ARCTIC RESPONSE TECHNOLOGY
OIL SPILL PREPAREDNESS

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# REMOTE SENSING GUIDE TO OIL SPILL DETECTION IN ICE-COVERED WATERS

## ARCTIC OIL SPILL RESPONSE TECHNOLOGY – JOINT INDUSTRY PROGRAMME

The oil and gas industry has made significant advances in the ability to detect, contain, and cleanup oil spills in arctic environments (Potter et al., 2012). Ongoing research continues to build upon more than fifty years of examining all aspects of oil spill preparedness, oil spill behaviour, and available options for oil spill response in the Arctic marine environment. This research has included hundreds of studies, laboratory and basin experiments, and field trials, conducted in the United States, Canada, and Scandinavia. To build on existing research and improve technologies and methodologies for arctic oil spill response, members from the IPIECA-Oil Spill Working Group, Industry Technical Advisory Committee (ITAC) and the American Petroleum Institute-Emergency Preparedness and Response Programme Group formed a joint committee in 2009. The committee's task was to review the oil and gas industry's prior and future work scope on prevention and response to oil spills in ice in order to identify and prioritise technology advances and research needs. One outcome was the recommendation to establish the Arctic Oil Spill Response Technology Joint Industry Programme (JIP) that would undertake targeted research projects identified to improve industry capabilities and coordination in the area of arctic oil spill response.

The JIP was launched in January 2012 and over the course of the programme is carrying out a series of advanced research projects in six key areas: dispersants, environmental effects, trajectory modelling, remote sensing, mechanical recovery, and in situ burning (ISB).

Recognizing the limitations of mechanical recovery systems available today, the JIP Mechanical Recovery research project was initiated with the following objectives:

- Examine results obtained from previous research projects and identify further improvement opportunities for design of mechanical recovery equipment and response strategies for oil spill recovery in ice;
- Develop a selection process by which novel concepts can be rigorously examined; and
- Select and develop the most promising concepts.

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## ACKNOWLEDGEMENTS

The authors would like to express appreciation to significant contributors to this project. In particular, we would like to thank David Dickins for his valuable advice developed from extensive experience with remote sensing technology while working in the Arctic. In addition, we would like to acknowledge Statoil ASA for its support during the preparation of this guide and Transport Canada for permission to use select ice regime photographs depicting varying ice concentrations and stages of development. Finally, we would like to thank Bob Ellis for the exceptional illustrations prepared for this guide.

## EXECUTIVE SUMMARY

This guide was developed with the operational user in mind for assessing and selecting appropriate remote sensing technologies and deployment platforms for oil spill detection and surveillance in ice-covered waters. At this time, the prevailing state of knowledge about remote sensor performance is largely based upon field experience gained in temperate climate spills and experimental tests conducted utilizing intentional spills in various ice conditions. This existing body of knowledge is applied to provide the user with a tool to assess the potential performance of various types of sensors against representative oil in ice distributions commonly occurring in the Arctic. The sensors included are those commercially available at this time that have demonstrated performance in one or more of the oil in ice distributions. The sensors are grouped according to possible deployment platforms (e.g., ice surface, aircraft, vessels, etc.) since the availability of each platform will be a major determinant for the successful use of each remote sensing system.

In most Arctic regions, few, if any, airborne sensing systems would be readily accessible, and the use of any aircraft systems under government control may be very restricted or entirely unavailable. There will also be logistical challenges to deploy and support such systems. Therefore, this guide is also intended to assist the user with the planning of a surveillance program with the best suite of sensors and platforms for specific types and amounts of ice, while considering possible oil distributions within the ice.

The experienced, human observer is one of the most important and reliable sensors for the spotting and tracking of oil on the surface in a broad range of ice concentrations. In addition to visual observation (VIS), potentially useful sensors for oil on, in or below ice include: Thermal Infrared (TIR) and Forward-looking Infrared (FLIR); high definition, still and video digital cameras (OPT); trained dogs and handlers for working on the surface of stable ice; Ground Penetrating Radar (GPR); Side-Looking Airborne Radar (SLAR); marine radar; multi-beam, broadband and narrowband sonar; Laser Fluorosensor (LFS); Light Detecting and Ranging system (LIDAR); and satellite-based Synthetic Apeture Radar (SAR).

With the rapid research and development in sensor technologies, it can be expected that a number of promising sensor technologies and evolving deployment platforms will become commercially available in the near future. Notable examples of sensing technologies showing potential, but not fully proven for commercial use, include airborne GPR, Frequency Modulated Continuous Wave (FMCW) radar and Nuclear Magnetic Resonance (NMR). Rapidly developing platforms include Autonomous Underwater Vehicles (AUVs) and Unmanned Aerial Vehicles (UAVs) with enhanced range, endurance, and payload capacities.

The report is organized into seven sections:

Sections 1–2: Explain the guide's organization and use, including the oil in ice distribution categories used to assess conditions, important operational factors for conducting effective oil detection and response, the expected performance ranking scheme, and an overview of the various platforms for deploying sensors and their potential limitations.

Sections 3–5: Present illustrations of the selected sensors and platforms for the oil in ice distribution categories and expected performance rankings together with tables summarizing the estimated operating capabilities and limitation for platforms and sensors.

Section 6: Provides a matrix of the expected performance of the selected platforms and sensors for all twelve oil in ice distribution categories. Based largely upon whether the oil is exposed on top of the ice or concealed by snow or ice, platform and sensor combinations are ranked *yes* (likely), *potential* (may be possible), *no* (not likely) or *not applicable*. *Not applicable* is indicated where the sensor technology is either currently unavailable to meet acceptable performance expectations or where safety issues could preclude field use.

Section 7: Lists the key references used to prepare this guide and assess the sensors and platforms

## ACRONYMNS

| | |
|---|---|
| AIS | Automatic Identification System |
| AUV | Autonomous Underwater Vehicle |
| BAOAC | Bonn Agreement Oil Appearance Code |
| CRREL | United States Army Corps of Engineers, Cold Regions Research and Engineering Laboratory |
| FAA | Federal Aviation Administration |
| EASA | European Aviation Safety Agency |
| cm | centimeter(s) |
| FLIR | Forward-looking Infrared |
| FMCW | Frequency Modulated Continuous Wave |
| GPR | Ground Penetrating Radar |
| GPS | Global Positioning System |
| HD | High Definition |
| hr | hours(s) |
| IR | Infrared |
| JIP | Arctic Oil Spill Response Technology Joint Industry Programme |
| LFS | Laser Fluorosensor |
| LIDAR | Light Detecting and Ranging |
| kHz | Kiloherz |
| km | kilometer(s) |
| kph | kilometer(s) per hour |
| m | meter(s) |
| m/s | meter(s) per second |
| mm | millimeter(s) |
| NMR | Nuclear Magnetic Resonance |
| OPT | High resolution optical cameras and high dynamic range underwater cameras |
| ROV | Remotely Operated Underwater Vehicle |
| SAR | Synthetic Aperture Radar |
| SLAR | Side-looking Airborne Radar |
| TIR | Thermal Infrared |
| UV | Ultraviolet |
| UAV | Unmanned Aerial Vehicle (fixed-wing or rotary-wing) |
| USCG | United States Coast Guard |
| VIS | Visual observation |

# 1. INTRODUCTION

The purpose of this remote sensing guide is to provide the user with a concise reference tool for assessing and selecting the most proven remote sensing technologies and deployment platforms for oil spill detection and surveillance in ice-covered waters. The guide also contains illustrations depicting the suite of sensors and platforms with the best chance of success for a given oil in ice distribution along with associated tables indicating sensor advantages and limitations. Based upon the state-of-knowledge from the most recent research and field experience, the guide presents the estimated performance ranking of commercially available sensors and platforms for the oil in ice distributions characteristically found in the Arctic.

## 2. GUIDE USE FUNDAMENTALS

This guide is constructed upon the practical notion that visual observation is the primary remote sensing method that could be conducted, if safe to do so, from the ice surface, offshore platform, vessel or aircraft. In addition, the guide contains an assessment of available remote sensing technologies and potential deployment platforms that could provide viable alternative methods to locate oil among, on, under or in ice, as well as during periods of restricted visibility. The guide is organized to provide the field observer/user with the following general information and guidance:

Section 2

- Characteristic oil in ice distribution categories to aid in assessing field conditions.
- Important operational factors for conducting effective oil detection and response.
- Selected remote sensing technologies with demonstrated field performance in the Arctic.
- An overview of the various platforms for deploying sensors and potential limitations.

Sections 3, 4 and 5

- Representative photographs illustrating the oil in ice categories used in this guide.
- Illustrations of the sensors and platforms with the best potential for the oil in ice distributions with accompanying tables indicating the expected performance of the selected sensor and platform combinations for each category.
- Tables summarizing the capabilities and limitations of different platform and sensor options for the oil in ice distribution categories.

Section 6

- A summary matrix that ranks the expected performance of commercially available, platforms and sensors for the twelve oil in ice distribution categories.

In using this guide, the following color scheme and ranking convention are used to indicate expected performance:

| Expected Performance | |
|---|---|
| Yes (likely) | Y |
| Potential (may be possible) | P |
| No (not likely) | N |
| Not applicable | |

Trained, experienced spill and ice observers are critical to properly identify and assess oil and ice interactions. It is also advisable that remote sensing specialists be available in the field and within the incident command organization who can assist with the determination of appropriate remote sensing technologies and interpretation of data for the ice conditions present during an incident.

Key considerations that need to be addressed during sensor/platform selection include:

- The nature of the release and oil properties.
- Current prevailing ice conditions and likely changes over time, including anticipated drift rates and directions of movement.
- Potential oil thicknesses and distribution on, in and/or under ice.
- Operational daylight hours.
- Restricted visibility (e.g., clouds, fog, blowing snow).
- Wind and sea states.
- Sensors and platforms currently available at the site or obtainable in a realistic timeframe given the changing conditions of the interacting oil and ice.

Multiple types of oil in ice distributions may be present within relatively short distances with rapidly changing weather conditions. Therefore, the user should consider the operational conditions and potential platforms that could carry a combination of sensors capable of augmenting and verifying the results of one another in varying visibility, wind and sea states. Additionally, the user should consider access to large numbers of Global Positioning System (GPS) tracking beacons or buoys that can withstand ice forces. These beacons can assist airborne and marine response resources to locate and follow the movement of oiled ice over a winter season if necessary.

Of foremost importance, the platforms for deploying the sensing technologies must be capable of safely operating in the ice and weather conditions with adequate infrastructure and operational support. As arctic locations are commonly challenged by long travel distances, lack of infrastructure and access to fuel supplies, the availability and accessibility of suitable remote sensing systems should be evaluated in advance, and contingency plans should be in place for equipment procurement and mobilization during an emergency.

For more background information on the current state of knowledge and capabilities of remote sensing technologies, the user is referred to the following Arctic Response Technology Joint Industry Programme (JIP) reports:

- Final Report 5.1: Oil Spill Detection and Mapping in Low Visibility and Ice: Surface Remote Sensing (Puestow et al. 2013);
- Final Report 5.2: Capabilities for Detection of Oil Spills under Sea Ice from Autonomous Underwater Vehicles (Wilkinson, Maksym, and Singh 2013); and
- Final Report 5.3: Detection of Oil On-In-and-Under Ice (Pegau, Garron and Zabilansky 2016).

## 2.1 Guide Assumptions

Effective use of the guide is based upon the following assumptions:

- User is familiar with commercially available sensors and support platforms.
- All safety issues and all sensor platforms have been reviewed and approved by the responsible party and comply with applicable regulatory authorities.
- The platforms (e.g., ice surface, aircraft, vessels, etc.) available to the field user are the primary driver in selecting suitable sensing technologies.
- Platforms and sensor systems may not be immediately available, reflecting the extra time to contract and configure platforms with the suite of desired sensors.
- The guide's user will assess sensors and platforms based upon the current and expected predominant ice and weather conditions.
- Most airborne sensor systems included in this guide are commonly found on surveillance aircraft used internationally for pollution detection.

## 2.2 Safety Considerations

Safety is the foremost consideration. The user of this guide must consider the safety criteria, procedures and restrictions for operations involving aircraft, vessels or personnel working directly on or over ice surfaces. A risk analysis and stringent safety plan must be prepared for all operations along with specific procedures for search and rescue. The feasiblity of using any particular sensor or combination of sensors will be determined largely by the operational safety issues involving personnel and the available deployment platforms. The selected remote sensing strategies and techniques will need to be adaptable to the changing conditions that could be expected at all of the operating locations needed for the mobilization and support of safe operations involving each sensing platform.

## 2.3 Oil in Ice Distribution Categories

Figure 2-1 shows the basic oil in ice distributions that an experienced observer should be able to discriminate in the field. A combination of these distributions may be present within a given area and could change quickly over time. Table 2-1 provides example illustrations and summary descriptions of the twelve oil in ice categories used in this guide.

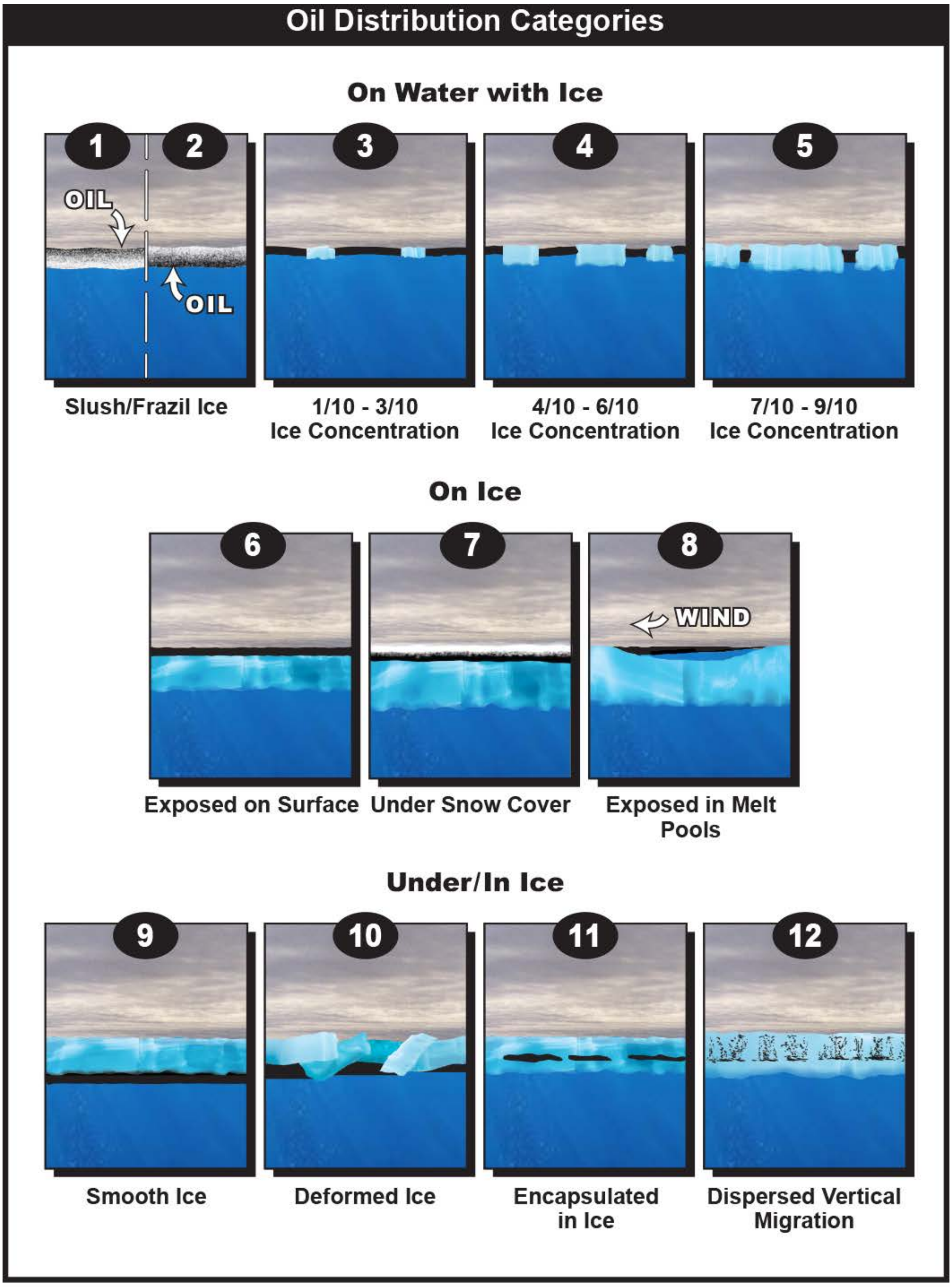
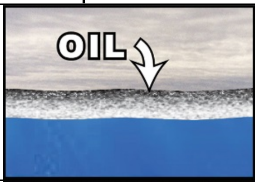
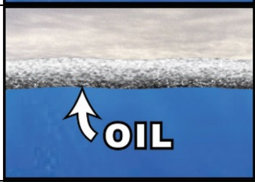
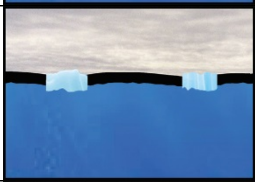
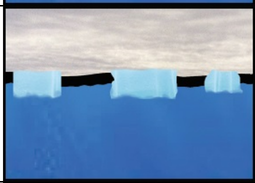
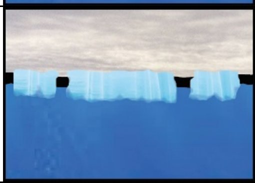
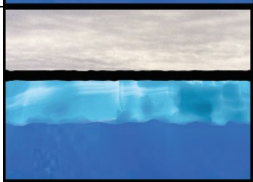
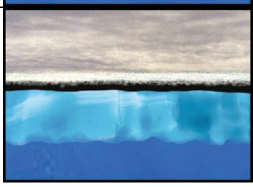
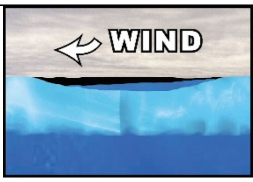
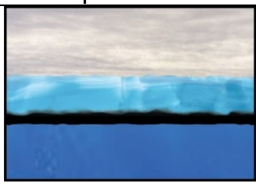
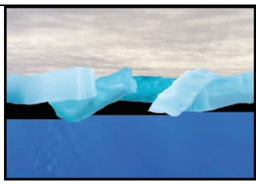
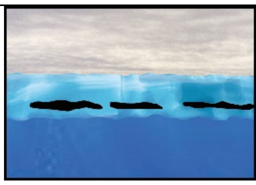
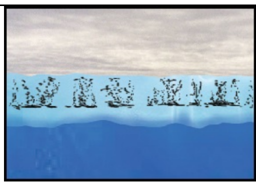



Figure 2-1 Oil in Ice Distribution Categories

Table 2-1 Oil in Ice Distribution Terminology

| Oil in Ice Distribution Category | | Description | |
|---|---|---|---|
| 1 | Oil falling on slush/frazil ice |   | Oil landing upon new ice forms (e.g., frazil, grease ice, and shuga) from a source above the ice/water surface. |
| 2 | Oil rising below slush/frazil ice |   | Oil coming from a source below the ice/water interface of new ice forms. High density oil may sink or remain in the water column below the ice/water matrix. Lighter components may separate and rise within the slush/frazil layer. |
| 3 | Oil on water in 1/10 to 3/10 ice concentrations |  | Oil spread on the water surface between ice floes covering from 1/10 to 3/10 of the water surface in a given area. The ice may be floating or grounded on the sea bed. |
| 4 | Oil on water in 4/10 to 6/10 ice concentrations |  | Oil spread on the water surface between ice floes covering from 4/10 to 6/10 of the water surface in a given area. The ice may be floating or grounded on the sea bed. |
| 5 | Oil on water in 7/10 to 9/10 ice concentrations |  | Oil spread on the water surface between ice floes covering from 7/10 to 9/10 of the water surface in a given area. The ice may be floating or grounded on the sea bed. |
| 6 | Oil exposed on ice surface |  | Oil on top of ice in any concentration. |
| 7 | Oil under snow cover |  | Oil on top of a solid ice surface covered by a layer of snow sufficiently deep to visually conceal the oil. |
| 8 | Oil exposed in spring melt pools |   | Oil surfacing through brine channels into melt pools on top of the ice as spring thaw advances (Category 8 often follows the migration of encapsulated oil shown below in Category 12). |

| Oil in Ice Distribution Category | | Description | |
|---|---|---|---|
| 9 | Oil under smooth ice |  | Oil under sea ice of any size and concentration with a relatively smooth surface. |
| 10 | Oil under deformed ice |  | Oil mixed with or under ice in any concentration that has been deformed into rafted, ridged and/or hummocked ice features. |
| 11 | Oil within encapsulated layer |  | One or more layers of oil trapped within ice as new ice continues to grow beneath that oil. |
| 12 | Dispersed vertical migration |  | Encapsulated oil dispersed within and possibly migrating toward the ice surface. |

## 2.4 Spill Response Considerations

### *2.4.1 Operational Factors*

Important "capabilities" and "limitations" associated with each remote sensing system include factors that relate to the platform/equipment involved, the environment, and the oil spill response operation to be supported. There are many different types of response (e.g., skimming, burning, dispersant application, shoreline cleanup, etc.), and for each response method it is essential to receive information on the location and distribution of oil. For each of the remote sensors identified in this guide, it is the detection of oil that is of primary concern. While some platform/sensor systems, under the right conditions, can support the mapping of an oiled area with estimates of thickness and/or coverage area, others may only provide for a limited "point" measurement detecting the presence of oil over a small footprint area. Whether detected visually by trained observers, electronically with sensing equipment, or by smell with dogs, experience has supported the following general observations in Table 2-2.

Table 2-2 Response Operational Factors

| Operational Factor | Description | General Observation |
|---|---|---|
| **Real-Time Information** | The transmission of information directly to a user of the data to enhance response, and possibly to other remote location users as needed and without delay. | Timing is critical. The direct transmission of data to response personnel is essential for the rapid positioning of equipment and the sustained elimination of oil before it is rendered undetectable or inaccessible. |
| **Oil Thickness** | The provision of an approximate oil thickness or at least an indication of the thickness classification (i.e., silvery sheen, rainbow, metallic, transition or dark, as distinguished by the Bonn Agreement Oil Appearance Code [BAOAC], Bonn Ageement 2012). | The approximate thickness of oil on water or trapped within ice/snow is the most important factor affecting the selection and effective use of mechanical, burning or dispersant response options. |
| **Darkness** | The ability to operate effectively during twilight and during night-time periods of complete darkness. | Reduced visibility, common in Arctic regions with periods of extreme cold and ice, often precludes the unique benefits of optical systems, and makes it difficult to work safely and effectively from aerial and surface platforms. The absence of solar radiation, heating exposed oil layers, also degrades the performance of most infrared sensing systems. |
| **False Targets** | The ability to distinguish oil from other materials or objects such as cloud shadows, ice color variations, temperature and salinity anomalies, water depth changes, marine life/vegetation, etc. | The reliability with which oil can be distinguished from false targets by eye and with sophisticated sensors continues as a significant challenge in avoiding costly, time-consuming efforts to reach and confirm "possible" oil concentrations. |
| **Low Visibility Conditions** | The ability to detect oil during periods of rain, snow, fog, cloud cover, and possibly even smoke from deliberate ignition. | While long periods of daylight during spring and summer facilitate the detection of spilled oil, other atmospheric conditions (such as fog, clouds, rain, etc.) seriously impede the performance of most sensors as well as visual efforts to see oil on water or within various combinations of ice and snow. |
| **Wind/Sea Conditions** | The ability to detect oil relatively independent of sea state, or within a specific range of wind/sea conditions. | High wind and sea conditions have a significant impact on vessels, as well as other surface operations (e.g., personnel working on stable ice). The lack of sea state may also degrade the performance of most marine radar and aerial radar systems (e.g., SLAR and SAR) as these sensors depend upon a sufficient amount of wind-wave action to differentiate the effects of wave dampening between oiled and non-oiled areas. Ice concentrations > 3/10 may well preclude sufficient waves between floes for the detection of the oil dampening effect. |

### *2.4.2 Selected Sensing Technologies*

The sensors selected for this guide are the most fully developed and commonly used for oil spill detection. Sensing systems generally utilize different complementary sensors to detect oil in a range of varying ice conditions. Table 2-3 summaries the sensor technologies included in this guide and capabilities for detecting oil.

Table 2-3 Remote Sensing Technologies

| Sensor | Sensor Abbreviation | Deployment Platform | Detection | Application |
|---|---|---|---|---|
| Visual / Optical | VIS / OPT | Stable ice surface, offshore platform, airborne, Unmanned Aerial Vehicle (UAV), shipborne, Autonomous Underwater Vehicle (AUV), Remotely Operated Vehicle (ROV) | Reflected visible light contrast between oil and water | Detection of oil extent and estimated layer thickness (e.g. BAOAC) |
| Thermal Infrared / Forward-looking Infrared | TIR / FLIR | Stable ice surface, offshore platform, airborne, shipborne | Thermal emissivity differences between oil and surrounding ice/water | Detection of oil extent and possibly distinguish between thin and thick oil slicks |
| Ultraviolet | UV | Airborne, UAV | Reflected ultraviolet contrast between oil and water | Detection of oil extent and detection of thin oil slicks and sheens |
| Laser Fluorosensor / Light Detecting and Ranging System | LFS / LIDAR | Airborne and under ice platforms | Fluoresced light emissions from aromatic components of oil | Detection of oil on or just below the sea surface and estimated layer thickness |
| Sonar (multi-beam, broadband and narrowband, single beam) | Sonar | AUV, ROV | Reflected acoustic signals to image oil below the ice or oil on water surfaces | 3D under ice mapping and detection of potential oil layers under ice or minimally encapsulated |
| Marine Radar (x-band) | Marine Radar | Offshore platform, shipborne | Variations of the reflected radar backscatter signals from oil and surrounding water | Detection of oil and extent on the sea surface within operating range limits |
| Side-looking Airborne Radar | SLAR | Fixed-wing aircraft | Differences in the backscatter signals from waves dampened by oil and surrounding water surfaces | Detection of oil and extent on the sea surface |
| Synthetic Aperture Radar | SAR | Satellite, airborne | Differences in the backscatter signals from waves dampened by oil and surrounding water surfaces | Detection of oil and extent on the sea surface |
| Ground-penetrating Radar | GPR | Stable ice surface, helicopter (oil on ice under snow) | Electromagnetic backscatter signals imaging oil and ice | Detection of oil through snow and ice |
| Dogs | Dogs | Stable ice surface | Olfactory hydrocarbon recognition | Detection of oil on, in and under snow and ice |

### *2.4.3 Sensor Platforms*

The various sensor platforms (e.g., ice surface, vessel, aircraft, satellite, etc.) that the observer/user may access will largely control the sensors available for oil detection and tracking. The following provides general background information on the primary deployment platforms and associated types of sensors commonly used on various platforms.

Stable Ice Surface

Landfast ice, grounded ice, or large floating ice floes could provide a safe load-bearing surface for visual observation, TIR/FLIR, dogs, and GPR operations. The main selection criteria are ice thickness and stability matched to the expected load of personnel and equipment and stability. Prior to operations on the ice, a risk assessment should be conducted by a qualified ice engineer or specialist to ascertain the ice thickness, integrity, load bearing capacity, and operational protocols and constraints.

The user is referred to Tactic L-7 in the Alaska Clean Seas (ACS), Technical Manual, Volume I, Tactic Descriptions for general guidance on ice thickness and load bearing capacity, selected vehicles and heavy equipment weights, load spacing, and safety considerations.

AUV/ROV

Underwater vehicles are rapidly evolving as a means to detect and map oil under sea ice. The two types of underwater vehicles included in this guide are the AUV and the ROV – the latter most commonly stationed on offshore exploration and production platforms, as well as offshore supply/support vessels.

The AUV has the advantage of being able to move about freely using pre-programmed, self-directed navigation to survey under the ice. The suite of sensors the AUV may carry is, at present, generally limited to optical cameras with underwater lighting, laser fluorosensors and sonar due to payload limitations and power supply requirements. Real-time reconnaissance data transmission is constrained by the bandwidth of the acoustic modems presently available. Most of the data and high quality imagery collected cannot be accessed until the AUV has been retrieved back to the surface.

An ROV could be used to deploy sensors under ice but its tether limits the unit's operating distance from several hundred meters for observation-class ROVs to more than 1,000 meters for work-class ROVs. The tether, however, provides the advantage of enhanced real-time data capability. Due to their range limitations, ROVs would be best suited for relatively small spills under ice or surveying along an ice edge, as found, for example, in the Norwegian Barents Sea.

Vessel/Aerostat

Most arctic ventures are likely to have dedicated vessels for operational support or oil spill response. Such vessels would normally be equipped with optical cameras, hand-held or vessel-mounted TIR/FLIR systems, and marine radar. One of the most effective sensors, of course, would be a trained human observer on the vessel to not only detect oil, but assess the nature and distribution of the oil. The observer could monitor the oil, react to changing conditions, and direct removal operations to the thickest oil concentrations.

The visible range from a vessel will be limited to the immediate vicinity and further restricted by darkness, fog and snow. Conditional upon good visibility and moderate winds, the field of view can be dramatically improved by deploying a tethered aerostat or a drone from the vessel. Such systems can support the spotting and surveillance of oil with real-time video, infrared (IR) imagery and an Automatic Identification System (AIS) for positioning.

Aircraft/UAV

Surveillance aircraft availability and support needs will largely determine the feasibility of deploying and sustaining airborne remote sensing systems. Because access to dedicated surveillance aircraft in the Arctic can be limited-to-nonexistent, advance planning would be necessary to ensure standby availability of aircraft equipped with portable or integrated sensors that could be mobilized in a timely way. Significant logistical and operational constraints should be expected for sourcing suitable aircraft from organizations in and possibly out of the country. Plans would need to include regional airstrip availability, fuel resupply, aircraft maintenance, and compliance with local airworthiness requirements (e.g. Federal Aviation Administration/European Aviation Safety Agency [FAA/EASA]). Above all, air operations can introduce significant safety issues, especially when operating offshore in remote Arctic regions. For example, helicopter operations over water and ice will require two engines and a demonstrated search and rescue capability.

Although many governments bordering ice-prone waters have pollution surveillance aircraft, these aircraft cannot be counted on to provide oil detection and tracking capability during an emergency incident. This is because government-controlled aircraft would require an approval process for temporary use outside of their assigned jurisdiction. Table 2-4 presents a summary of the government maritime pollution surveillance aircraft and their integrated suites of sensors potentially suitable for oil spill detection and tracking in the Arctic. The table also shows which of these aircraft are known to have conducted arctic surveillance missions. In addition to the sensors indicated in the table, the listed aircraft all utilize trained observers, along with high resolution, hand-held, digital still and video cameras. Many of these aircraft possess downlink transmission capabilities to vessels, with the exception of some older systems (e.g. Netherlands).

UAVs are emerging as a practical and adaptable option for deploying high definition (HD) optical cameras, TIR/FLIR and possibly UV sensors from an offshore platform or vessel. At present, commercially available UAVs are subject to size and operational restrictions in most jurisdictions that limit their sensor capacity and effective range. Other considerations potentially affecting UAV performance include high winds, deployment and recovery from offshore platfroms or vessels, and poor visibility. At present, they are largely useful for close range surveillance generally within sight of the operator. In particular, the rotary-wing UAV can vertically take-off and land and hover at low levels over the surface for close inspection of the oil and ice conditions. One of the key advantages of rotary-wing UAVs is their ability to remain fixed in position over a moving slick, thereby providing consistent imagery from the same angle. Fixed-wing UAVs have the capability to remain airborne for longer times and cover larger areas, but like their manned aircraft counterparts, suffer from having to image a slick for short periods while in forward motion, turning and repositioning for additional passes. UAVs can also perform other important surveillance tasks such as air sampling and marine mammal monitoring. Although the UAV has the potential for safely collecting real-time video of a spill from a vessel or command center, it will still be necessary for a trained human observer to interpret the images and to assess oil and ice conditions directly from the air whenever possible.

Table 2-4 Summary of Government Maritime Pollution Surveillance Aircraft with Arctic Potential

| Country | Operator | Aircraft | Approximate Endurance (hr) | Fleet Size | UV/IR Linescanner | FLIR/Visible Turret (EO/IR) | SLAR | LFS | Maritime Search Radar | Microwave Radiometer | Visible Linescanner | Known Arctic Deployment |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| United States[1] | Coast Guard | HC-144A/C27J | 10 / 12 | 32 | | x | x | | x | | | |
| Canada | Environment | Dash 8/Dash 7 | 7 | 3 | x | x | x | | x | | | x |
| Canada[2] | Fisheries | King Air B200 | 8 | 3 | | x | | | x | | | |
| Iceland | Coast Guard | Dash 8 Q-300 | 10 | 1 | x | x | | | x | | | x |
| Denmark[3,4] | Air Force | Challenger CL-604 | 8 | 4 | | x | x | | x | | | x |
| Sweden | Coast Guard | Dash 8 Q-300 | 10 | 3 | x | x | | | x | | | x |
| Finland | Border Guard | Do 228 | 10 | 2 | x | x | x | | x | | | |
| Germany | Navy | Do 228 | 10 | 3 | x | x | x | x | x | x | x | |
| Netherlands[5] | Coast Guard | Do 228 | 10 | 2 | | x | x | | x | | | |
| Norway | Coast Guard | King Air B350ER | 8 | 1 | x | x | x | | x | | | x |

Source: DF Dickins

Notes:

1. The United States Coast Guard (USCG) is transitioning all surveillance aircraft to be equipped with SAR, replacing older HC-130H aircraft configured with SLAR.
2. Operated under contract to the Canadian Government by PAL Aerospace. Primary tasking is fisheries patrols, but is required to provide support to other government departments for pollution surveillance.
3. New Danish aircraft will be the King Air B200, entering service in 2016 and complementing the existing Challenger fleet.
4. SLAR is planned as part of a 2017/ 2018 major systems upgrade for the Danish Challenger aircraft.
5. The UV/IR line scanner has been removed from both of the Netherlands aircraft pending plans to refit in the future.

<u>Satellite</u>

Imaging satellites utilize SAR for day and night surveillance of sea ice, independent of cloud cover and weather. Satellite imagery can be used to detect large oil slicks on water when there is enough wave action to discern differences in dampened wave activity between the water and the oiled area. The presence of ice can interfere with the ability to detect oil by dampening surface waves to the point there is no discernable surface difference between oil and water – similar limitations are encountered using SAR imagery to differentiate slicks at sea under calm conditions. Based upon the current state of knowledge from field experience and testing, it is estimated that SAR imagery would be useful for detection of a large slick in ice concentrations of 3/10s or less (Dickins 2010). Under those conditions, the experienced gained with using SAR imagery to map large slicks at sea should still apply (e.g., *Prestige* tanker spill and *Deepwater Horizon*). The satellites potentially available for use and their resolution capabilities will be determined by the spill's location, as well as the time delay to acquire imagery. Pre-planning is advisable to identify the orbital frequencies and resolution capabilities of satellites in the area of operations. With the ever increasing number of commercial SAR satellites in orbit, it is possible in many Arctic regions to obtain multiple images from different incidence angles and bandwidths during a single 24-hour period. Table 2-5 includes examples of commercial SAR satellites in orbit that could provide image sources for purchase (Parker 2012). In the next few years, a number of smaller, more economical, commerical SAR satellites are scheduled for launch by Canadian and United States companies that could increase the frequency of available imagery at a reduced cost.

Table 2-5 Commercial Satellites Providing SAR Imagery

| Satellite | Band | Resolution (m) | Image Swath (km) | Return Pass Rate (Days) |
|---|---|---|---|---|
| COSMO SkyMed | X Band | 1 – 100 | 10 – 200 | 16 |
| PAZ | X Band | 1 – 18 | 5 – 150 | 11 |
| RADARSAT-2 | C Band | 3 – 100 | 20 – 500 | 24 |
| TerraSAR-X / TanDEM-X | X Band | 1 – 18 | 5 – 150 | 11 |

### *2.4.4 Evolving Sensor Technologies*

This guide was prepared based upon commercially available sensors that have demonstrated performance in the Arctic, and does not include some sensor technologies still in evolving stages of development and testing. Notable examples of sensing technologies showing great promise, but not fully proven for commercial use, include airborne GPR for oil on ice, and FMCW radar and NMR for oil in ice.

Tank and field experiments (2004-2006) demonstrated that GPR operating directly on ice surfaces can successfully detect and map the presence of oil films as thin as 1-3 cm, trapped beneath solid ice 1 m or more in thickness, or encapsulated as layers within ice (Dickins et al. 2006). In 2008 field testing, the GPR radar suspended beneath a helicopter traveling at speeds up to 20 knots and altitude up to 20 m successfully detected a thin layer of crude oil buried under hard-packed snow (Bradford et al. 2010). Modeling of expected GPR performance in different spill scenarios showed that off-the-shelf, commercially available GPR should be capable of reliably detecting oil on ice under snow over a wide range of temperature conditions. However, modeling also indicated that the same system is not capable of reliable oil in ice detection due to the significant attenuation of the signal though other than very cold (relatively non-conductive) sea ice. This conclusion was recently confirmed at the US Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) in experiments involving elevated GPR over oil test cells (Pegau, Garron, and Zabilansky, 2016).

FMCW radar was developed as a airborne sensing tool operating with a much more focused, higher energy radar cone that functions over a wider range of frequencies. This potentially would overcome some of the drawbacks of trying to use off-the-shelf GPR systems in an airborne mode, for which they were never designed. The new radar was specifically aimed at being able to detect oil layers under and trapped within an ice sheet over a wide range of winter conditions. A protoype FMCW radar was developed in 2011 and tested on several occasions (2011-12 and 2015) over large ice basins at CRREL (Dickins, Marshall and Hay 2012; Pegau et al. 2016). Results were inconclusive for a number of reasons: the ice sheet was too warm in the first two test series and the prototype hardware proved unreliable over long term testing conducted in 2015. As a result, further testing is planned for early 2017 to confirm whether an improved protoype FMCW system is capable of oil in ice detection when suspended over a cold ice sheet representative of arctic conditions.

NMR is another technology being evaluated as a potential airborne means to detect oil trapped under or in ice. Full-scale testing of a prototype NMR antenna was conducted in 2014 over an outdoor frozen test pond at CRREL. Additional testing is underway (October 2016) at a site close to St. John's, Newfoundland. At present, significant drawbacks to NMR operations include the need for helicopters to fly with a large 6-meter diameter, circular antenna while remaining stationary for short periods over the ice. Such positioning over the surface at discrete sampling points is necessary in order to gather sufficient data for processing.

# 3. OIL ON WATER WITH ICE (ANY CONCENTRATION)

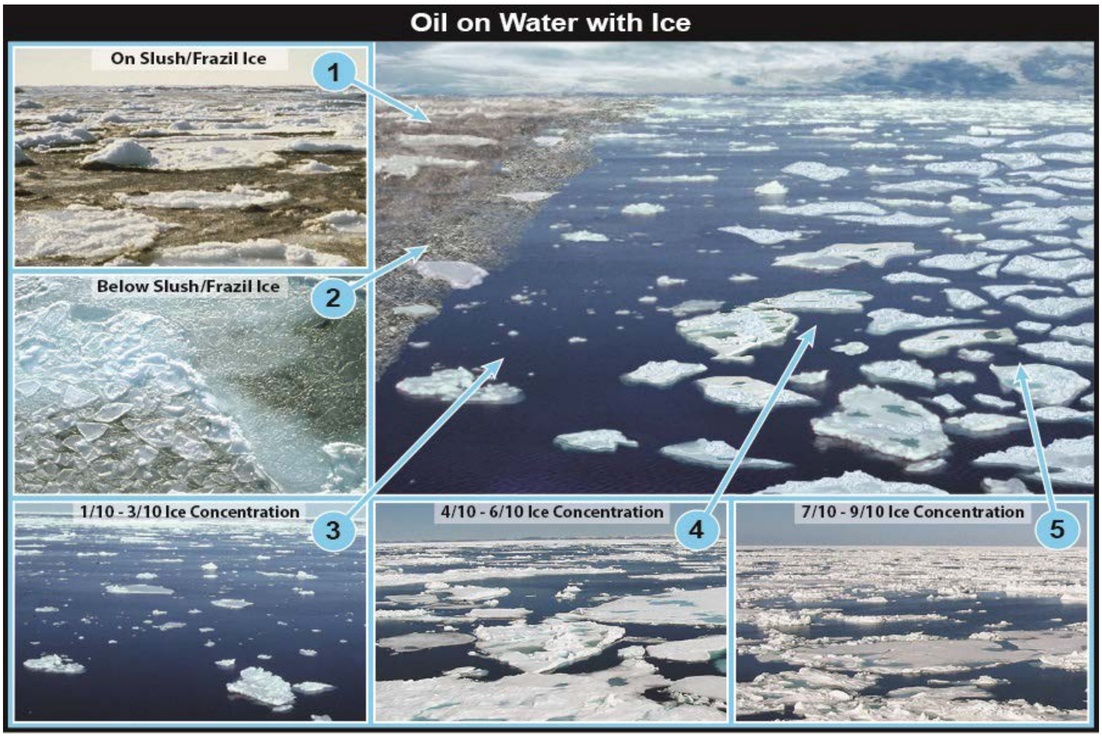
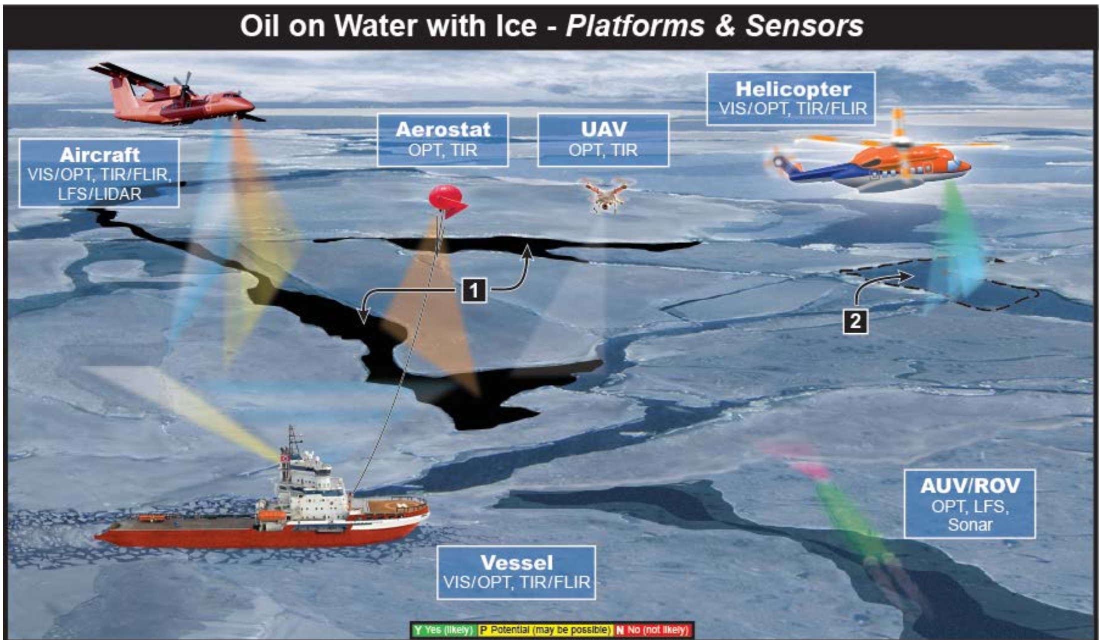



Figure 3-1 Oil on Water with Ice (Categories 1 – 5)




| 1 Oil on Slush/Frazil Ice | Aircraft/UAV | Vessel / Aerostat, Offshore Platform | AUV/ROV |
|---|---|---|---|
| | Y VIS/OPT | Y VIS/OPT | P LFS |
| | Y TIR/FLIR | Y TIR/FLIR | P Sonar |
| | Y LFS/LIDAR | | |

| 2 Oil below Slush/Frazil Ice | Aircraft/UAV | Vessel / Aerostat, Offshore Platform | AUV/ROV |
|---|---|---|---|
| | P VIS/OPT | P VIS/OPT | P OPT |
| | P TIR/FLIR | P TIR/FLIR | P LFS |
| | P LFS/LIDAR | | P Sonar |

Figure 3-2 Platforms and Sensors for Oil on Water with Slush/Frazil Ice (Categories 1 – 2)

Table 3-1 Remote Sensing Options for Oil on Water with Slush/Frazil Ice (Categories 1 – 2)

| Platforms | Sensors | Key Capabilities | Limitations |
|---|---|---|---|
| Offshore Platform, Vessel, Aircraft, UAV | VIS/OPT | • Real-time detection and mapping of visible oil on ice and water surfaces<br>• Estimation of oil thicknesses by BAOAC and/or direct measurement<br>• Marine mammal detection and monitoring | • Skilled observer required to detect and estimate oil thickness and extent<br>• Performance degraded by darkness, fog, rain and snow<br>• Personnel safety for use of stable ice surface as a platform |
| | TIR/FLIR | • Real-time monitoring from multiple platforms for improved oil encounter rate<br>• Detection of oil thicknesses >0.01 mm<br>• Marine mammal detection and monitoring<br>• UAVs can be launched/retrieved from offshore platforms/vessels and rotary-wing UAVs are capable of vertical take-off/landing and hover over target | • Performance degraded by fog, rain and snow<br>• Unreliable for very thin oil thicknesses<br>• High rate of false positives in bright light<br>• Small payload capacity for commercial UAVs<br>• Local jurisdiction UAV operating restrictions for weight, speed, altitude and operational separation distances |
| Aerostat | OPT, TIR | • Aerostats can be deployed from working multipurpose vessels for continuous real-time surveillance and spotting<br>• Marine mammal detection and monitoring | • Performance degraded by darkness, fog, rain and snow<br>• Operational wind speed limits (≤22 m/s or ≤40 knots)<br>• Small payload capacities for vessel-tethered aerostats<br>• View coverage |
| Fixed-wing Aircraft | LFS/ LIDAR | • Detection of oil on or near the water surface<br>• Classification of oil type and measurement of oil thicknesses between 0.1 and 20 microns on water surfaces | • Performance degraded by fog, rain and snow<br>• LFS requires low altitude flying (<500 m)<br>• Dedicated aircraft required for large units with high power consumption – not generally available on existing aircraft |
| AUV/ ROV | OPT | • Detection and 2D mapping of oil under ice<br>• Provides under ice imagery in low light conditions using high dynamic range camera and strobe light | • Performance degraded by low light and water with low clarity<br>• Power requirements for supplemental lighting<br>• Bandwidth limitations for onboard processing of imagery and telemetry |
| | LFS | • Detection of fresh oil under ice and in water column<br>• Measurement of oil thicknesses between 0.1 and 20 micron | • Florescence polarization needed to reduce false alarms |
| | Sonar | • Detection of fresh oil under ice unaffected by visibility on the surface<br>• Demonstrated potential in basin tests to detect encapsulated oil through up to 6-7 cm of new ice and provide estimated thicknesses for oil layers >1 cm (may perform better under field conditions)<br>• Multibeam may represent the optimum system in that it provides 3D imaging under ice surface topography as well as oil detection<br>• Optimal frequencies for detecting oil under the ice or encapsulated oil are 100 to 200 kHz | • Trained operator needed to interpret multibeam data<br>• Encapsulated oil detectable with up to ~4-7 cm of new ice beneath the oil layer – this limitation may diminish somewhat with the ability to use higher powers in an open ocean setting (compared to basin tests) |

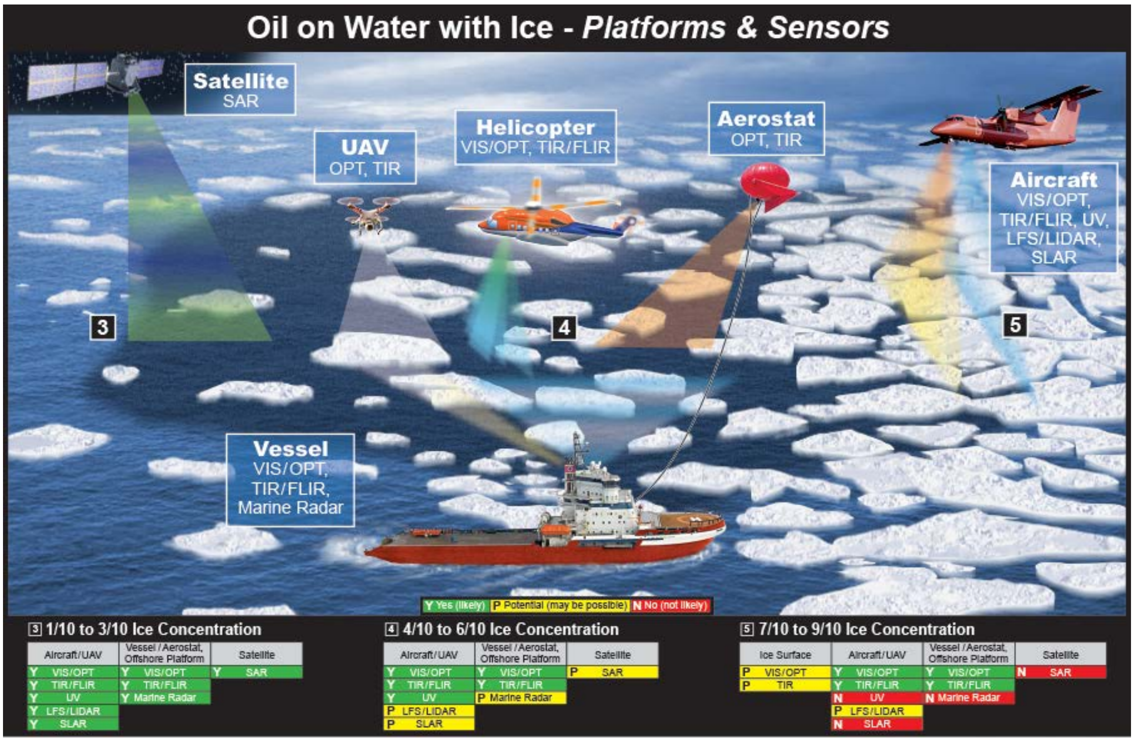



Figure 3-3 Platforms and Sensors for Oil on Water with Varying Ice Concentrations (Categories 3 – 5)

Table 3-2 Remote Sensing Options for Oil on Water with Varying Ice Concentrations (Categories 3 – 5)

| Platforms | Sensors | Key Capabilities | Limitations |
|---|---|---|---|
| Stable Ice Surface, Offshore Platform, Vessel, Aircraft, UAV | VIS/OPT | • Real-time detection and mapping of visible oil on ice and water surfaces<br>• Estimation of oil thicknesses by BAOAC or direct measurement<br>• Marine mammal detection and monitoring | • Skilled observer required to detect and estimate oil thickness and extent<br>• Performance degraded by darkness, fog, rain and snow<br>• Personnel safety for use of stable ice surface as a platform |
| | TIR/FLIR | • Real-time monitoring from multiple platforms for improved oil encounter rate<br>• Detection of oil thicknesses >0.01 mm<br>• Marine mammal detection and monitoring<br>• UAVs can be launched/retrieved from offshore platforms/vessels and rotary-wing UAVs are capable of vertical take-off/landing and hover over target | • Performance degraded by fog, rain and snow<br>• Unreliable for very thin oil thicknesses<br>• High rate of false positives in bright light<br>• Small payload capacity for commercial UAVs<br>• Local jurisdiction UAV operating restrictions for weight, speed, altitude and operational separation distances |
| Vessel | Marine Radar (x-band) | • Detection of oil as long as there is sufficient wind wave action to differentiate between oiled and non-oiled ocean areas<br>• Support for aircraft and satellite detection at specific locations | • Performance degraded by wind speeds less than ~5.5 kph (~3 knots) and greater than ~22.5 kph (~12 knots) and wave heights between 0.2 to 1 m<br>• Antenna height limits effective range to about 8 km<br>• Marine radar degraded by calm seas and could be expected to deteriorate with increasing ice concentrations |
| Aerostat | OPT, TIR | • Aerostats can be deployed from working multipurpose vessels for continuous real-time surveillance and spotting<br>• Marine mammal detection and monitoring | • Performance degraded by darkness, fog, rain and snow<br>• Operational wind speed limits (≤22 m/s or ≤40 knots)<br>• Small payload capacities for vessel-tethered aerostats<br>• View coverage |
| Fixed-wing Aircraft | UV | • Detection of oil thicknesses between 0.1 and 10 microns<br>• Support for TIR/FLIR to determine the oil's areal extent<br>• Identification of thin versus thick oiled areas when used in conjunction with infrared imagery | • Cannot detect oil thicknesses >10 micron<br>• Low flying altitude and narrow coverage range<br>• Requires daylight and clear atmospheric conditions<br>• Susceptible to false alarms |
| | LFS/ LIDAR | • Detection of oil on or near water surface<br>• Classification of oil type and measurement of oil thicknesses between 0.1 and 20 microns on water surfaces | • Performance degraded by fog, rain and snow<br>• LFS requires low altitude flying (<500 m)<br>• Dedicated aircraft required for large units with high power consumption – not generally available on existing aircraft |
| | SLAR | • Detection of oil over large areas in wind-wave heights between 0.2 and 1 m, or in smooth swell conditions<br>• Up to 40 km coverage range from each side of aircraft (dependent upon flight altitude)<br>• Useable day and night through clouds and fog | • Calm seas (wind speeds <5.5 kph or ~3 knots) or rough seas (wind speeds >22.5 kph or 12 knots)<br>• False alarms possible in low wind or ice conditions that dampen waves<br>• Unreliable detection in close pack ice |
| Satellite | SLAR | • Broad swath coverage ~100 to 10,000 km<br>• Spatial resolution <1 to 250 m<br>• Useable day and night detection through clouds and fog | • Requires trained interpretation specialist<br>• Image collection frequency and delivery lag times<br>• High rate of false alarms<br>• Unreliable detection in close pack ice |

# 4. OIL ON ICE (ANY CONCENTRATION)

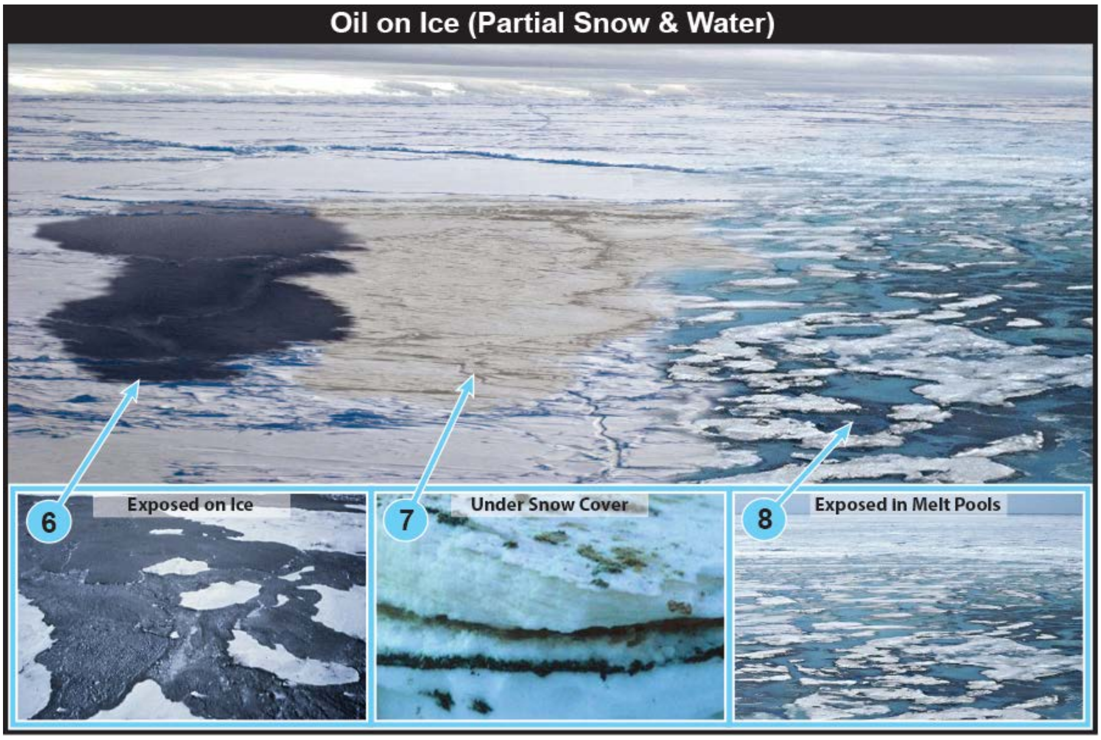



Figure 4-1 Oil on Ice (Categories 6 – 8)

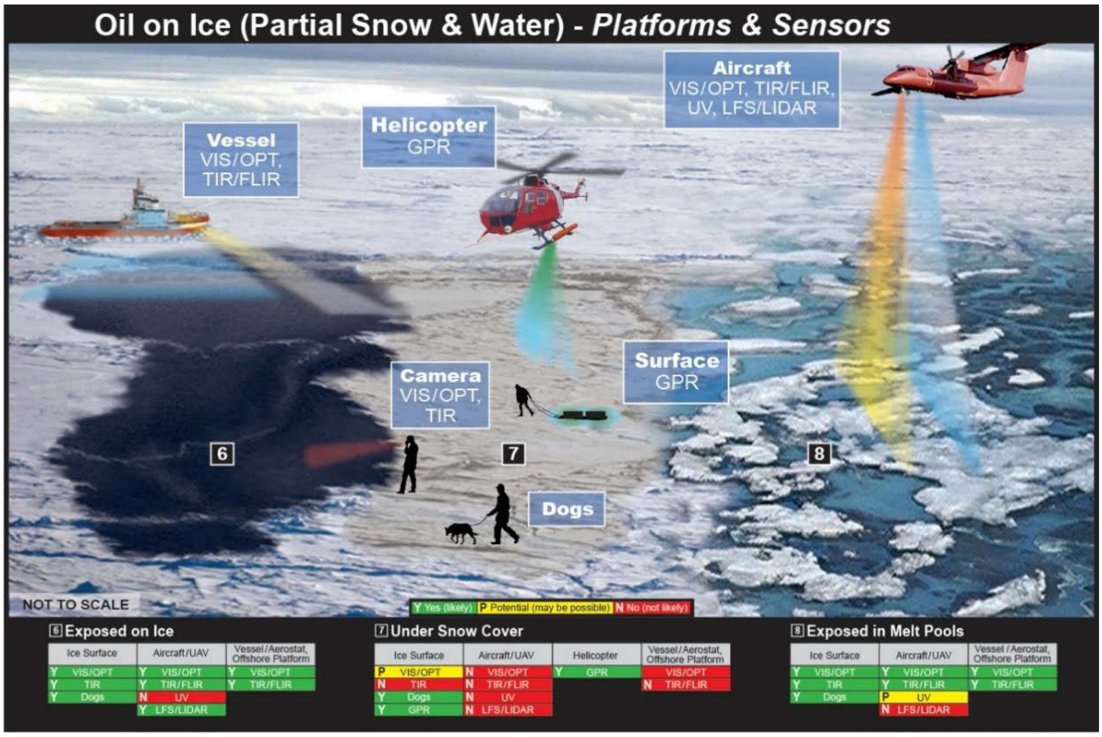



Figure 4-2 Platforms and Sensors for Oil on Ice (Categories 6 – 8)

Table 4-1 Remote Sensing Options for Oil on Ice (Categories 6 – 8)

| Platforms | Sensors | Key Capabilities | Limitations |
|---|---|---|---|
| Stable Ice Surface, Offshore Platform, Vessel, Aircraft, UAV | VIS/OPT | • Real-time detection and mapping of visible oil on ice and water surfaces<br>• Estimation of oil thicknesses by BAOAC and/or direct measurement<br>• Marine mammal detection and monitoring | • Skilled observer required to detect and estimate oil thickness and extent<br>• Performance degraded by darkness, fog, rain and snow<br>• Personnel safety for use of stable ice surface as a platform<br>• False positives (e.g. dirt on the ice exposed in the spring) with difficulty in distinguishing between oiled and clean melt pools under different lighting conditions |
| | TIR/FLIR | • Real-time monitoring from multiple platforms for improved oil encounter rate<br>• Detection of oil thicknesses >0.01 mm<br>• Marine mammal detection and monitoring<br>• UAVs can be launched/retrieved from offshore platforms/vessels and rotary-wing UAVs are capable of vertical take-off/landing and hover over target | • Performance degraded by fog, rain and snow<br>• Unreliable for very thin oil thicknesses<br>• High rate of false positives in bright light<br>• Small payload capacity for commercial UAVs<br>• Local jurisdiction UAV operating restrictions for weight, speed, altitude and operational separation distances |
| Aerostat | OPT, TIR | • Aerostats can be deployed from working multipurpose vessels for continuous real-time surveillance<br>• Marine mammal detection and monitoring | • Performance degraded by darkness, fog, rain and snow<br>• Operational wind speed limits (≤22 m/s or ≤40 knots)<br>• Small payload capacities for vessel-tethered aerostats<br>• View coverage |
| Fixed-wing Aircraft | UV | • Detection of oil in spring melt pools) thicknesses between 0.1 and 10 microns)<br>• Support for TIR/FLIR to determine the oil's areal extent<br>• Identification of thin versus thick oiled areas when used in conjunction with infrared imagery | • Cannot detect oil thicknesses >10 micron<br>• Low flying altitude and narrow coverage range<br>• Require daylight and clear atmospheric conditions<br>• Susceptible to false alarms |
| | LFS/ LIDAR | • Detection of oil exposed on ice surfaces<br>• Classification of oil type and measurement of oil thicknesses between 0.1 and 20 microns on water surfaces | • Performance degraded by fog, rain and snow<br>• LFS requires low altitude flying (<500 m)<br>• Dedicated aircraft required for large units with high power consumption – not generally available on existing aircraft |
| Stable, ice Surface, Helicopter | GPR | • Detection of oil on the ice surface under snow | • Qualified operator is required to accurately interpret data |
| Stable Ice Surface | Dogs | • Detection of oil hidden under snow<br>• Can be equipped with GPS positioning devices for marking sites and tracking<br>• Sensitivity to hydrocarbon odors for significant distances downwind from source (several kilometers of more) | • Safety of dogs and handlers working on floating pack ice<br>• Excessive exposure to cold and working hours<br>• Requires specially trained dogs and experienced handlers<br>• Safe transportation, warm shelter, medical support and food<br>• Wildlife interaction avoidance |

# 5. OIL UNDER/IN ICE (ANY CONCENTRATION)

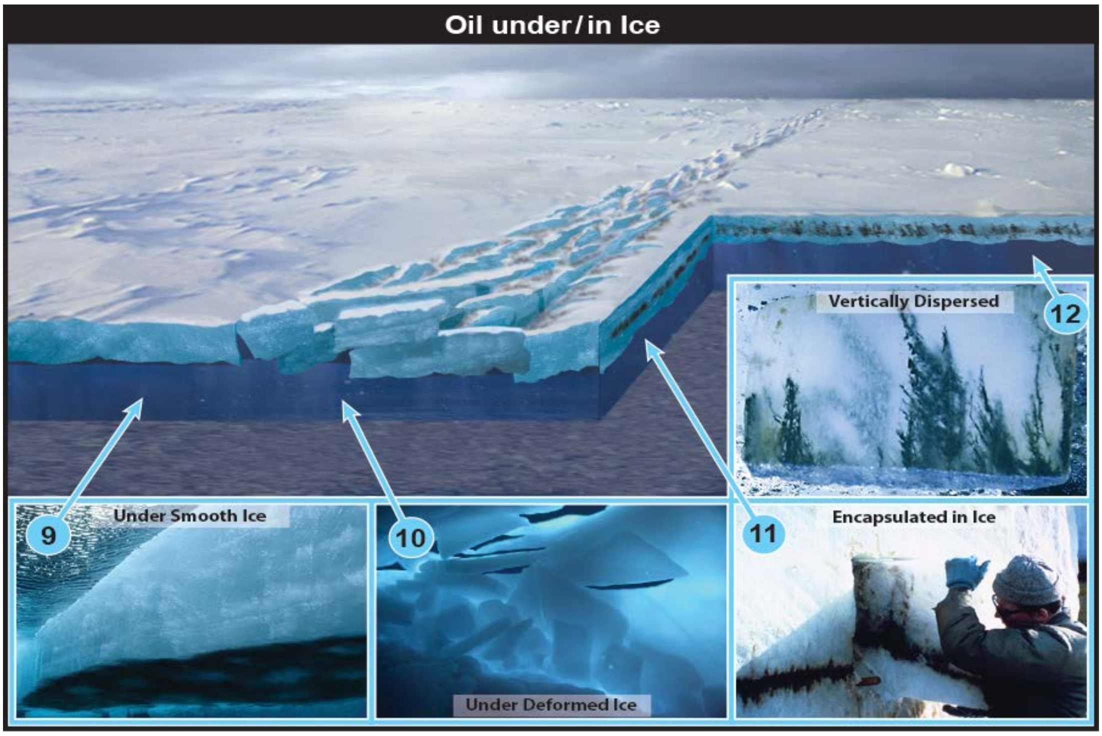



Figure 5-1 Oil under/in Ice (Categories 9 – 12)

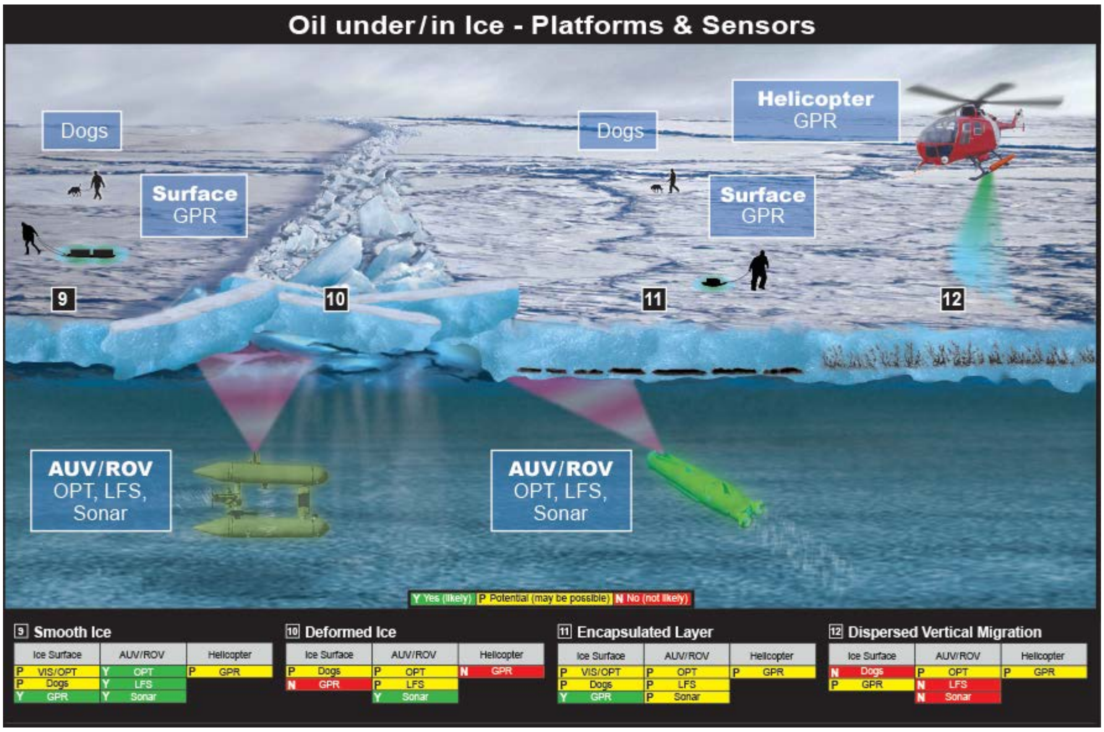



Figure 5-2 Platforms and Sensors for Oil under/in Ice (Categories 9 – 12)

Table 5-1 Remote Sensing Options for Oil under/in Ice (Categories 9 – 12)

| Platforms | Sensors | Key Capabilities | Limitations |
|---|---|---|---|
| Stable Ice Surface, helicopter | VIS/OPT | • Real-time detection and mapping of visible oil spread under ice<br>• Estimation of oil thicknesses by direct measurement | • Requires artificial illumination source below ice to detect oil<br>• Skilled observer to detect oil and estimate oil thickness and extent<br>• Practical application needs conditions where the ice is relatively clear of snow and the ice is not too thick |
| | Dogs | • Potential detection of oil under or in ice with greater probability where oil is mixed into deformed ice with some pathway to the surface for odors<br>• Can be equipped with GPS positioning devices for marking sites and tracking<br>• Sensitivity to hydrocarbon odors for significant distances downwind from source (several kilometers or more) | • Safety of dogs and handlers working on floating pack ice<br>• Excessive exposure to cold and working hours<br>• Requires specially trained dogs and experienced handlers<br>• Safe transportation, warm shelter, medical support and food<br>• Wildlife interaction avoidance |
| | GPR | • Detection of oil under and confined within ice | • Qualified operator is required to accurately interpret data<br>• Helicopter-support GPR performance significantly degraded by warm ice temperatures – possible detection only for oil layers at shallow depth in the ice |
| AUV/ROV | OPT | • Detection of oil and 2-D mapping of oil under ice<br>• Provides under ice imagery in low light conditions using high dynamic range camera and strobe light | • Performance degraded by low light and water with low clarity<br>• Power requirements for supplemental lighting given llikely low levels of natural light beneath snow-covered ice<br>• Bandwidth limitations for onboard processing of imagery and telemetry |
| | LFS | • Detection of fresh oil under ice and in water column<br>• Measurement of oil thicknesses between 0.1 and 20 micron | • Florescence polarization needed to reduce false alarms |
| | Sonar | • Detection of  fresh oil under ice unaffected by visibility on the surface<br>• Demonstrated potential in basin tests to detect encapsulated oil through up to 6-7 cm of new ice and provide estimated thicknesses for oil layers >1 cm (may perform better under field conditions)<br>• Optimal frequencies for detecting oil under the ice or encapsulated oil are 100 to 200 kHz | • Trained operator needed to interpret multibeam data<br>• Encapsulated oil detectable with up to ~4-7 cm of new ice beneath the oil layer – this limitation may diminish somewhat with the ability to use higher powers in an open ocean setting (compared to basin tests) |

## 6. REMOTE SENSING TECHNOLOGY PERFORMANCE MATRIX

Table 6-1 provides a summary of the expected performance of various commercially available sensors and platforms for the twelve oil in ice ice distribution categories presented in the previous sections. Not applicable (a blank cell) is indicated where technology is not currently available or acceptable to meet performance expectations, or where unsafe conditions are likely to preclude field use.

Effective oil spill detection will normally require multiple sensors, each having the capability to detect oil for the ice conditions encountered. The suite of sensors selected should have the ability to compliment and confirm one another.

Table 6-1 Remote Sensing Capabilities versus Oil in Ice Distribution Categories (1 – 12)

| | | Platform / Sensor | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Stable Ice Surface[1] | | | | AUV/ROV | | | Offshore Platform/ Vessel/Aerostat[5] | | | Aircraft/UAV | | | | | | Satellite |
| Oil in Ice Distribution | | VIS/ OPT[2] | TIR[2] | Dogs | GPR[3] | OPT | LFS | Sonar | VIS/ OPT[2] | TIR/ FLIR[2] | Marine Radar[6] | VIS/ OPT[2] | TIR/ FLIR[2] | UV[2] | LFS/ LIDAR[2,7] | SLAR[6,7] | GPR[3,7] | SAR[6] |
| *Oil on water with ice* | | | | | | | | | | | | | | | | | | |
| 1 | Oil falling on slush/frazil ice | | | | | | P[4] | P[4] | Y | Y | N | Y | Y | N | Y[6] | N | | N |
| 2 | Oil rising below slush/frazil ice | | | | | P[4] | P[4] | P[4] | P[4] | P[4] | N | P[4] | P[4] | N | P[6] | N | | N |
| 3 | 1/10 to 3/10 concentrations | | | | | | | | Y | Y | Y | Y | Y | Y | Y[6] | Y | | Y |
| 4 | 4/10 to 6/10 concentrations | | | | | | | | Y | Y | P | Y | Y | Y | P[6] | P | | P |
| 5 | 7/10 to 9/10 concentrations | P | P | | | | | | Y | Y | N | Y | Y | N | P[6] | N | | N |
| *Oil on ice – any concentration* | | | | | | | | | | | | | | | | | | |
| 6 | Exposed on solid ice surface | Y | Y | Y | | | | | Y | Y | | Y | Y | N | Y | N | | N |
| 7 | Under snow cover | P | N | Y | Y | | | | N | N | | N | N | N | N | N | Y | N |
| 8 | Exposed in spring melt pools | Y | Y | Y | | | | | Y | Y | | Y | Y | P | N | N | | N |
| *Oil under/in ice – any concentration* | | | | | | | | | | | | | | | | | | |
| 9 | Smooth ice | P[8] | | P | Y | Y | Y | Y | | | | | | | | N | P | N |
| 10 | Deformed ice | | | P | N | P[9] | P[9] | Y[9] | | | | | | | | N | N | N |
| 11 | Encapsulated layer | P[8] | | P | Y | P[10] | P[10] | P[10] | | | | | | | | N | P | N |
| 12 | Dispersed vertical migration | | | N | P | P | N | N | | | | | | | | N | P | N |

Expected Performance

| | |
|---|---|
| Yes (likely) | Y |
| Potential (may be possible) | P |
| No (not likely) | N |
| Not applicable | |

Notes

1. Operations dependent on satisfying all personnel safety requirements.
2. Degraded by dark/cloud cover/fog/rain/snow.
3. Conditional upon having cold relatively low conductivity ice.
4. Dependent upon properties of the oil (primarily density). Heavy oils will reside at depth.
5. Aerostats support HD video, infrared camera, and AIS. Aerostat operations dependent upon acceptable wind speed conditions.
6. Degraded by certain wind/sea state combinations (e.g. either too calm or too rough).
7. Not supported by the commercial UAV aircraft currently available.
8. Possible with artificial illumination below ice.
9. Oil targets may be hidden by pressure ridge keels/blocks in deformed ice.
10. As long as the oil is trapped in the lower ice section (e.g. bottom 8-10 cm). For optical sensors, in a fairly thin ice sheet (~<60 cm) allowing sufficient daylight to penetrate (providing a contrast).

Table 6-2 Remote Sensing Platform and Sensor Key

| Platform/Sensor | Description |
|---|---|
| Aerostat | Moored surveillance balloon (requires vessel or small boat platform) |
| AUV | Autonomous underwater vehicle |
| Dogs | Dogs trained for olfactory detection of hydrocarbon fumes |
| FLIR | Forward-looking infrared sensor |
| GPR | Ground penetrating radar (airborne derivative under development known as Frequency Modulated Continuous Wave radar) |
| LFS | Laser fluorosensor (can be airborne or subsea) |
| LIDAR | Light detecting and ranging system, including spectral fluoroscence/reflectance LIDAR systems |
| Marine Radar | High speed shipborne radar |
| OPT | High definition cameras and underwater, high dynamic range cameras |
| ROV | Remotely operated underwater vehicle with umbilical cable |
| SAR | Synthetic aperture radar (historically used by aircraft, now limited to satellite platforms) |
| Sonar | Acoustic sensors including narrowband single-beam sonar, multi-beam imaging sonar, broadband sonar, and side-scan sonar |
| SLAR | Side-looking airborne radar (commonly fitted to surveillance aircraft) |
| TIR | Thermal infrared sensor (short, medium and long wave sensors). Presently fitted to aircraft or vessels as FLIR (medium to long wave) |
| UV | Airborne ultraviolet reflectance scanner (traditionally combined with IR in one system as UV/IR) |
| UAV | Unmanned aerial vehicle (fixed-wing or rotary-wing) |
| VIS | Visual observation |

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