging if the ice is very level, as thicknesses much less than 1 cm will be hard to discriminate. On the other hand, the relatively modest variations in thickness will aid in discrimination of contaminated sites from clean sites. Where thicker hollows exist, sonar should be effective at identifying thickness.

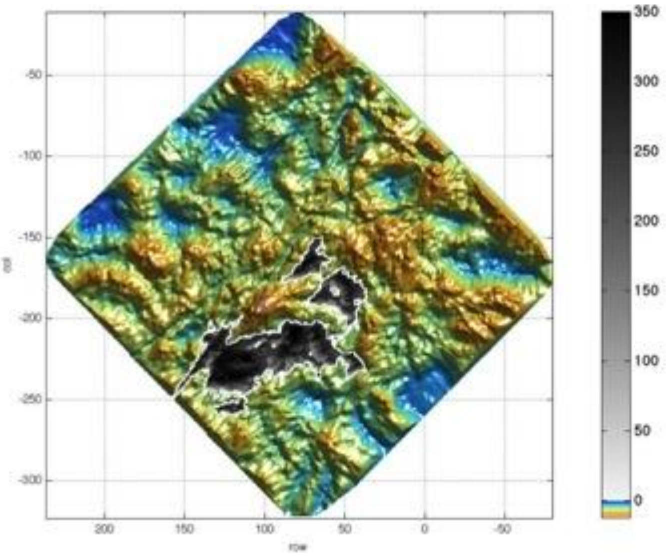

Figure 5.4. *Rubble field: Results from an under ice oil trajectory model run on real ice topography of a rubble field obtained from an upward looking multibeam sonar mounted on an autonomous underwater vehicle.*

Oil encapsulation is likely in this scenario if response is delayed (or if monitoring of the spill is required during clean-up operations). While we do not yet know how effective any of the candidate sensors will be at detecting encapsulated oil, these ice conditions promise to be the most favourable. Level ice and the ability to conduct precisely located repeat surveys (in the case of monitoring the evolution of the spill) will enhance the efficacy of detection of encapsulated oil

In heavily deformed area (such as

the Stamukhi zone), detection will likely be more difficult. In this case the oil may be pooled in interconnected hollows, as suggested by oil model runs oil spread under an ice rubble field. (Figure 5.4)

But as noted, in these conditions, an ROV platform may be more effective, and close proximity to the ice may improve the effectiveness of laser fluorescence. Sonar effectiveness may be reduced because of acoustic reverberation from the shallow bottom and nearby ridges, although this is likely only in really tight conditions.

5.3 Scenario 2: Blowout under drifting pack zone (far shore)

Scenario 2 is a sub-sea blowout type event whereby an oil and gas mixture is released at depth from the well-head. The Deep Water Horizon accident highlighted some of the significant difficulties that could be associated with this type of incident; especially the logistics needed to stem the flow of oil and gas. Given these difficulties we will provide only a brief overview of the challenges associated with oil detection under a sub-sea blowout condition.

This will be a summer release within the drifting pack zone - essentially a retreating marginal ice zone (see Chapter 1). It is assumed that the flow of oil and gas will continue until a pre-engineered capping system is installed. This could be logistical and technically difficult, therefore there is potential for a large quantity (hundreds of thousands of barrels) of oil and gas to be released before a cap is in place and the flow of oil has ceased. Therefore the detection response strategy may depend on how long the blow-out remains uncapped. The target time line for an uncontrolled Arctic release to be stopped (via a cap) is in the range of 5-10 days (Per comm., 2013). However during the Deepwater horizon oil spill it took 87 days for the well to be capped. If the flow of oil and gas cannot be successfully stemmed within the summer melt period, then the oil and gas release could continue through freeze-up and possibly into the period of continuous ice cover

The health and safety issues associated with working in an environment that may contain high concentrations of gas are beyond the scope of this report. We assume it is safe for a vessel to operate within the vicinity of the well. Full operations may only be permitted be after the release has been stopped, depending on water depth and VOC levels at the surface

5.3.1 Ice conditions

Given the extremely mobile nature of drifting pack the concentration of sea ice around the drilling rig will constantly vary. Drift ice typically moves at 5-10 km/day (e.g. Lepparanta, 2005), however the drift is not regular in speed or direction, so the trajectory of a given ice floe is likely to include loops and other deviations from the long-term surface-current direction. Depending on the length of time that has elapsed the ‘conveyor belt’ of floes that drift through the oil/gas plume may be many 10s or 100s of kilometres from the blowout site. This is a formidable challenge for both mapping the extent of the spill and monitoring its evolution.

The changing nature of the wind and ocean currents in the locality of the rig may lead to periods of time where the rig is surrounded by an open sea, and others where it is surrounded by a 100% ice cover. Under divergent conditions, a broken ice cover will have growing areas of open water between the floes, and these openings remain ice-free during the summer months. However under convergence these open areas begin to close until there is almost no evidence of open water. For this scenario we assume a 75% ice diverging ice cover of first year sea ice

5.3.2 Environmental conditions

During the summer month's snow, sleet and rain are possible in the Arctic. Significant cloud cover and fog is common, but storm activity is less frequent. We will assume an air temperature of around freezing, reduced visibility because of fog, a light breeze and near 24-hour daylight.

5.3.3 Oil dynamics

Released oil and gas would rise towards the sea surface as a buoyant plume of gas bubbles and oil droplets. The exact nature and extent of the plume will be a function of the depth of the release, ocean currents, and the density difference between the water column and the rising the oil droplets. Eventually the gas and a proportion of the oil droplets will reach the bottom of the ice and/or ocean surface. Exactly how the gas interacts with the ice is not clearly understood.

If the ice drift speed is large relative to the rate oil release, it may form a very thin (< 1 mm), discontinuous layer on the ice underside. In fact these thin films may my absorbed into the skeletal layer of the growing sea ice, thus making detection more difficult. At lower drift speeds, or higher flow rates the oil layer could form a continuous layer on the ice underside of varying thickness, whether this oil will flow and gather to greater thicknesses in depressions and undulations under the ice is unknown. If significant quantities of oil gather under the ice then ice thickness variations will cause it to form a pattern of slicks and pools underneath the ice (figure 5.2).

Given the broken nature of the ice and therefore is possible that some oil may be contained within leads. Under confined oil within these opening maybe constrained on all sides. The model of Wilkinson et al., (2007) shows that if the oil continuously gathers in a lead (fully constrained by floes) it will eventually reach a thickness where it will flow under an ice floe (fig 5.5). This would only occur under closing ice conditions or within a well-defined lead. Generally oil would spread along interconnected opening between the floes, as necessary to maintain a balance of spreading forces and surface tension at the slick perimeter. Under these conditions there should not be a build-up of very thick oil layer.

We assume that the variability in ice conditions and ice drift speed during the spill leads to both a thin, discontinuous layer of oil under some floes, as well as thicker oil slicks and oil filled depressions in others, and oil of varying thickness (though generally thin) in open water areas between floes.

In summer, the porous ice will also admit some of the oil to percolate up through the brine network, so that some oil may be found within the ice, and even on its surface. The latter may help give an initial indication of the presence of oil from above.

5.3.4 Response strategy and logistics

Given the broken ice conditions it may be possible to see evidence of oil between the floes, and possible some on the surface of some floes from above. However the amount contained under the ice will be unknown. In order to enhance the detectability of oil under drifting ice with an AUV/ROV other technology could be used to narrow the area of operation. For example GPS tracker buoys, as well as remote sensing (e.g. Synthetic Aperture Radar), could be deployed to monitor the drift of the contaminated floes. Furthermore given the divergent nature of the pack within this scenario airborne reconnaissance (conditions permitting) could guide ships to regions where oil can be seen in open water around floes from where AUV missions would originate.

The AUV missions would need to be conducted from a support vessel. AUV operations are possible from a variety of vessels. For the SeaBed Class and other relatively small AUVs operations can operate from quite small vessels, but most larger, long-range AUVs will require larger support vessels with dedicated support equipment. For example, the Autosub requires a vessel large enough to accommodate two shipping containers on the fantail, one of which contains the dedicated launch gantry. All ship-based AUV/ROV missions need access to open water adjacent to the ship. This can be achieved from inside the ship itself i.e. from a moon pool, though we believe this has not been performed before and therefore most operations will be conducted through a lead, or through an open water region produced by the ship.

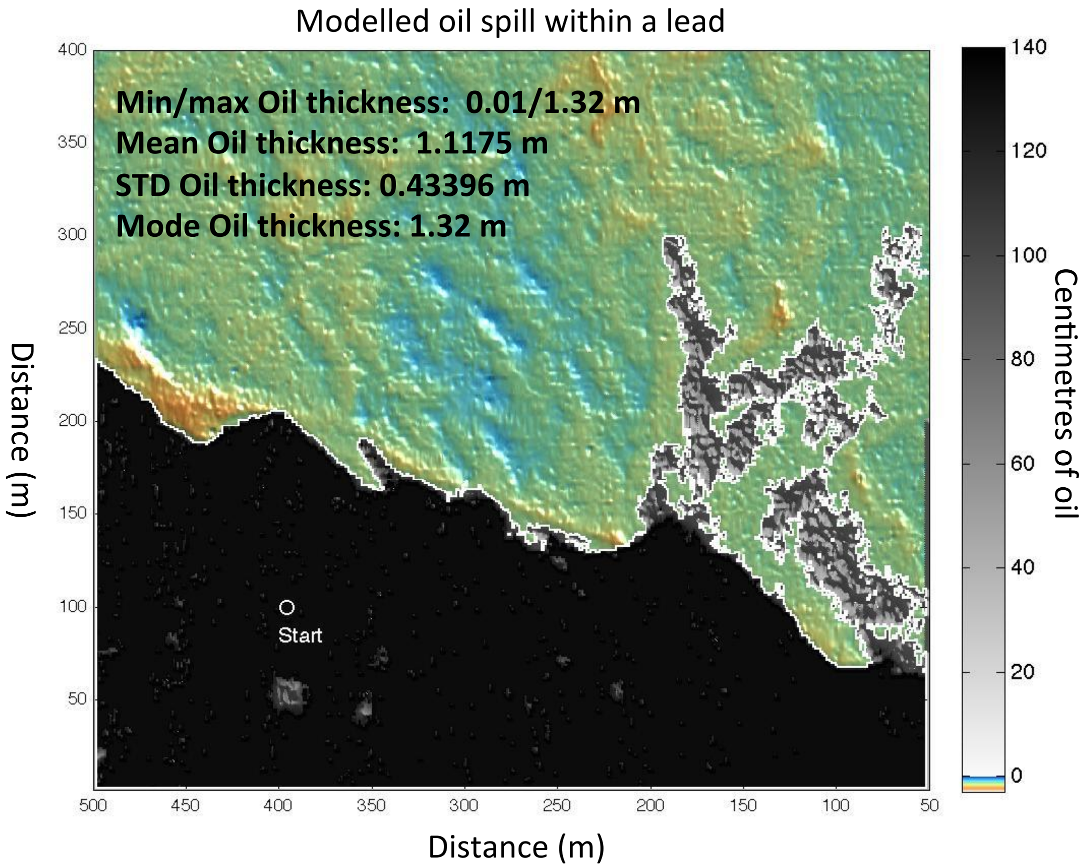

Figure 5.4. *Results from an oil trajectory model run under real ice topography obtained from an upward looking multibeam sonar mounted on an autonomous underwater vehicle. Oil gathered in a fully constrained lead until it reached a thickness that is could flow under the floe.*

For this scenario, we assume the AUV is launched from outside the ice edge within a large area of open water surrounded by loose floes. For deployment and recovery, the vessel should have a crane.

In this scenario, the extent of the spill may be very large (10s of kilometres across or more). In this case, smaller AUVs may be useful for mapping selected areas within the ice pack, but to map the entire spill a long range AUV is most likely needed. Here, there could be a trade-off between vehicle flexibility and ability to map large areas. For larger vehicles, a large area of open water is required for deployment and recovery. Smaller vehicles can be deployed and recovered more easily from within the pack, at the expense of the length of mission.

In this scenario, we assume a mission support similar to those previously used for the SeaBed class of vehicles under sea ice, although we note that the precise logistic set up may vary depending on vehicle choice.

The basic requirements for operation include the ability to maintain an open water area next to the support vessel for recovery, and a crane or gantry for deployment and recovery. Recovery of the vehicle in open water is aided if a small boat is available to hook the vehicle on return. Ideally, the support vessel should have dynamic positioning capability so that vehicle navigation with acoustic transponders will be more precise.

For very large spills, it is recommended that significant resources be deployed so that the spill can be mapped completely and efficiently. This could include multiple vessels, multiple AUVs, and aerial reconnaissance support.

5.3.5 AUV navigation

AUV navigation under a continuous ice cover is aided by DVL lock on the ice underside. In broken ice conditions, this is more difficult as the lock is lost as the vehicle transits between floes. However, in most cases for the near future, wells will be located on the continental shelf in water depths less than 300 m. in this case; a DVL from the seafloor can be used, so that navigation is in a geographic, rather than ice centric, reference frame. It should be remembered however that Imperial/BP lease blocks of current interest are beyond 500 m water depth, and Chevron’s Beaufort Sea lease block is in water depths of 1,200 m and greater (pers comm., 2013).

As in scenario 1, vehicle navigation systems would be supplemented by an Ultra Short Baseline (USBL) system that would allow the vehicle to return via a homing behaviour. This system would consist of several acoustic transponders suspended over the side of the ship. Smaller, nearby support vessels or boats could also be used to support additional transponders to aid navigation.

5.3.6 AUV Sensor payload

The sensor payload would include the same sensors as in scenario 1 (i.e. cameras, sonar, and laser fluorosensor), with some of the same possible limitation of sensor real estate on the vehicle. However, if a larger vehicle is used for long-range mapping of a large spill, additional sensor space may be available. Given the spill originated from an undersea plume, a LISST, fluorometer or other in situ sensor may be incorporated to detect hydrocarbons in the water column. Such sensors could also be particularly useful for detecting low concentrations of hydrocarbons. For such larger spills, it may be useful to use a second vehicle for in water column detection.

5.3.7 AUV mission

There are a number of mission strategies that could be tried, depending on resources such as range and number of vehicles available, and expected size of the spill, and capabilities of the support vessel. Here we describe a basic mission with the SeaBed 100 (or similar) vehicle.

Once a prospective site is determined by aerial reconnaissance (if available), a USBL acoustic navigation system will be deployed over the side of the ship (and ideally, with an additional transponder from a nearby location from a small boat), and the vehicle will be deployed in an available area of open water.

A typical mission would run a coarse lawn-mower pattern using DVL lock on the seafloor. A coarse mission pattern will allow a large area to be surveyed (and relatively quickly), at the expense of complete spatial coverage within the search area. For a vehicle with a 50 km range, this might cover an area of about 3-4 km square. For larger spills, it will be more efficient to run single, straight transects.

If the spill is patchy, single transect missions could be programmed so that once a positive detection of significant quantities of oil is detected, smaller, short lawn-mower patterns could be initiated to map the extent of these large oil volume areas, where clean-up efforts, or tracking of the spill, might best be concentrated

With smaller AUVs, the range is limited to tens of kilometres. For a larger spill, multiple such missions from various locations within the loose packed ice could be conducted to complete a survey of very extensive areas. Alternatively, a larger vehicle (e.g. AutoSub) could be deployed on a longer, single mission (hundreds of kilometres in length). At present, these larger vehicles generally require large open water areas for deployment and recovery.

In conditions where there is significant ice cover and the spill covers many tens of kilometres, complete mapping of the spill would be a challenge. Further development of AUV technology may play a key role here, with improved navigation, deployment and recovery capability for larger vehicles, and/or improved capabilities for multiple vehicle missions.

5.3.8 Mission limitations and effectiveness

This scenario is perhaps one of the least limiting in terms of AUV logistics and ease of missions, given availability of open water, access of support vessels, good depth of water (while still permitting DVL navigation off the bottom in most cases). The primary factor affecting mission effectiveness is the sheer size of the spill. For spills tens to hundreds of kilometers in extent, complete mapping is impractical in a relatively short timeframe, and some compromise on the coarseness of the survey grid will need to be made. An additional consideration is that for longer missions, the ice may drift significantly during the mission. For example, a long-range AUV such as Autosub can deploy on missions of 24 hours or greater during which time the ice may drift several kilometers. To most accurately map such a spill will require some modeling of the spill evolution during data processing (see section 3.6).

Another factor for long-range missions is the capacity for real-time data relay is limited. Acoustic telemetry of data is presently possible over ranges of several kilometers in open ocean but in relatively shallow water performance is degraded due to multipath effects (e.g. Singh et al., 2009). However, there is rapid development of AUV capability in this area, and multiple vehicle networks may soon be practical (e.g. Murphy et al., submitted). Another possible option currently in development is hybrid AUV/ROVs, where an autonomous vehicle could be connected to an operator with a tether tens of kilometers in length.

The effectiveness of the sensor suite will likely vary considerably depending on the particular ice and oil conditions, although with the complete sensor suite one sensor or another should be effective in most conditions. Under ice, camera systems should be most effective, supplemented by sonar where reasonably thick slicks occur (i.e. > 2 cm or so in depressions in the ice underside), and laser fluorescence. For very thin slicks under ice, we still expect cameras to be effective, although discrimination of oil may be less clear than for thicker slicks. In this case laser fluorescence may be a useful complement. In open water areas, laser fluorescence may be useful given the possibility of very thin slicks. Multispectral radiometers may be most effective in this scenario, although these have not been tested. The major limiting factor for laser fluorescence, given thin ice or open water, will be high noise levels from bright sunlight. Because complete sensor coverage of the entire slick may not be possible from below, quantification of the volume of oil will be less accurate than is possible for smaller slicks (and because the thickness of very thin oil may be difficult to quantify), although we note that the greater volume under ice of irregular thickness is arguably the most important to detect and easiest to quantify.

Overall, because of the expected large extent of the spill and challenging environment for rapid response and clean-up (in terms of highly mobile ice), it is recommended that significant resources be brought to bear for the search and mapping strategy. This should include multiple vehicles, including long-range AUVs, with vehicles mapping oil both at the surface with remote techniques, and in situ sensors on the same, or other vehicles at depth to detect low concentration hydrocarbons and map potential dispersal of the plume.

5.4 Scenario 3: Shipping accident within the Northwest Passage (remote).

This scenario is a result of an oil tanker grounding during early freeze-up (September) within the Northwest Passage, Canadian archipelago. Because of the grounding the vessel suffers damage and releases oil from one or more of its cargo tanks. We assume the accident occurs in a remote location, and because it is a grounding event it will most likely be near the coastline.

5.4.1 Ice conditions

This is a late season accident and occurs around the time of the onset of new ice formation. Exactly how freeze up progresses is very much dependent on the meteorological conditions at the time, for example calm conditions will produce a level ice cover, whilst tempestuous conditions will produce an ice cover that is much more deformed through ice break up, ridging/rafting, and refreeze processes (see Chapter 1.2). Given the limited fetch available in the Canadian Archipelago it is unlikely that large amounts of frazil and pancake will be present. We assume that there will be a continuous covering of nilas at the spill site.

Nilas when only a few centimetres in thickness is transparent and very flexible, but as the ice grows thicker the nilas takes on a white appearance and becomes opaque. We assume white nilas is present. In most years in the Northwest Passage, some amount of old – potentially multiyear – ice persists through the summer, which may be mobile.

The elapsed time between the time of the spill and when the ice becomes fast will determine the spatial distribution of oil. If the ice is not fast then oil under the ice will be transported away from the site by the drifting ice. We assume that the ice in the region was fast ice. Generally speaking much of the ice within the Canadian archipelago is fast ice by early winter, and therefore detection techniques will be similar to scenario 1.

5.4.2 Environmental conditions

As we are approaching the winter months there will be reduced hours of sunlight at this time of year. Air temperatures will be around -10° C, good visibility, and a light breeze.

5.4.3 Oil dynamics

An accidental release of oil from a shipping accident would release a limited quantity of oil, either through one catastrophic event or as a series of partial releases. In the case of the vessel sinking any oil releases will continue until all the oil is released, or is halted through external intervention. As a continuous, thin ice cover develops over the site the oil spreading regime would be the same as that expressed under scenario 1. However given the relatively fragile nature of nilas there may be breaks in this ice cover that allows oil to pool at the ocean surface. Either way the oil will be quickly incorporated into the growing ice cover. This suggests that the encapsulated oil will remain near the ice surface. Any oil on the ice-snow surface will be open to atmospheric weathering processes, and over time will spread outwards along the ice/snow surface. Once the flow of oil has stopped subsequent snowfalls will cover the oil, reducing but not eliminating the weathering rate. Detection techniques such as helicopter-mounted radar could be used to detect oil under the snow, but these techniques are not covered by this report.

If the spilled oil has access to the ocean surface (i.e. atmosphere) weathering processes would begin. In this case oil incorporated in the forming sea ice would have different properties from its original state. We assume no weathering has taken place and we ignore oil reaching the shore.

If thicker ice that has survived the summer is also present, the oil is likely to still be mostly confined to under the thin ice, but some may be thrust under the old ice if the spill initially occurs in the vicinity of this ice (accumulating as it rises from depth), or is thrust under the ice due to winds closing an ice cover prior to new ice formation.

5.4.4 Response strategy and logistics

Under this scenario the spatial dimensions of the spill will be unknown, and depending on the volume of oil released, may be large (kilometres across or more). In this case the response strategy will be a mixture of scenario 1 and 2. As with scenario 1, a continuous fast ice cover is present, however given the strength and thickness of the new ice it would not be possible for people to operate from the ice. Mapping by AUV/ROV would need to be carried out from a support ship (see scenario 2), most likely through a hole in the ice cover made by the vessel.

Given the ease at which open water can be created by the ship a long-range AUV may be the vehicle of choice in this instance. Although under cold conditions these newly produced open areas are liable to refreeze. These vehicles can cover from 10s to 100s of kilometres, with a significant scientific payload, in one mission. Larger vehicles require a larger area of open water for deployment and recovery than smaller AUVs. Smaller vehicles can be deployed and recovered more easily from within the pack, at the expense of the length of mission.

The basic requirements for operation are similar to those required for scenario 2. These are: ability to maintain an open water area next to the support vessel for recovery, a crane or gantry for deployment and recovery. Navigation transponders would be lowered from the ship and deployed directly on the ice. For very large spills, it is recommended that significant resources be deployed so that the spill can be mapped completely and efficiently. This could include multiple vessels and multiple AUVs.

5.4.5 AUV navigation

AUV navigation will be as in scenario 1. Under a continuous ice cover, navigation is aided by DVL lock on the ice underside. As the ice cover is fast, navigation accuracy should be very good. As the grounded vessel will be near the shoreline it would be expected that the AUV could also use DVL lock from the seafloor. In this case navigation is in a geographic, rather than ice centric, reference frame, although this is equivalent if the ice is fast.

5.4.6 AUV Sensor payload

The sensor payload would include the same sensors as in scenarios 1 and 2. These are: upward looking cameras, sonar, laser fluorosensor and multispectral radiometer. However, given the spill is located (mostly) under thin ice much of the oil will most likely be in encapsulated. Until further research is performed (see Chapters 3 and 4) the exact possibilities of successful detection of encapsulated are not known. However laser fluorosensors, radiometers, and possibly sonars theoretically provide the ability to detect encapsulated oil. Under thin ice cameras may also work.

5.4.7 AUV mission

As with scenario 1 a two-stage process may be preferable. The first stage defines the extent of the spill, whilst the second concentrates on mapping the properties of the spill i.e. spatial variability of oil thickness

<u>Stage 1- Identification and extent of spill location</u>: Using estimates of the volume of oil released an under ice oil spill model could statistically calculate the expected area of coverage under the nilas ice cover. The search scenario would then be performed over the extent suggested by the model. This could be achieved through a coarse mowing-the-lawn type survey. Low-volume data could be transmitted to the AUV operator in real time. Once the AUV returns to the deployment hole, data would be downloaded and the extent of the oil spill determined.

<u>Stage 2- Spill extent and thickness</u>: Once Stage 1 has been completed a second survey would be conducted to quantify the area and thickness (if possible) of the oil spill. Based on the results of stage 1 the vehicle would be programmed to perform a more focused mowing-the-lawn survey.

5.4.8 Mission limitations and effectiveness

The logistic set-up for this scenario is straightforward, provided vessel access to the spill site is possible within an adequate amount of time. The AUV deployment, recovery and missions are quite similar to those that have been previously accomplished with the SeaBed class of vehicles. Larger vehicles have also performed similar missions, although with generally larger open water areas for recovery (e.g. Autosub). The primary factor affecting mission effectiveness is the ability to detect encapsulated oil. Testing of sensors to detect encapsulated oil should be a priority to determine the viability of AUV-based quantification of oil in this scenario. The second factor could be the volume of oil released and hence the extent of this spill. Large volume spills could include multiple vessels, multiple AUVs operations, and if needed aerial reconnaissance support. These all need to be tightly organised and integrated.

5.5 Summary

We have explored three oil spill scenarios in ice-covered waters that occur in differing ice conditions, season, and with differing oil release scenarios. While not covering the full extent of possible scenarios, or identifying all logistical challenges that might exist for AUV operations under sea ice, these cover the general breadth of ice, oil, and environmental conditions likely to be found at an oil spill in the Arctic.

For each of these scenarios, the logistical support requirements are similar to those used previously for recent polar AUV operations, and the general scope of the missions are similar to those that have previously been completed. There are two primary areas where further work should be explored: (1) extensive sensor testing in laboratory settings with ice and oil conditions similar to these scenarios is necessary for all prospective sensors – particularly for encapsulated oil, and (2) further development of capability for medium to long range AUV operations under ice and in complex ice environments is necessary so that a “turn-key” system for rapid response can be assured. This should include further testing of longer-range missions, telemetry, and navigation under sea ice.

Finally, it is important that logistical support for such operations (vessels and ice camp infrastructure) be available for rapid deployment. Capability of multiple vehicle operations, possibly including ROV or hybrid AUV/ROVs would be an asset in responding to extensive spills.

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CHAPTER 6. SUMMARY AND RECOMMENDATIONS

The risk of an oil spill in ice-covered waters has been an issue since hydrocarbon development and extraction expanded to Arctic waters in the 1970s. Renewed interest in both hydrocarbon exploration and shipping in the Arctic increase the regions of the Arctic Ocean where spills might occur, so there is now a greater need to develop effective means of responding to potential oil spills in ice-covered waters.

The presence of sea ice confounds methods of remote oil detection developed for use in open water. While some limited success with on-ice detection has been achieved, these techniques suffer from the need to “see” through the ice, and are often severely hampered by the logistical and environmental challenges of operating on the ice cover, which is often not possible. Airborne systems obviate many of these logistical challenges, but are still challenging due to the need see through the ice cover.

As recent advances in unmanned underwater vehicle (UUV) technology have now made routine under-ice operation of UUVs feasible, there is now the possibility of a new method of oil detection under sea ice – from below. This is a largely unexplored technique, and requires evaluation of both the capabilities of UUVs for operation under a variety of ice conditions, and the evaluation of sensors that are suitable for remote detection of oil under water. This report provides an assessment of the state of the art in sensor technology that may be useful for detection and mapping of oil beneath sea ice, and the capability and requirements of autonomous platforms that can carry these sensors, namely autonomous underwater vehicles (AUVs) and remotely-operated vehicles (ROVs).

6.1 Summary of oil detection under ice from UUVs

The Arctic marine environment is one of the more challenging areas of the world in which to operate. Detection of oil in ice-covered waters is complicated by the many manifestations that the oil and ice conditions can take, and the interactions of oil and ice (see Chapter 1). The details of these interactions are not fully known, as only a handful of limited controlled releases of oil under sea ice have been undertaken. Oil trapped beneath the ice will flow buoyantly along the topographic variations that are ubiquitous on the ice underside – even for very level ice. Depending on the ice morphology, the oil can pool to many centimetres or more in thickness, in contrast to open water spills which may be only a few microns in thickness. However, this pooling behaviour can lead to a patchy distribution of the oil.

The behaviour of oil under ice depends largely on the season, the presence or absence of gas, and the film thickness. In the summer, the warm, porous ice may permit the buoyant oil to percolate upward through the ice microstructure, possibly reaching the ice surface. In winter, ice may freeze beneath the oil, encapsulating it within the ice.

The particular conditions that might be encountered may also be changing. Recent rapid warming of the Arctic has resulted in a 50% reduction of the extent of summer sea ice, changes in ice type, declines in thickness, and a reduction in the frequency of thick ridges. As the Arctic transitions to a seasonal ice cover (possibly within the next few decades), increased area of open water, increased fetch for wave generation, and increased storminess will lead to a change to increased presence of marginal ice zone conditions. These changes may lead to greater logistical challenges in responding to spills.

These complexities demand that technologies capable of detecting and mapping the extent of an ice spill in ice-covered waters ideally should be able to operate in ice conditions varying from fast ice to continuous pack to the broken scattered floes of the marginal ice zone, be able to detect scattered pools of varying thicknesses, and detect oil within the ice.

UUVs, and in particular, AUVs, have the advantage of being able to operate beneath the ice, largely independent of ice conditions. They can offer a direct view of the oil from below, unimpeded by the ice. These vehicles can carry a suite of sensors with varying capabilities, so that oil could potentially be detected under the range of conditions likely to occur.

Underwater vehicles can be classified into three distinct classes (see Chapter 2):

1. Manned submersibles, often called Human Occupied Vehicles (HOVs) are the classical bathyspheres that are used to transport a few occupants to the depths of the sea.
2. Remotely Operated Vehicles (ROVs) are vehicles that are unmanned and operated with the help of a tether that connects them to operators working on a mother ship on the surface.

Autonomous Underwater Vehicles (AUVs) are unmanned, untethered robotic vehicles that are preprogramed assets that comprise a maturing technology.

A variety of reliable UUVs can now be purchased commercially. ROVs are a relatively mature technology, and many larger ROVs can integrate a variety of sensors (including some larger sensors that have already been used for, or potentially could be adapted for, oil detection. Such a system may be a useful tool under certain circumstances – i.e. where there is good logistical support on ice or from a vessel available, where it is safe to deploy a tethered vehicle and long range surveys are not required.

For logistical considerations, flexibility of deployment and range, AUVs are likely the most promising underwater platform for oil spill detection. The absence of a tether makes them easier to deploy and recover, and importantly extends the range of the vehicle. However, the autonomy of the AUVs introduces a range of technical issues that must be considered, including real-time data analysis, accurate navigation in complex, drifting ice conditions, and the possible need for collision avoidance techniques if operating close to the ice underside or in shallow water.

AUV technology has matured to the point where routine operation under sea ice by experienced operators is now possible with small and nimble vehicles with relatively low logistical requirements. The detection and mapping of oil spilled beneath sea ice over relatively large areas may now be more practical using an AUV. In some situations, such as very shallow water, in the vicinity of grounded ridges, or when very close proximity to the ice underside is required, and ROV may be more practical. As technology develops, hybrid systems, with an autonomous vehicle connected to the surface by a very long fibre-optic tether, may be an appropriate approach to allow more control of the vehicle and improved data telemetry, while at the same time permitting relatively long-range missions.

6.1.1 Potential UUV sensor payloads

A critical consideration is the sensor payload (see Chapter 3). These can be divided into two classes – sensors that can detect oil in situ within the water column, and sensors that detect oil pooled beneath or within the ice remotely (at the vehicle operating depth of several to tens of meters below the ice). For the latter, there have been few (if any) relevant experimental trials of sensors. For the former, there is little difference with open ocean in situ techniques, although again, there have been only a handful of tests in most cases. The most promising sensors for water column detection are:

1. Echosounders (sonar)
2. In-situ mass spectrometry
3. Fluorescence (including laser-induced fluorescence), and
4. Laser particle size analyzers (e.g. laser in-situ scattering and transmissometery)

Each of these techniques have shown some promise in detecting small volumes of oil or other hydrocarbons dispersed in the water column; notably each has successfully detected oil within the Deepwater Horizon Macondo well plume. As the UUV-based techniques for these situations and sensors do not differ substantively in the presence of an ice cover (other than the UUV logistics), the focus of this report has been on those sensors capable of remotely detecting oil trapped immediately beneath the ice surface. These include:

1. Camera systems
2. Sonar
3. Laser fluorosensors
4. Multispectral radiometers

Each of these systems has seen very limited recent evaluation for oil detection under sea ice. While cameras have been used in some oil release experiments, to our knowledge, only one test of sonar under laboratory-grown sea ice has been performed, and only one or two tests of these sensors in experiments comparable to the remote oil-under-ice problem (i.e. detection of heavy, submerged oil on the seafloor (see Chapter 3).

It is difficult to evaluate the capabilities of these sensors without much more extensive testing of each, both in the laboratory, and in realistic field trials. Based on the very limited results available, experience with these sensors in other scenarios, and theoretical and practical considerations, it is likely that the performance of each sensor will vary considerably depending on the particular oil, ice, and environmental conditions (see Chapters 3-5). However, given that it is possible to accommodate several or all candidate systems on many UUV platforms, a suite of sensors should be used.

Camera systems will likely be the most straightforward and simplest to evaluate, given the contrast between oil and ice. In turbid water, thick ice, or ice with a significant snow cover, light levels may be low and a strobe system may be needed to artificially ‘light up’ the ice bottom. Furthermore, under heavily deformed ice the vehicle may need to operate 10 m or more from the ice underside. In both cases the discrimination of oil and ice visually may be more difficult. At present, the limited bandwidth of underwater acoustic communications will limit the volume of imagery that can be observed in real-time from an AUV.

Sonar systems offer an intriguing capability, in that the detection of oil would most likely depend on the detection of both the oil/water and ice/oil interfaces, and thus detection of oil thickness, and hence volume may be possible. Sonar performance will be highly dependent on the particular oil spill scenario, as it will ultimately be a function of the thickness of the spill and the required range of the AUV from the target. In principle, multibeam sonars offer the ability to map wide swaths of the ice underside. The choice of a particular sonar system will be a balance of the range of the system and the ability to resolve thin layers of oil. In simple terms, this balance is governed by frequency of the sonar. In practice, a sensor suite might include multiple sonar systems or transducers. A variety of sonar frequencies and capabilities may be applicable to the problem. Of particular interest are broadband systems, which can achieve superior range resolution at low frequencies. Extensive, realistic tests are required to determine the capabilities of sonar systems.

Laser fluorosensors may be a useful complement to these systems, particularly for low volumes of oil, in the dark, or in broken ice where oil may be found between ice floes. As with cameras, to our knowledge, there have been no realistic tests of these systems for detection of oil under ice.

It is currently unclear how effective any of these systems may be in detecting encapsulated oil. Their effectiveness will depend on the thickness of the lower layer of ice, as sonar, laser fluorosensors, radiometers, and cameras all will all be strongly affected by scattering of light (or sound energy, in the case of sonar) in the ice. In this case, radiometers may be useful for detecting the attenuation of ambient light through the ice by the oil.

A diversity of conditions may occur under different spill scenarios in ice-covered waters, including highly variable ice properties and morphology, water clarity variations, depth of the water column, and the nature of the oil spill. These conditions will impose logistical constraints on AUV missions, as well as impacting sensor effectiveness. It is unlikely that there will be a one-solution-fits-all approach to oil detection in ice covered seas. The techniques used will vary greatly from mission to mission, and perhaps within any given mission (see Chapters 4 and 5). At present, cameras, sonars, radiometers, and laser fluorosensors appear to be show the most promise, but performance is likely highly dependent on conditions (see Chapter 4). The most effective oil mapping strategy would include a fusion of data from several, or all, of these onboard sensors. This might also include several different sonar systems (for example multibeam sonar for mapping and single beam sonars at several frequencies for determining thickness). One potential advantage of such a suite is it may be possible to not only map the extent of the spill, but also to quantify its volume where acoustic methods are capable of discriminating the thickness of pooled oil.

6.1.2 UUV oil spill operations under sea ice

In Chapter 5, three hypothetical scenarios were evaluated to identify the range of conditions and logistical challenges that might be encountered for under-ice AUV missions. These scenarios included: Pipeline breach within the fast ice zone (near shore), Blowout under drifting pack zone (far shore), and Shipping accident within the Northwest Passage (remote). For rapid response, it is critical that logistical support be readily available. There will likely be different approaches depending on the scenario. For fast ice, this would include the support necessary to deploy rapidly onto fast ice and operate from a small, mobile ice camp. This would most likely involve small, easy to deploy AUVs. In pack ice a vessel capable of supporting AUV operations is most likely needed. The ultimate choice of vehicle may vary depending on the spill scenario, for example, ROVs or hover-capable AUVs suitable for small spills or where detailed or close-range inspection is desired or long range AUVs to map large spills. For any scenario, the sensor payload could be more or less the same, which simplifies the vehicle deployment. Larger ROVs and some large AUVs can accommodate some larger sensors (such as broadband sonar) that currently cannot be accommodated in smaller platforms. Large vehicles, however, require greater logistical support and deployment and recovery is more complex.

For large spills, such as might occur for a well-head blowout, an effective strategy may be to use multiple vehicles. This might include multiple identical systems for efficient mapping of large areas, or a combination of different sensor suites for remote under-ice detection and in situ water column detection, or different vehicles for broad scale and close range detailed inspection.

With the latest generation of UUVs, all these logistical capabilities currently exist, but further development and investment is required to refine an appropriate system, or systems, into a rapidly deployable, operational response tool.

6.2 Recommendations

UUVs offer a very attractive solution for oil detection under ice with a realistic potential to be transitioned to an operational oil-spill response system within a decade. However, because little work has been carried out to develop operational level (as opposed to those for scientific research) AUVs under sea ice, and almost no work has been carried out developing and testing appropriate sensor payloads for AUVs, there are still a number of issues that need to be developed and tested before a complete system can be developed.

Off-the-shelf versions of potential sensors are already suitable for fixed structure, AUV and ROV payloads. However, none of these are truly operational for oil spill detection at present. Even including camera systems, the clear ability to reliably detect oil under ice in the range of expected conditions has not yet been clearly demonstrated. For each potential sensor system, further testing, both in the laboratory and in realistic field trials is necessary to optimize the system design and the processing required to discriminate oil in a variety of situations. Cameras may be the exception where performance is well understood in many situations.

Based on this review we outline recommendations for future development and testing of both AUV technology and capability and an appropriate sensor payload to be pursued over the next several years. These recommendations are aimed towards development of a complete system for operational oil spill response. Development will require several stages:

1. Sensor evaluation and development
2. AUV development and testing
3. Development of an operational AUV system

These first two stages are interlinked. It is important that they develop in tandem so that an appropriate complete AUV and sensor system can be developed.

6.2.1 Recommendations for sensor evaluation and development

Extensive testing of each sensor type is required. There have been almost no oil-under-ice tests of the sensors mentioned in this report and fundamental background information is desperately needed. At this stage *in situ* field studies are not ideal; controlled and repeatable experiments must be performed. Focused ice-tank experiments are recommended to characterise sensor signal response. Some preliminary work is underway to characterize sonar and laser fluorescence signal response in simple ice tank experiments. These will not be definitive, but are expected to provide useful guidance for more elaborate and detailed laboratory experiments.

The steps necessary to develop a suitable sensor suite are as follows:

(1) Laboratory ice-tank testing of the physical characteristics of the sensor signal in order to determine the theoretical potential of the technique. This will guide the choice and/or development of a particular sensor

(2) Laboratory testing of prototype sensors in realistic oil under ice tests, including encapsulation of oil. This will need

(3) Development and miniaturization of prototype sensors so that they can be integrated into an AUV platform

Below we describe the key preliminary laboratory tests for each sensor:

(1) Laboratory ice-tank tests

Sonar

1. Experiments should identify an appropriate choice of frequency (or frequencies), which may vary depending on oil slick thickness and range, and the best choice of system parameters (beamwidth, bandwidth, etc.)
2. Narrow and broadband techniques need to be explored. However broadband should be a priority due to the limitations of low-frequency narrowband systems.
3. The ability to map the extent of the oil also needs to be explored. For this, multibeam techniques may be more appropriate.

Laser Fluorosensors

1. Determination of the best method for reduction of ambient noise (sunlight) and range limitations
2. Experimental tests to identify the best technique to discriminate oil from organic matter. For oil under ice, fluorescence polarization and excitation-emission matrix (EEM) techniques are likely to be the most effective in real life scenarios.

Multispectral radiometers

These are likely to be less effective than other techniques, but may be effective in some circumstance where others may fail (e.g. encapsulated oil). Tests should aim at understanding the differential attenuation/absorption of light in different wavelength bands by different oil types located under/within sea ice of different snow and ice thicknesses.

Cameras

Testing is needed to ensure the optimal and the maximum distance for the accurate discrimination of oil located under sea ice is known. This should be performed for a variety of oil spill and ice scenarios.

Oil encapsulation

Basic laboratory studies of sound scattering and light propagation and attenuation during oil encapsulation need to be performed to determine the fundamental limitations of all systems for detecting oil (of varying thickness) entrapped within ice (for varying depths of encapsulation).

Goals*: <u>To identify the most promising techniques for detection of oil both beneath and within sea ice, including the primary limitations.</u>*

(2) Laboratory prototype testing

Once the basic characteristics of the sensor system have been determined, prototype systems (off the shelf, or purpose built) should be tested in more realistic conditions than can be achieved in small ice tank tests. It may be practical to perform these experiments in conjunction with preliminary tests described above. These tests should include:

1. **Deep tanks tests** (~ 5m depth). Many of the sensors may perform well at close range; performance may degrade at longer range (e.g. due to sonar beam spread, or attenuation of a laser fluorosensor signal).
2. **Large test basin tests**. Tests that simulate realistic field conditions are needed to evaluate sensor performance in more realistic scenarios. These should include variable ice conditions (new and older ice types) and thickness and for variable oil conditions (e.g. thick pools, versus thin, dispersed slicks). For these experiments, multiple sensor systems should be tested simultaneously

Goals: *<u>To quantify the detection limits for each selected sensor under a range of realistic scenarios including different ice conditions (i.e. ice types, growing ice, and melting ice), oil types, environment (sunlight etc.) and oil spill characteristics.</u>*

(3) Miniaturization and development of AUV-deployable sensors

Many commercially available sensors are already deployable on small AUVS. These include radiometers, cameras, and many sonar systems. However, the best sensors for oil detection in many scenarios may sensors which may both need to be adapted into a compact, low-power system:

1. Broadband sonar
2. Laser fluorosensor

Goals*: <u>To transition the most effective technology to an AUV platform.</u>*

6.2.2 Recommendations for AUV evaluation and improvement

AUV operations under ice are a very recent and burgeoning capability. In parallel to the sensor development and evaluation <u>described above,</u> we believe that there should be a focus on AUV operations under ice. Specifically these operations should focus on conditions that were outlined in the different ice type scenarios. ROV operations should also be trailed for scenarios where they may be an appropriate platform (e.g. small spills under fast ice).

It is important to understand the readiness of the AUV/ROV industry to perform missions under sea ice. One way forward is to seek tenders for a practical demonstration of the concept of AUV/ROV oil detection surveys under sea ice. The elements of the missions need to be predetermined, but could include: launch and recovery within sea ice, navigation capabilities, and real-time acoustic data communication integrated with the standard command and control structures associated with offshore platforms. We would expect this demonstration to be conducted with small, inexpensive AUVs capable of rapid deployment in remote areas with minimal overhead infrastructure.

Despite the current capabilities of AUVs for under ice missions, there is significant scope for improvement in capabilities of AUVs for under ice oil spill response. Recommended enhancements over the next several years, in rough order of priority include:

1. Improvements in the ability to deploy and recover vehicles through small holes in the sea ice, or alternatively, to develop the means to create access holes from the deck of support vessel in compact ice conditions
2. Improvements in vehicle navigation capabilities in complex ice conditions, e.g. collision avoidance algorithms for autonomous vehicles operating close to the ice underside in the vicinity of ridges, and for mapping in areas where the ice floes may be moving.
3. Development of adaptive oil spill search strategies to optimize spill mapping, possibly including automated oil identification from fusion of multisensor data.
4. Improvements in telemetry of high-bandwidth data (including improved acoustic communication networks) so that operators can make real-time decisions while missions are underway. There are specific challenges under sea ice due to the acoustic environment and the inability to surface to transmit data.
5. Transition of the technology to an easy to use system where non-specialists can routinely conduct missions within the framework of the existing command and control structures that are prevalent within the offshore community so that required operational expertise is comparable to that of many commercially available ROV systems.
6. Multiple, coordinated vehicle strategies to optimize mapping of large spills. This could also include several different specialized vehicles, e.g. a long-range AUV with a remote sensing suite mapping at 10 m beneath the ice, while a second vehicle searched for plumes or dispersed oil in the water column, and a third, hover-capable vehicle could operate in close proximity to the ice those areas identified as contaminated. Advances in this area are being pursued for a variety of purposes.

The order of priority here reflects both the operational need, as well as the need to achieve some goals prior to others. Many of these capabilities are currently achievable, and indeed, have been achieved to varying degrees within research AUVs. Targeted investment may be required to develop improved capabilities for the specific task of oil spill detection and mapping beneath sea ice.

Goals: To improve, where needed, the readiness of AUV technology for under sea ice oil spill detection operations.

6.2.3 Development of an operational UUV system

Goals: Integration of a sensor suite (6.2.1), with improvements to AUV operations (6.2.2), to provide a flexible operational AUV platform. Realistic field trials of this platform are needed to clearly demonstrate the readiness of AUV technology for under sea ice oil spill detection operations. Integration of a sensor suite with ROVs should also be pursued for certain scenarios.

Development of an operational AUV platform can be most effectively completed only after completion of the steps outlined in sections 6.2.1 and 6.2.2 above. The final system design may depend on the application. For instance, one vehicle and sensor suite might be used under fast ice, where deployment can be from the ice and there is a realistic chance of mounting an effective clean-up response. In pack ice, launch of a larger vehicle may be appropriate and the goal may be longer term monitoring of the spill. This development requires two steps:

Integration of the sensor suite

The most appropriate sensor suite must be integrated into the vehicle. Techniques for fusion of multiple sensor data streams to provide optimized detection capability should be explored, both for real-time and post-mission identification.

UUV field trials

Realistic field trials of the complete system are required to prove its operational capabilities for oil spill response. This should include the following:

1. **Open water tests**. Limited release of oil in controlled experiments, or in response to accidental spills where possible.
2. Tests with deployment of an oil proxy under natural sea ice, where the effects of ice thickness and roughness variability can be evaluated.
3. If possible, real oil spill field trials in ice covered seas should be performed under a variety of environmental (ocean, ice and atmosphere) conditions. This will provide the widest range of scenarios so that the capabilities of the complete platform and sensor suite can be determined prior to operational use.

Focused and specific tests of each sensor/UUV system should be sought from potential experts/contractors with the aim being to characterise each system under a number of dedicated scenarios, i.e. oil type, oil thickness, oil located under ice, oil encapsulated within the ice cover, turbid water, etc. From these tests a well-informed understanding of UUV limitations and multi-sensor possibilities can be quantified. Provision for a second round of test should be built in to allow for solutions to gaps in the sensor capability or UUV technology that are highlighted by these tests,

6.3 Summary of key recommendations

The recommendations described above provide detailed steps toward the development of a complete AUV system for oil detection under ice. Here we outline those key steps which are likely to most advance this capability in the next several years

1. **Testing and development of sonar system**. Single beam sonar has shown promise in the detection of oil under se ice through the clear distinction between the oil/water and ice/oil interfaces. However a variety of sonar systems with different frequencies and capabilities may be applicable to this problem e.g. single beam, multibeam, parametric

or broadband. Further theoretical and laboratory based research is needed to ensure we deliver the best system possible. Of particular interest are broadband systems, which can achieve superior range resolution at low frequencies. Their successful use in a variety of oceanographic applications including fine-scale turbulence and small scatterers (e.g. oil droplets) dispersed in the water, suggest further investigation is needed.

2. **Testing and development of laser fluorometry.** These systems are almost untried underwater and may allow detection of oil in thin slicks and encapsulated oil, which may not be possible with other systems. Advances in low-power, compact systems are needed.
3. **Testing of radiometers:** It has been crudely shown that oil effectively attenuates light in the 300-600 nm range, with transmission being much higher at longer wavelengths. Controlled tests with modern radiometers are needed to obtain more detailed information on the spectral attenuation of light due to oil of different thicknesses. Off-the-shelf hyperspectral units offering a different numbers of wavelength bins are readily available.
4. **Testing of cameras:** Camera systems are well developed however, further testing is needed to ensure the optimal (and maximum) distance for the accurate discrimination of oil is known for a variety of oil spill and ice scenarios. This requires detailed laboratory and possibly realistic field trials.
5. **Miniaturization/low-power versions of sensors and sensor suite:** For maximum flexibility sensors should be able to be integrated on both small and large AUV/ROVs. However, research may reveal that the best sensors for oil detection may not have a compact, low-power system presently available. In this instance investment will be needed to ensure that these systems are modified so that they are suitable for AUV/ROV integration.
6. **Realistic "field" trials.** While small-scale laboratory tests are the first step, sensor performance in real-life conditions (range from the ice, ice and oil spill characteristics) may be quite different. Many of these experiments can, and should, be carried out in large tanks (both in breadth and depth) where performance at near realistic ranges, complex ice morphology, realistic oil dispersals, and realistic water conditions (e.g. biological matter) can be tested. Eventually, controlled release field trials will be necessary. Given the need to test all sensors in similar experiments, it may be most practical to coordinate sonar, laser fluorosensor and radiometer experiments.
7. **AUV deployment and recovery in ice.** The most challenging aspect of AUV logistics in ice is the deployment and recovery through small holes in the ice. Methods for AUV navigation to reliably return to small holes in the ice need to be refined.
8. **AUV under ice missions and navigation in complex conditions.** AUV missions under ice are now routinely possible where the AUV can maintain a safe depth clear of the ice. Precise navigation (and hence accurate oil location) is now achievable beneath single floes, but more challenging across a region of moving pack ice. Advances in AUV navigation should focus on collision avoidance algorithms for operation close to the ice underside and in the vicinity of ridges, and for mapping in areas where the ice floes may be moving so that the oil can be mapped in the same reference frame as other spill response assets.

Transition to an operational platform. To effectively integrate an AUV system into a spill response operation, the technology must be transitioned from research systems to an operational platform that can be operated by trained non-specialists. This will first require completion of the research-level tasks 1-5 listed above. This transition will require

(1) transition of mission planning and monitoring software to user-friendly products,

(2) improvements in telemetry of real-time data so that an operator can monitor sensor and vehicle status information in a robust, intuitive way, and

(3) development of data fusion algorithms (possibly running on-board the vehicle) so that robust identification of oil can be achieved by the operator without intensive interpretation or processing of the data. Steps towards such a system can be effectively made in tandem with the key recommendations outline above.