THE DETECTION OF OIL IN AND WITH ICE USING SAR

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Introduction

The release of oil into the oceans represents an environmental hazard to wildlife, namely fish, birds and marine mammals, and can adversely affect humans that depend on the sea. Therefore considerable resources have been spent in cleaning up spills due to accident or design. To reduce the environmental impact it is important that spills be detected early so that remediation can be started. In temperate and tropical latitudes, volatile components of a spill evaporate rapidly and even the heavier components tend to disappear within months or a few years through breakup mechanisms involving solar UV, wind and wave actions, solubility, accretion to particulate matter with subsequent descent to the ocean floor and bacteriological processes. However, in arctic regions the natural processes are slowed down by the low temperature so that oil may persist for much longer and, over time, can have a much greater impact.

Efficient remediation requires knowledge of the spill. If the offender is a ship discharging oily bilge water, the name of the ship must be determined unambiguously and its association with the spill established unequivocally; otherwise litigation will not succeed. Therefore timely detection is needed. Also an estimate of the size and nature of the spill is desirable to determine the extent of the cleanup resources to be allocated.

The detection of oil in the open ocean is becoming operational. Appropriate sensors are available that can be located on satellites and aircraft to provide wide area and local surveillance respectively. There have been several review articles dealing with the various aspects of sensors and operations, such as Fingas [1], Fingas and Brown [2], Dickins [3] and Mahr and Chase [4]. Typically satellite borne Synthetic Aperture Radar (SAR) and/or Electro Optics (EO) sensors [5] are used for wide area surveillance and Maritime Patrol Aircraft (MPA) are used for verifying spills and, where necessary, for identifying ships and oil platforms. Aircraft may carry laser sensors to detect fluorescence from oil [6]. However, there are significant sources of false alarms and an operational system typically requires an operator trained in discrimination.

Active sensors, such as radar and fluorosensors [4], [7] can operate in darkness. This is particularly important in the high arctic during the winter when it may be dark for the entire day. On the other hand, because an individual sensor may not be reliable and give rise to false alarms, a mixture of sensors is desirable and this includes arctic surveillance. During arctic winter months, a passive sensor may not be useful.

A list of potential sensors for oil on open water and ice is provided in Table 1. The ground resolution of the sensors is important. In some cases the resolution cell is kilometers in size and small spills simply cannot be resolved. For open water there have been many studies of spills and some of these that utilize SAR are described in [8], [9], [10] and [11].

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TABLE 1 **Sensors**	
Synthetic Aperture Radar	Active sensor using microwave radiation to image surface at high resolution. Satellite examples: RADARSAT and Envisat [12], [13], ALOS, TerraSARX [14].
Electro Optic Radiometer/Spectrometer/ Hyperspectral device	Passive sensor receiving radiation over a wide spectral range from IR to UV with low to moderate ground resolution. Satellite examples: MODIS [15], [16], [17], Landsat, AVHRR [5], [18].
Fluorometer	Active sensor. Excites fluorescence in oil using a laser or Xenon flash tube. Aircraft borne or local [19].
Scatterometer	An active radar technique designed to measure the radar scattering cross section of the ground [20]. The resolution is too low for satellite detection of spills.
Impulse Radar	Active radar sensor but can be operated locally or on low flying aircraft.
Acoustic	Active sensor but local operation using acoustic imaging.

The detection of oil on the open ocean by radar relies on the effect of even very thin layers in suppressing the capillary waves on the sea surface responsible for radar backscatter. One consequence is that, if the wind speed is less than about 2 m/s with or without surface oil, the backscatter tends to be so small that the signals disappear into the thermal noise. When the wind speed is greater than about 12 m/s, the effect of the oil is overcome by excessive wave actions and again the oil is difficult to detect.

Fluorescence can be excited in oil either on the sea surface or on ice so that again detection using a fluorometer relies on a physical distinction in the properties of oil and sea water or ice [7]. However, it is not effective when the oil is under ice or in pockets within the ice because the exciting radiation must penetrate the ice to reach the oil and the fluorescence must propagate back to the surface.

In general the choice of an active sensor is dictated by

1. Misinterpretation of look-alikes including the effect of noise, which can be expressed as a probability of a false alarm.
2. The likelihood that the exciting signals and the returned signals will be attenuated by the intervening medium or missed in some other manner. In principle this can be expressed in terms of a probability of detection.

When oil is spilled in arctic ice, some is likely to end up floating on the water surface, some may be spilled on the ice surface and some may enter the body of the ice through capillary action. Over time and with partial melting, oil may fill pockets within the ice and lie on its surface in pools. The transport processes of oil under and in ice have been discussed in [21] and [22].

A survey of ice conditions in the Arctic has been described by Pag [23]. First year ice tends to grow quickly to a thickness of between 1.2 m and 1.5 m and then growth slows because of the insulating properties of the ice layer. The average thickness is about 1.7 m; the modal thickness is slightly less. First year ice is usually less than 2 m thick in contrast with multi-year ice, which is usually thicker than 2.5 m. The ice is often covered in snow with an average depth of about 0.2 m.

SAR Sensor

Both airborne and space-borne SARs have been used in surveillance applications. The well-known radar equation can be applied to SAR design and can provide a reliable estimate of backscatter. Since ice is routinely monitored by various agencies, the radar backscatter characteristics are well-known [2]. Using single polarimetric SAR, such as RADARSAT-1, and especially dual polarimetric SAR, such as RADARSAT-2, ice types can be distinguished reliably. This task does not require very high resolution and resolutions of 100 m are adequate. Typically this is achieved with beam modes that involve multi-look processing, which averages out the speckle noise that is typical of coherent sensors. However, the problem with detecting oil on ice is the rather small effect produced by a layer of oil on the radar backscatter compared with the variations associated with natural fluctuations in the ice surface and from volume scattering. In the case of oil within the ice or beneath it, again the backscatter from oil will compete with that from brine pockets and natural variations in salinity but importantly the incident and scattered radar signals may be highly attenuated. Thus the backscattered signals from oil may:

1. Be overcome by speckle in the image or thermal noise in the radar receiver,
2. Be swamped by natural fluctuations,
3. Be severely attenuated by electromagnetic wave dissipation within the ice body.

As can be seen from Fig. 1, the attenuation depends strongly on salinity. At a C-band radar frequency (e.g. 5.5 GHz), which is typical of many SARs, the attenuation produced by first year ice is greater than 40dB/m and that by multi-year ice is typically 10dB/m. The backscattered signal from the bottom surface of the ice depends on the change in the permittivities at the interfaces and the bottom roughness. Table 1 provides nominal permittivity values [24] based on well known data including laboratory measurements of crude oil [25].

TABLE 1
Complex Permittivities

Sea Water	(55.0, -55.0)
Ice	(3.0, -0.4)
Oil	(2.0, 0.0)

In an early study it was concluded that the detection of oil on or in sea ice using only SAR image magnitude data was not likely to be successful [26].

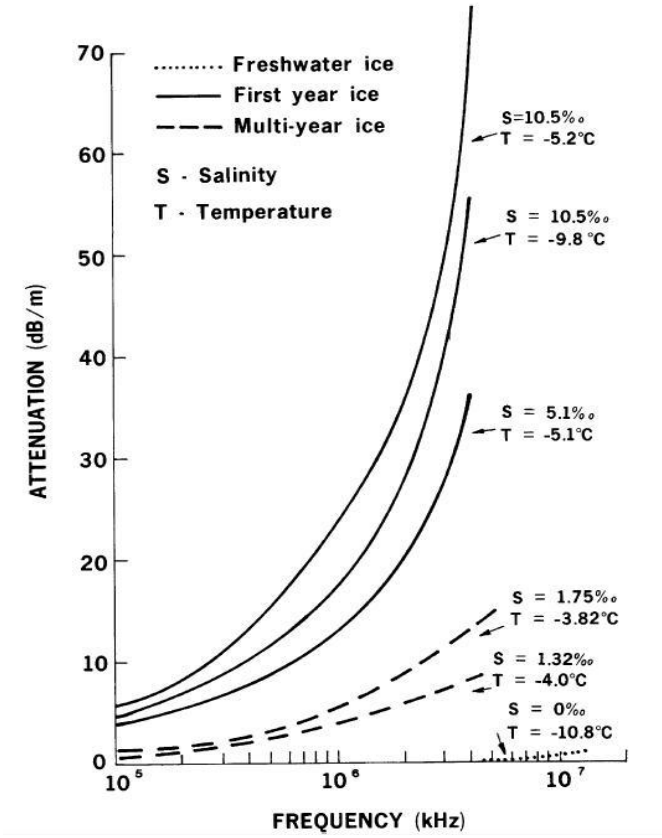

Fig. 1. One way attenuation in various ice types as a function of frequency (from [2]).

SAR Scattering Estimates

Currently SARs are operating at L-band (PalSAR), C-band (RADARSAT-1 and 2, Envisat) and X-band (TerraSARX). Fig. 1 shows that X-band is unlikely to be useful for detecting oil in or under ice because of the very high attenuation in both first year and multi-year ice. For a semi-quantitative analysis of both PalSAR and RADARSAT, the thermal noise expressed by the Noise Equivalent Sigma Zero (NESZ) can be set at about -28dB (e.g. http://www.radarsat2.info/product/RS-2_Product_Description.pdf) for wide swath beams and about -40 dB for the standard RADARSAT-2 quad-pol beam. Backscatter coefficients have been provided for C-band in [20] and [27] and these are mutually consistent. Fig. 2 shows how these vary over incidence angle and, in particular those most often used in SAR, namely in the range 20 to 50 degrees.

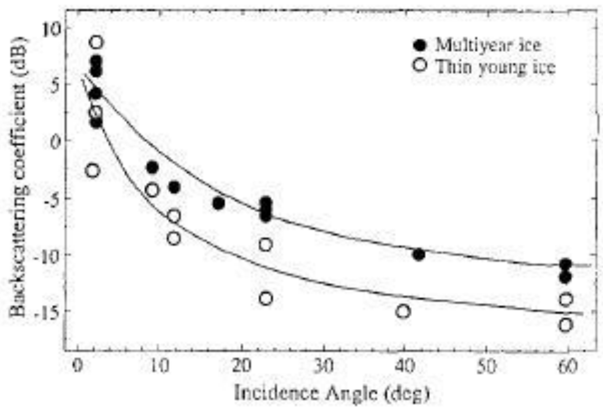

Fig. 2. Backscatter coefficient of sea ice at C-band (from [20]).

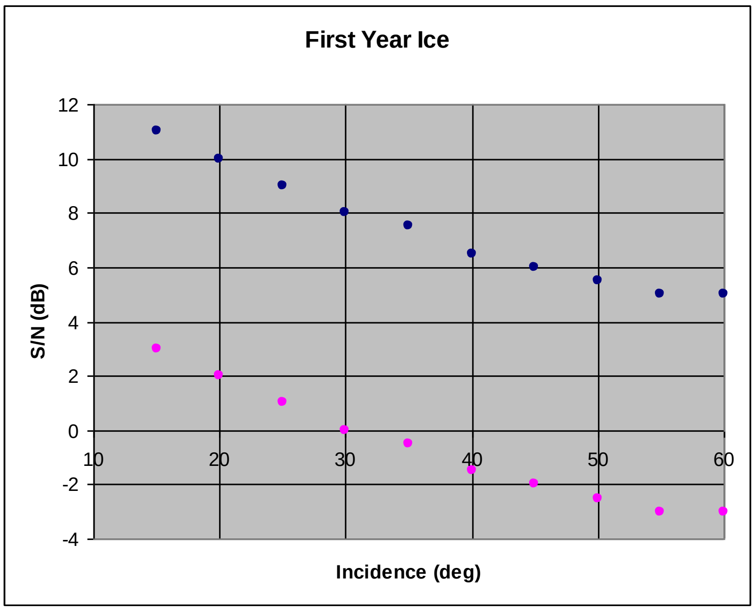

Fig. 3. Optimistic signal to noise ratio for first year ice-water interface.
Ice thickness 10 cm (•) and 20 cm (•).

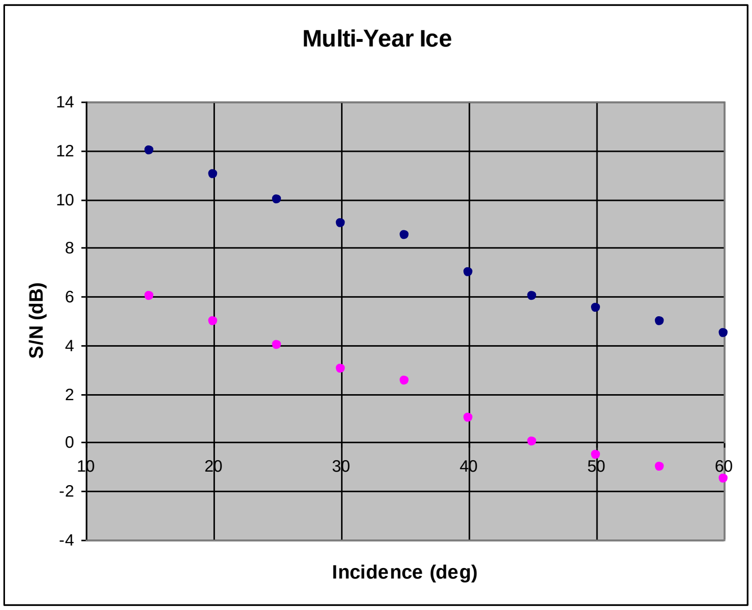

Fig. 4. Optimistic signal to noise ratio for multiyear ice-water interface.
Ice thickness 1.0 m (●) and 1.5 m (●).

Firstly we examine the effect of the thermal noise as expressed by the NESZ set equal to -28 dB. At an incidence angle of 30 degrees, the backscatter coefficient (sigma0) for first year ice is about -13 dB and for multiyear ice it is about -8 dB. Therefore the signal to noise for single resolution cells is about 15 dB and 20 dB respectively. The attenuation at C-band for first year ice is greater than 40 dB/m and for multiyear ice at least 6 dB/m each way. Therefore for ice of thickness 20 cm, the signal to noise ratios for 100 percent reflection from the bottom of the ice at the interface of water or oil are -1 dB and 17.6 dB respectively. Therefore we can conclude that thermal noise does not limit the detection of oil at the top surface of ice but attenuation through the ice does limit the detection of oil at the interface between oil and water when the ice thickness is appreciable, especially for first year ice. The C-band S/N ratios are estimated in Figs. 3 and 4.

We see that signals can penetrate to the bottom of multi-year ice that is less than about 2 m thick. Clearly a lower radar frequency would be advantageous to reduce attenuation. However the S/N for the standard quad-polarization beam is much better.

Secondly we examine the effect of a change in refractive index at the interface between ice and oil and ice and water to estimate the reflection coefficients. These are the Fresnel coefficients and, since from the above we expect to operate the SAR at low incidence angles to minimize attenuation, the coefficients for normal incidence will be used. The values will assist us to determine the sensitivity of SAR signals to oil. The coefficients are reasonably insensitive to the microwave radar frequency. This parallels the discussions in [26] and [28], which were prompted by a suggestion by Jackins and Gaumaud [29] that detection could be based on resonances within layers of oil, ice and water. This was shown to be false [28] because of dissipation.

At low incidence angles, the reflection and transmission coefficients, *R* and *T*, are independent of polarization:

$$R = \left| \frac{n_1 - n_2}{n_1 + n_2} \right|^2 , \quad T = 1 - R \tag{1}$$

where $n_{1,2}$ are the refractive indices of the media at microwave frequencies, which are each equal to the square root of the respective complex permittivity. Table 2 provides the reflection and transmission coefficients using data from Table 1; these apply to the transmitted and reflected power. The reversal of the two media at the interface has no effect so that the coefficients for Ice-Oil are identical to those for Oil-Ice.

TABLE 2
FRESNEL COEFFICIENTS

Interface	**Reflection, *R***	**Transmission *T***
Air-Ice	0.07	0.93
Air-Oil	0.03	0.97
Air-Water	0.66	0.34
Ice-Water	0.47	0.53
Ice-Oil	0.01	0.99
Oil-Water	0.55	0.45

It is noteworthy that the coefficients are not much modified by the effect of the dissipation within the materials and that the reflection coefficient for an ice-oil interface is quite small, which is in contrast to the other interfaces, which are relatively reflective. Thus, if incident normally, the radar signal will easily penetrate oil at an ice-oil interface or ice at an oil-ice interface. This obviously represents a hurdle for a detection system. The radar wavelength is likely to be comparable or even larger than the typical thickness of an oil or ice layer and this is another factor that the estimations must include. However, it is likely only to make detection more difficult; as noted, Moorcroft and Tunaley have shown that electromagnetic resonances are likely to be suppressed by the conductivity of saline ice and water [28].

Another important effect is that of speckle. This is a type of multiplicative noise characteristic of coherent radar. Speckle affects the signal to noise ratio of each resolution cell according to the number of looks used in the processing. The number of looks is the number of sub-aperture images that are combined in the final image product. For RADARSAT-2, there are 8 looks in a ScanSAR wide image product. On the assumption that all looks are independent, which is not entirely valid, the maximum signal to noise ratio for each resolution cell in such an image is limited to about 4 dB. Since this will often be significantly greater than the signal to noise ratios in Figs. 3 and 4, speckle is not expected to be a limiting factor for ScanSAR wide images but it may be a problem for high resolution quad-pol images; in such cases integration over a number of resolution cells may be required to increase the S/N to an acceptable level.

Oil Detection Using SAR

To detect oil in ice, it is necessary to identify some feature of oil within a SAR image that is more or less unique. It is unlikely that magnitude images would be suitable because the signal tends to penetrate oil easily at oil-ice interfaces that might occur when oil

1. Pools at the surface,
2. Is occluded within the ice,
3. Lies between the bottom of the ice and the sea surface.

The only realistic possibilities for success involve polarimetric imagery, complex imagery or both.

Complex pixel data provides information about the structure of the scatterers because the phase is directly related to scatterer position. The phase is also determined by the relative permittivities of the scatterers. Alone, complex data is probably not very useful for oil detection because the structures of normal and oily ice can be quite similar. Polarimetry provides information about the type of scatterer. This is most effective in full quad-polarimetric data in contrast to dual-polarized data. For example, it is possible to distinguish dipole, corner and plate reflectors and various discrimination or decomposition techniques are available.

Full polarimetric SAR imagery has potential for detecting oil because the reflections or scattering from ice-oil and ice-brine interfaces are different in the complex domain. The real part of the refractive index of oil is less than that of ice and the refractive index of brine is greater than that of ice. This implies that the phase shifts on reflection will be small for ice-oil and greater than 90° for ice-brine.

Unfortunately changes just in phase are likely to be confused with changes in scatterer position. However, with polarimetric data we measure the differences between signals with differing polarizations though the differences depend on incidence angle. This eliminates the scatterer position and provides a potential for discrimination.

However, as seen in Table 2, the oil-ice reflection coefficient is likely to be quite small so that a loss of up to 20 dB in reflectivity will be incurred relative to ice-brine. It may be possible to compensate for this loss by integration at the expense of resolution.

Conclusions

As shown in previous studies, it is unlikely that SAR magnitude images would be useful in detecting oil lying in or on ice. This is because, in terms of magnitudes, there is insufficient difference between oil-ice and oil-brine radar signatures. Another complication occurs because of heavy attenuation in first year ice. C-band radar can only penetrate first year ice to a depth of about 0.2 m, while the average depth is about 1.7 m. The penetration depth for multi-year ice is about 2 m compared with typical depths of more than 2.5 m. Improvement can be obtained by using a SAR with a lower frequency or by using integration over many resolution cells.

Fully polarimetric SAR has a potential for detecting oil in or on ice because of the ordering of the real parts of the refractive indices, namely in the sequence oil, ice and brine. A serious problem will be the low signal to noise ratio associated with the low reflectivity at an oil-ice interface. It is unlikely that dual polarized SAR would be a useful candidate because it lacks much of the information required for effective discrimination in a poor S/N environment.

An initial study should begin with a determination of the structure of oily ice. It is likely that this would lead to a model that is based on a random distribution of prolate and possibly oblate spheroids with certain distributions of sizes, axial ratios and orientation. The polarimetric scattering at various microwave frequencies should then be estimated and roughly analyzed to determine whether available decomposition methods are appropriate for the detection of oil spills. It may be necessary to develop new decomposition approaches tailored to spills.

If the initial study is promising, the viability of polarimetric SAR can be studied in more detail by full simulations of typical oily ice scenarios. Whether a space-borne polarimetric SAR operating at C, L or P band can form the basis wide area surveillance system for spills in arctic ice can only be established in a definitive way by observation of existing spills.

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