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Discrimination of oil spills from newly formed sea ice by synthetic aperture radar

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ABSTRACT

In this paper we examine the potential of multi-polarization SAR systems to detect and discriminate oil pollution from uncontaminated recently formed thin sea ice in the Arctic Ocean, where both oil and thin sea ice have similar low backscatter returns on SAR imagery. In this study, we present a theoretical model of the relative permittivity of oil-in-sea-ice mixtures and apply it to determine the effect of dielectric properties on the co-polarized backscatter ratio for sea ice, ocean, and oil. To support the theoretical discussion, we investigate available multi-polarization and multi-frequency SAR measurements. We compare SAR data collected over oil spills in seawater in the Gulf of Mexico and the North Sea with available similar data covering sea ice in the Arctic region. The results suggest that multi-polarization SAR systems will be useful to detect Arctic oil spills should a spill occur in new and young sea ice conditions, particularly in the marginal ice zones adjacent to the main polar ice pack.

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1. Introduction

The reduction in extent and thickness of the Arctic sea ice makes new shipping routes and natural resources more easily accessible at high latitudes. Increased activity is expected in the Arctic regions from the international maritime industry and the oil and gas sector in the coming years (Smith & Stephenson, 2013; US Arctic Research Commission and the US Army Corps of Engineers, 2012). An improved understanding of oil spill remote sensing in Arctic conditions is needed to develop the technological capability to address the increased risk.

To identify oil spilled in the Arctic environment, and specifically in the presence of ice, is recognized as a significant issue (OGP/IPIECA, 2012). The range of feasible Arctic oil spill scenarios is much larger than those normally encountered in open seawater, encompassing oil on top of or mixed with cold seawater, and also mixed with sea ice (Fingas & Hollebone, 2003), and oil on top, within, or under various thicker ice types (Bradford, Dickins, & Brandvik, 2010). Also, currently very little is known about weathering and behavior of oil spills in Arctic sea ice conditions (Brandvik & Faksness, 2009; Fingas & Hollebone, 2013; NRC, 2003), which adds to the challenge of detecting and characterizing oil slicks in ice-infested waters using remote sensing techniques. In addition, the existing literature on remote sensing techniques for oil spill monitoring in ice-infested waters and pack ice is sparse (Bradford et al., 2010; Dickins, 2010; Praks, Eskelinen, Pulliainen, Pyhälahti, & Hallikainen, 2004). According to Dickins (2010) (see also C-CORE (2013)), the use of satellite SARs to detect oil in ice is likely to be limited to open pack conditions (<4/10) and where the oiled surface produces a unique signature compared to the uncontaminated surroundings. This is the general condition addressed in this study.

Here we attempt to address this lack by modeling the SAR response to one specific Arctic spill scenario, focusing on oil mixed in or next to thin sea ice features in the marginal ice zone (MIZ). Examples of relevant ice types are the thinnest ice categories including new ice (frazil, grease and slush), nilas (<5–10 cm thick), and young ice (10–30 cm thick) (WMO, 2007). These types of ice predominately appear dark in SAR imagery, and thus have a similar backscatter to marine slicks, including from both mineral (manmade spills and natural seeps) and biogenic sources. Low wind regions also have low backscatter returns, resulting in the potential of numerous false positives within the Arctic environment. In this study, we will refer to the ice thickness categories listed above inclusively as new/young ice.

For our study, we focus on the difference in the *co-polarization ratio*, defined as the ratio of the radar cross sections from polarization-preserving scattering (VV/HH, where the first (second) letter indicates the polarization of the incident (scattered) radiation, either horizontal or vertical), for unslicked and slicked surfaces. For Bragg scattering, which is the common baseline model for ocean wave scattering (Valenzuela, 1978), the co-polarization ratio is a function of the complex dielectric constant (permittivity) of the medium and the incidence angle. The co-polarization ratio of both biogenic slicks and mineral slicks is observed to be lower than open seawater (Brekke, Holt, Jones, & Skrunes, 2013). We also expect new/young sea ice to have dielectric

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properties closer to open seawater than thicker sea ice. It therefore seems appropriate to investigate the potential of discriminating oil-in-sea-ice mixtures from new/young ice using multi-polarization SAR. However, multi-polarization SAR data from real oil spills in the Arctic are not available, and there is a lack of field data (Dickins, 2011) and laboratory experiments pertinent to Arctic oil spills.

Hence, as a first step, we focus on a theoretical investigation of the potential of multi-polarization and multi-frequency SAR data to discriminate new/young ice from oil spills in the MIZ. First, we present a theoretical analysis of the relative permittivity of oil-in-sea-ice mixtures and the impact of dielectric properties on the co-polarization ratio for various relevant media. Second, to establish confidence in the theory, we compare SAR imagery of detected oil spills in the Gulf of Mexico and in the North Sea with available collections of sea ice data from the Arctic region.

This paper is a thorough exposition of the principal ideas outlined in Brekke et al. (2013). The manuscript is organized as follows. Section 2 reviews SAR technologies applicable to oil pollution monitoring. Section 3 introduces oil weathering processes and their relevance in Arctic conditions. Dielectric properties of relevant media, mixture modeling, and the concept of penetration depth are discussed in Section 4. The co-polarization ratio is introduced in Section 5, and discussed in relation to various relevant surface media and oil/ice emulsions (mixtures). An analysis of acquired SAR measurements is presented in Section 6. Section 7 comments on the choice of scattering model, followed by conclusions and prospects for further study in Section 8.

2. SAR systems for oil slick observations in the Arctic

An overview of current SAR system categories, including sensor examples, is given in Table 1. The simplest type of SAR systems transmits on one polarization and receives on the same (like) polarization. Current operational oil slick monitoring services are mainly based on mono-channel co-polarization (VV or HH) SAR products. With only single polarization radar backscatter data, the information that one can extract about the slicks is limited to the extent and shape of the spill; damping and backscatter level properties of the spill relative to surrounding water; and contextual information and texture (Brekke & Solberg, 2005).

Table 1
Categories of SAR systems and examples of current sensors that can be used for oil slick surveillance in the Arctic. A more detailed discussion on polarization diversity can be found in Raney (2011).

Radar type	Product	Sensor examples (year)
Quad-polarization	4 × 4 (or 3 × 3 at reciprocity[a]) complex covariance matrix	Radarsat-2 (2007-) ALOS-2 (~2014)
Compact polarization	2 × 2 complex covariance matrix	Radarsat constellation Mission (~2016) ALOS-2 (~2014)
Dual-polarization (e.g. VV, HH and CPD[b])	2 × 2 complex covariance matrix	TerraSAR-X (2007-)
Dual-polarization (e.g. VV and HH magnitude)	Two real images[c]	ENVISAT ASAR (2002–2012) COSMO-SkyMed (2007-)
Mono-polarization (magnitude)	One real image	Radarsat-1 (1995–2013)

[a] For the convenience of the reader, we explicitly show this covariance matrix structure as an example. By assuming reciprocity and vectorizing Eq. (1) on Lexicographic form, we get $k_L = \left[S_{hh}, \sqrt{2}S_{hv}, S_{vv}\right]$. From this, the 3 × 3 covariance matrix is computed as $\mathbf{C}_{3\times3} = \langle k_L \cdot k_L^{*T}\rangle = \begin{bmatrix} \langle S_{hh}\cdot S_{hh}^{*}\rangle & \sqrt{2}\langle S_{hh}\cdot S_{hv}^{*}\rangle & \langle S_{hh}\cdot S_{vv}^{*}\rangle \\ \sqrt{2}\langle S_{hv}\cdot S_{hh}^{*}\rangle & 2\langle S_{hv}\cdot S_{hv}^{*}\rangle & \sqrt{2}\langle S_{hv}\cdot S_{vv}^{*}\rangle \\ \langle S_{vv}\cdot S_{hh}^{*}\rangle & \sqrt{2}\langle S_{vv}\cdot S_{hv}^{*}\rangle & \langle S_{vv}\cdot S_{vv}^{*}\rangle \end{bmatrix}$, where ^{*T} represents complex conjugate and transpose and $\langle\cdot\rangle$ represents averaging over a pixel neighborhood (Massonnet & Souyris, 2008).

[b] CPD: co-polarization phase difference.

[c] Note: The digital values of the individual images will be complex if the data is delivered in single look complex (SLC) format, but, it will still be an incoherent dual-polarization product.

Quad-polarimetric SAR systems extend our capabilities to characterize marine slicks because they provide a quantitative measure of the relative phase and amplitudes of the different polarization backscattered radiation. The polarimetric scattering matrix (Sinclair matrix), which contains all the complex scattering coefficients that describe the target, is given as:

$$S_{2\times2} = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} = \begin{bmatrix} |S_{HH}|e^{i\phi_{HH}} & |S_{HV}|e^{i\phi_{HV}} \\ |S_{VH}|e^{i\phi_{VH}} & |S_{VV}|e^{i\phi_{VV}} \end{bmatrix} \tag{1}$$

where $|S_{TR}|$ represents the magnitude of the scattering element, and ϕ_{TR} is the relative phase of the transmitted (T) and received (R) polarization, respectively. **S** is acquired for every resolution cell, and the scattering coefficients are measured at different linear combinations of transmitted and received polarization (VV, HH, VH and HV). Polarimetric SAR systems allow us to link scattering processes and variations in the backscattered signal to the physical characteristics of the medium measured.

The National Aeronautics and Space Administration (NASA) Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) is a coherent quad-polarimetric airborne SAR instrument. An analysis of UAVSAR data acquired over the Deepwater Horizon spill in 2010 has shown sensitivity of the L-band instrument to the oil slicks physical characteristics, specifically to the volume fraction of the water-in-oil emulsion (Jones, Minchew, Holt, & Hensley, 2011; Leifer et al., 2012; Minchew, Jones, & Holt, 2012). With the launch of Advanced Land Observing Satellite (ALOS) in 2006 and TerraSAR-X and Radarsat-2 in 2007, coherent dual- and quad-polarimetric SAR measurements also became available from space. Recent advances in the field show the potential of polarimetric SAR measurements for discrimination between different types of oil or surfactants and in deriving valuable information about the oil slick's physical properties (Migliaccio, Gambardella, & Tranfaglia, 2007; Migliaccio, Nunziata, & Gambardella, 2009; Minchew et al., 2012; Nunziata, Gambardella, & Migliaccio, 2008; Shirvany, Chabert, & Tourneret, 2012; Skrunes, Brekke, & Eltoft, 2012a,b,c,d, 2014).

To take full advantage of the additional information discussed above, true polarimetric SAR modes, with the relative phase between the different polarization backscattered radiation, are required. Hence, the alternating polarization (AP) mode of ENVISAT and the current Ping-Pong (PP) mode of Cosmo-SkyMed, which are multi-polarization but not polarimetric, i.e., do not contain relative phase information, are not ideal for oil slick characterization. These modes have a time delay between the transmissions of the horizontal and vertical polarized signals that is sufficiently long to cause incoherent imaging over sea surfaces (Nunziata, Montuori, & Migliaccio, 2011). According to Raney (2011), these data products can simply be described as *images*, as they do not include the relative phase between the two received channels. Techniques applicable to these data types are primarily, and in general, restricted to ratios or differences of their respective images (Raney, 2011; Skrunes, Brekke, Eltoft, & Miegebielle, 2013).

In compact polarimetry, one polarization is transmitted and two orthogonal polarizations are received, together with their relative phase. With this technique, one realizes some of the benefits of quad-polarimetric SAR systems, but not all. For satellite SARs that are data rate limited and trade swath width for additional transmitted pulses of different polarization, an advantage of compact polarimetric over quad-polarimetric systems is the extended coverage. However, with compact polarimetry one only gets access to a 2 × 2 covariance matrix, whereas quad-polarimetric systems measure the 4 × 4 covariance matrix (Raney, 2011). Compact polarimetry for oil slick detection has been investigated by simulating compact polarization from Radarsat-2

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