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X-, C-, and L-band SAR signatures of newly formed sea ice in Arctic leads during winter and spring

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ABSTRACT

We examine an extensive synthetic aperture radar (SAR) data set from the Arctic Ocean spanning a time period from January to June 2015, with the aim of identifying multi-polarization parameters that can be used to accurately separate newly formed sea ice from the surroundings. Newly formed sea ice areas both provide favourable routing for ship traffic, and are key to Arctic climate science because they enable heat exchange between the ocean and the atmosphere. Our data set encompasses three different frequencies, X-, C- and L-band, at a range of incidence angles, and were acquired under different environmental conditions. Our results suggest that by combining the scattering entropy and the co-polarization ratio we can successfully separate the newly formed sea ice from open water and thicker sea ice within all three frequencies throughout the winter and spring season. We observe a high correlation between scattering entropy values calculated using quad-polarization C- and L-band data and scattering entropy values calculated using the same scenes reduced to the co-polarization channels (HH and VV). We therefore conclude that dual-polarization (HH and VV) X-band scenes can be directly used to complement quad-polarimetric C- and L-band scenes for studies of newly formed sea ice. To confine the quad-polarimetric data sets to their co-polarization channels one can ensure a higher signal-to-noise ratio. Incidence angles below 35° are needed to keep the signal-to-noise ratios sufficiently high for the scattering entropy and co-polarization ratio. Due to its lack of incidence angle dependency, the polarization difference can provide additional support in newly formed sea ice studies. The regular coverage of the Arctic Ocean with C-band SAR means that such scenes should be included in any automatic monitoring, however, X- and L-band SAR can, based on their difference in penetration depth, provide additional information about newly formed sea ice types and surface structure.

1. Introduction

Maritime activities in the Arctic region mean routing and operations within ice infested areas. Areas with newly formed sea ice or open water, such as leads, are important for a more cost-effective passage through the ice. They are also important for energy exchange between the ocean and the atmosphere and can permit transmission of enough light into the ocean to initiate and sustain algae blooms in regions where otherwise the consolidated ice cover wouldn't allow (Assmy et al., 2017). Synthetic aperture radar (SAR) satellite scenes offer spatial resolutions down to the meter scale and are independent of light and clouds. Due to this all-season capability SAR is widely used for sea ice monitoring and C-band SAR has traditionally been used to monitor sea ice extent, concentration, drift speed and ice type, e.g., Maillard et al. (2005), Thomas et al. (2011), and Walker et al. (2006). Work by, e.g., Casey et al. (2016), Dierking and Busche (2006), Eriksson et al. (2010), and Lehtiranta et al. (2015) has identified that other SAR frequencies can contribute useful information for sea ice classification where Casey et al. (2016) investigated how L-band SAR can contribute to sea ice type products during the melt season. Using X-, C- and L-band SAR satellite data in combination allows us to utilise the multiple missions currently available (Johansson et al., 2017).

In addition to SAR sensors, passive microwave sensors have been used to estimate newly formed sea ice thickness as well as to study the sea ice freeze-up. Notably work by, e.g., Kaleschke et al. (2012) focused on the initial growth in the freeze-up period, Markus et al. (2009) used a time series to assess changes in the freeze-up, and work by Martin et al. (2004) focused in thin ice thickness estimates.

With respect to SAR studies, e.g., Zakhvatkina et al. (2017), have shown that dual or quad polarimetric SAR is needed to accurately

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identify and separate the newly formed sea ice from the surrounding thicker sea ice. Here we define *newly formed sea ice* as the thinnest ice categories including new ice (frazil, grease and slush), nilas (0.05–0.10 m thick), and young ice (0.10–0.30 m thick) (WMO, 1970). Identifying a set of SAR parameters that can be used for identification of newly formed sea ice and separating it from other ice types under varying temperature and incidence angle conditions is the scope of this work. The availability of a temporally extensive multi-frequency SAR data set with acquisitions in X-, C- and L-band, respectively, allows a comprehensive study comparing the frequency dependent radar response to sea ice under varying temperature and incidence angle conditions. The parameters and their variability with temperature and incidence angle can then be used as additional information for manual sea ice chart products as produced by ice services around the world, and as input into automatic sea ice type analysis.

Fully polarimetric satellite scenes typically have a small areal coverage, though enables high resolution parameter retrieval. To enable both high spatial coverage and increased amount of polarimetric information, the compact polarimetry (CP) SAR mode was introduced (Raney, 2007). Works by, e.g., Dabboor and Geldsetzer (2014) and Geldsetzer et al. (2015), have demonstrated its usability for polarimetric sea ice observations where the latter study also focused on newer sea ice types. Some of the compact polarimetry parameters investigated in those studies have corresponding fully polarimetric parameters used in this study, e.g., the Stokes vector second component (from CP) is similar to the polarization difference and the right co-polarized ratio (from CP) is similar to the co-polarization ratio assuming reflection symmetry and reciprocity. The right co-polarized ratio is defined as the ration between right circular on transmit, horizontal on receive and right circular on transmit, vertical on receive, RH/RV. Moreover, the degree of polarization (from CP) is similar to the scattering entropy (Cloude et al., 2012). In Geldsetzer et al. (2015), separation between newly formed sea ice and multi-year ice was possibly using, e.g., the degree of polarization. Results by Espeseth et al. (2017) comparing RISAT-1 compact polarimetry data and Radarsat-2 full polarimetry data measurements have shown that the compact polarimetry and full polarimetry can be comparable. Recent and upcoming compact polarimetry SAR missions includes C-band missions, such as RISAT-1 (ended) and RADARSAT Constellationmission (upcoming), and L-band missions, such as ALOS-2 (ongoing) and ALOS-4 (upcoming). These missions will enable multi-frequency sea ice studies using compact polarimetry. This study, however, is confined to conventional coherent linear on transmit and linear on receive SAR systems.

The manuscript is organised as follows. Section 2 gives a review of previous related studies. Section 3 describes the experimental setup and the data collection. Satellite data processing and extracted polarimetric information is introduced in Section 4. A multi-sensor analysis is presented in Section 5 and in Section 6 implications for operational monitoring of sea ice is discussed, followed by conclusions in Section 7.

2. Background and previous studies

Dual-polarization SAR data has, when available, been preferred to single polarization data due to easier separation between different sea ice types (Dierking, 2010; Sandven et al., 2008). Furthermore, dual-polarization data can be used to differentiate between open water and sea ice, e.g., Scheuchl et al. (2004), Arkett et al. (2006), and Geldsetzer and Yackel (2009), and are used by operational services around the world for this purpose. Dual-polarization has primarily consisted of the following combination; HH and HV. The first letter refers to the transmitted polarization and the second the received polarization. The cross-polarization channels (HV and VH) have been identified as an important asset for improved sea ice classification (Dierking, 2010). One reason for this is the reduced incidence angle dependence on the backscatter for these two channels compared to the co-polarization channels (HH and VV). The HV and VH channels have lower backscatter values and are closer to the noise floor than the HH and VV channels. Using spacebourne SAR data, Partington et al. (2010) concluded that for newly formed sea ice studies the HV-channel was only useful for incidence angles below 30° due to the signal's proximity the noise floor. Using airborne L-band SAR, Wakabayashi et al. (2004) concluded that incidence angles < 45° were needed to differentiate between different sea ice types due to the low signal-to-noise ratio (SNR) of the HV-channel.

Dual-polarization SAR satellite products with a combination of the two co-polarization channels HH and VV, have been found particularly useful for newly formed sea ice separation from surrounding ice (see Ressel and Singha, 2016 and references therein). The TerraSAR-X satellite has experimental quad-polarization capabilities (Ressel and Singha, 2016; Johansson et al., 2017) but also offers the HH/VV combination as an option for the standard dual-polarization acquisitions. From this follows that the backscatter values from the respective co-polarization channels can be used for identification of different sea ice classes, and such identification can then be complemented and improved by also calculating parameters such as the co-polarization ratio and the polarimetric difference. Making use of quad-polarimetric SAR, Dierking and Wesche (2014), Gill et al. (2013), Wakabayashi et al. (2004), Wakabayashi and Sakai (2010), and Wakabayashi et al. (2013), investigated the value of retrieving information about scattering mechanisms for sea ice classification. Combining the polarimetric information related to the scattering mechanisms and the variation in the radiometry of the backscatter signal of the sea ice enables us to further exploit the possibilities that quad-polarimetric SAR offers for sea ice identification and classification. Substantial work investigating polarimetric responses from SAR sensors mainly operating at C-band has been done by, e.g., Drinkwater et al. (1991), Geldsetzer and Yackel (2009), and Gill et al. (2013), though these studies have mainly focused their efforts towards first-year and multi-year sea ice.

Geophysical parameters such as the dielectric constant and the surface roughness affect the SAR signal over sea ice. In addition, is the backscatter signal affected by the imaging configuration, i.e., the incidence angle (see, e.g., Gill and Yackel, 2012; Lundhaug, 2002; Shokr, 2009; Zakhvatkina et al., 2013), the SAR frequency, the resolution, and the polarization.

2.1. Polarimetric effects on sea ice thickness and type

During initial sea ice growth the backscatter HH and VV intensity values (σ^0_{HH} and σ^0_{VV}) increase with thickness (Nghiem et al., 1997). For C- and L-band, the backscatter values increase by 6–10 dB when the thickness increases 0.03 m (Nghiem et al., 1997). These backscatter changes are also reflected in the co-polarization ratio ($\sigma^0_{VV}/\sigma^0_{HH}$), where an increased thin ice thickness was correlated with a decrease in co-polarization ratio, e.g. Brath et al. (2013), Dierking (2010), Drinkwater et al. (1991), Geldsetzer and Yackel (2009), Kern et al. (2006), Nakamura et al. (2005), Nghiem and Bertoia (2001), Onstott (1992), Wakabayashi et al. (2004), Winebrenner and Farmer (1995), and Zhang et al. (2016). Kern et al. (2006) found that for a sea ice thickness above 0.6 m the co-polarization ratio approaches 0 dB in C-band SAR. L-band SAR studies by Wakabayashi and Sakai (2010) and Wakabayashi et al. (2013) linked changes in scattering entropy to sea ice thickness when the sea ice was less than 0.6 m thick. Dierking and Wesche (2014) observed that young ice and rafted thin ice areas also have lower scattering entropy values compared to the surrounding thicker sea ice.

The change in the backscatter values in response to an increase in thickness also relates to the incidence angle used during the study. Onstott (1992) and Wakabayashi et al. (2004), among others, found that for incidence angles above 40° the decline in co-polarization ratio with increased sea ice thickness were more pronounced than for incidence angles below 40°. A higher incidence angle may therefore be beneficial for separation of newly formed sea ice from the surroundings. However, a study by Partington et al. (2010) found that newly formed