

# Can Mineral Oil Slicks Be Distinguished From Newly Formed Sea Ice Using Synthetic Aperture Radar?

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**Abstract**—In this feasibility study discriminating oil slicks and newly formed sea ice using SAR imagery is investigated, using imagery from the L-band high-resolution Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) airborne and the satellite C-band RADARSAT-2 (RS-2) systems. To determine the separability of these two varying but similar appearing low backscatter ocean surfaces, multi-polarization features are utilized from both SAR datasets. The discrimination is evaluated using the Kolmogorov-Smirnov separability test. All imagery was obtained during several sea ice campaigns in the Arctic and separate oil spill campaigns in Norway and the Gulf of Mexico, with each campaign collecting *in-situ* observations. We observe that the polarization difference (VV-HH) reliably separates the mineral oil slicks and newly formed sea ice using UAVSAR images, due to the low noise floor and subsequent high signal-to-noise ratio (SNR) radiometric performance of the airborne system. The comparably higher noise floor and related lower SNR hampers the separability in the RS-2 images. Simulated noise floors were generated by adding white Gaussian noise to the UAVSAR data, which show that discrimination between the two low backscatter phenomena using multi-polarization features is possible provided that both datasets are still well above the noise floor. The pixel resolution has a limited effect on the separability. The results of this study provide an approach to distinguish oil slicks from newly formed sea ice, which might be of special interest should an oil spill occur within the marginal ice zone.

**Index Terms**—Oil slick, newly formed sea ice, SAR, polarimetry, UAVSAR, RADARSAT-2, SNR, L-band, C-band

## I. INTRODUCTION

THE thinning of sea ice and the reduced sea ice cover in the Arctic [1] over the last decade has led to an increase in maritime traffic and petroleum-related activities, activities that have associated potential risks of oil spills in this challenging environment [2]–[5]. There is a wide spread international concern of a potential spill in the Arctic environment, where detection of oil in ice-infested waters using synthetic aperture radar (SAR) is difficult during conditions of both new ice formation and ice concentrations greater than 40%, for smaller spills [6]. An oil spill within or near newly formed sea ice has not yet been known to occur nor captured on radar imagery.

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Therefore, in this feasibility study we examine the situation in radar imagery when sea ice appears most similar to an oil spill in an otherwise clean ocean, using both fully-polarimetric (FP) and multi-frequency data, in order to investigate the possibilities of discriminating between new ice formation and oil spills using uniform datasets. FP (HH/HV/VH/VV) satellite images have a small areal coverage and are not suitable for regular monitoring of the vast Arctic region. However, these images can be used to investigate whether various sea ice types and ocean conditions, including oil slicks and the similar-appearing sea ice can be discriminated using all three operationally available dual-polarimetric modes provided by presently operational satellite sensors such as Sentinel-1 (C-band) and ALOS-2 (L-band).

We examine FP SAR images from spaceborne C-band RADARSAT-2 (RS-2) SAR images as well as airborne L-band SAR images acquired on-board the National Aeronautics and Space Administration (NASA) Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) sensor, to identify multi-polarization features that can separate oil slicks from newly formed sea ice types over a range of incidence angles (IA). UAVSAR images were chosen due to the low instrument noise floor as well as the high resolution, and the RS-2 data based on the operationally used C-band frequency. The SAR data was acquired during sea ice field campaigns in the Arctic Ocean and oil spill field campaigns in the open ocean, i.e. the discrimination is tested between scenes containing either oil slicks or newly formed sea ice. *In-situ* observations were also obtained during the respective campaigns which can be used for validation of both the sea ice and oil slicks properties. In Figure 1, two photographs depicting the oil slick from oil-on-water (OOW) 2015 in the North Sea and in the Gulf of Mexico Mississippi Canyon 20 block (MC-20) are shown together with a photograph of newly formed sea ice observed during the Beaufort-Chukchi Sea 2015 campaign.

The manuscript starts with Section II covering a review of related studies, followed by a description of the SAR data processing and the multi-polarization features. In Section III the SAR data covering the oil-on-water exercises and the sea ice campaigns are introduced. The methods used here are described in Section IV. Results and discussions are presented in Section V and finally Section VI provides conclusions.

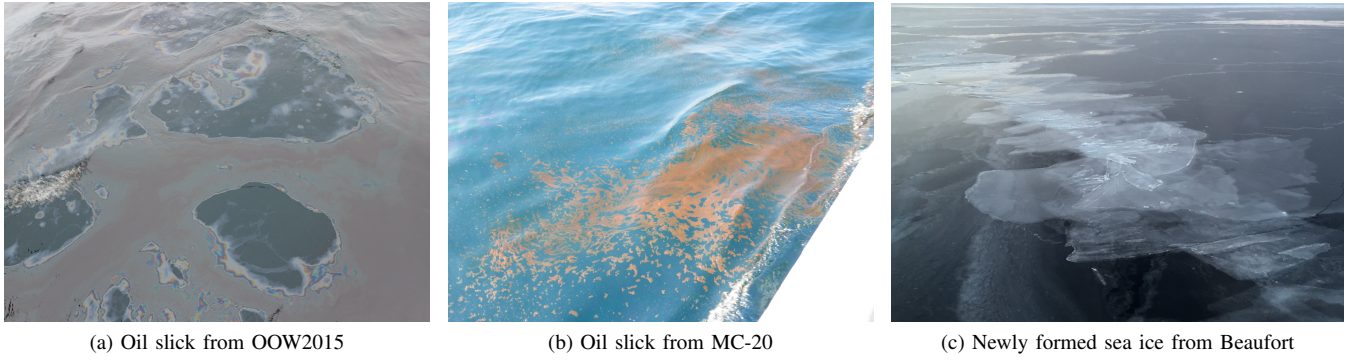


Fig. 1. (a) Closeup of an oil emulsion from the OOW2015 campaign on 10 June 2015, photo by Øyvind Breivik. (b) Oil slick observed in MC-20, photo by Benjamin Holt. (c) Newly formed sea ice from the Beaufort-Chukchi Sea campaign on 5 October 2015, photo by Benjamin Holt.

## II. BACKGROUND AND POLARIMETRY

Low backscatter ocean signatures related to marine slicks and in young sea ice have been extensively studied for decades [7]–[10]. However, studies on discriminating oil slicks from newly formed sea ice using remote sensing instruments are sparse. Most studies, e.g., [11]–[14] focus on oil injection underneath the sea ice, investigations of the migration pattern of the oil up through newly formed sea ice, how oil is altered in cold temperatures and within sea ice and its subsequent impacts on the dielectric constant, and when the oil can be detected using various remote sensing instruments. One exception is [15] where they investigated utilizing FP SAR data, in this case the co-polarization ratio and the phase difference for the two different mediums, based on a simple theoretical model of the dielectric constant.

With low backscatter we mean areas that relative to either a wind-roughened ocean surface or older/thicker sea ice, have a lower radar return, as well as being on the lower end of ocean-ice radar signatures. With respect to low backscatter for sea ice, the newly formed sea ice has been observed to be around 4-5 dB lower than e.g. first-year ice in both C- and L-band SAR [16]. Similar results have been found in many other studies, primarily based on C-band SAR, e.g. [17], [18]. In [19] newly formed sea ice was reported to have backscatter values of -25 dB.

The damping of the surface waves from mineral oil slicks varies with type and thickness of oil (crude oil, water content in emulsified oils), age of the slick (weathering and emulsification) and of drift and mixing speed (wind and currents) see, e.g., [10], [20], [21]. The low backscatter may also be a result of a reduction of the complex dielectric constant ( $\epsilon$ ) [22]. The  $\epsilon$  values for the mediums in L-band, are for clean water 58.26 -i41.48 at -1.8°C and with a salinity of 34.42 [23], for oil slick 2.3-i0.01 [24], [25] and for newly formed sea ice 4.23-i0.12 [26]. A study by [27] found that both the real and the imaginary part of the dielectric constant were affected by oil within sea ice (a reduction in permittivity and reduced volume scattering), and were different from the uncontaminated sea ice (higher permittivity values and higher volume scattering). This finding indicates that this parameter may be useful to identify oil within sea ice.

Significant effort has gone towards establishing oil slick

detection algorithms as well as developing discrimination tools relying on SAR data e.g., [28]. In these studies, the shape of slicks is commonly used to separate the oil slicks from other low backscatter phenomena, but should an oil slick occur, e.g., at the ice margin, the sea ice edges may influence the spatial extent of the slick and, e.g., *feathering* as a descriptive feature may not occur. Out of the confirmed oil slicks in the HELCOM report [29] 76% were elongated, and thereby have a shape comparable to leads [30], an area where new ice regularly forms. Sea ice floes may also affect the shape of a slick and the oil may migrate underneath the sea ice. Therefore, the study here focuses on the backscatter and polarimetric parameter values and will not take into account the shape of the oil slicks, nor will it consider oil slicks under sea ice.

To establish multi-polarization features that can be used for the separation between newly formed sea ice and open water, we use FP data that enables extraction of multi-polarization features using the full scattering matrix  $\mathbf{S}$  as below:

$$\mathbf{S} = \begin{bmatrix} S_{HH} & S_{VH} \\ S_{HV} & S_{VV} \end{bmatrix} = \begin{bmatrix} |S_{HH}|e^{i\phi_{HH}} & |S_{VH}|e^{i\phi_{VH}} \\ |S_{HV}|e^{i\phi_{HV}} & |S_{VV}|e^{i\phi_{VV}} \end{bmatrix}. \quad (1)$$

The first letter in the subscript refers to the transmitted polarization and the second to the received polarization.  $|\cdot|$  and  $\phi$  denote the amplitudes and the phases of the measured complex scattering coefficients. The images are first calibrated to sigma nought, and thereafter multi-looked to reduce speckle.

A set of 6 different multi-polarization features was selected for the separability analysis, listed in Table I. The selected multi-polarization features emphasise different aspects of the backscatter information, such as the scattering processes and textural variation, and they have a proven suitability in discriminating oil slicks from surrounding open water (e.g., [22], [28], [31]) or in discriminating newly formed sea ice from surrounding thicker sea ice and open water (e.g., [16], [18], [32]). When analysing SETHI airborne L-band SAR and UAVSAR data [28] found that out of 12 multi-polarization features,  $\sigma_{HV}$  and  $\sigma_{VV}$  were the most suitable parameters for oil slick detection in open water, and the normalised radar cross section (NRCS) data are therefore included in the analysis. As available satellite data, such as from RS-2 and Sentinel-1 (S-1), provide the dual-polarization mode of HH/HV or VV/VH the cross-polarization ratio ( $\gamma_{co}$ ) is also investigated. For sea ice classification the co-polarization ratio

( $\gamma_{co}$ ) is a useful parameter for separating the thicker sea ice from thinner sea ice and open water areas, e.g. [16], [19], [32]. However,  $\gamma_{co}$  increases with IA for both the newly formed sea ice and mineral oil slicks [15], [18]. This IA dependence leads us to also include the polarization difference ( $PD$ ) as it was shown to be less sensitive to IA variations compared to  $\gamma_{co}$ , to be less sensitive to additive noise [33]–[35] and less sensitive to the wind direction [34]. Initial studies using features derived from the covariance and coherency matrices were carried out, though these results were not as promising compared to the parameters included here and were therefore excluded from the study.

According to two-scale Bragg scattering models like tilted-Bragg model [36] or X-Bragg model [37], the multi-polarization features above the line in Table I are dependent on both large and small scale surface roughness and below the line on large-scale roughness. All parameters are dependent on the IA and the dielectric constant.

TABLE I

MULTI-POLARIZATION FEATURES USED IN THIS STUDY. THE  $\langle \cdot \rangle$  MEANS THAT THE DATA IS AVERAGED OVER A NEIGHBORHOOD OF  $N$  PIXELS. WE HAVE ASSUMED RECIPROcity  $HV = VH$ .  $PD$  IS DEFINED ON A LINEAR SCALE AND MAY SUPPRESS NON-POLARIZED SCATTERING [38] AND THE OTHER MULTI-POLARIZATION FEATURES ARE DEFINED ON A LOG-SCALE.

Feature	Definition
Sigma nought backscatter	$\sigma_{HH}^0 = \langle  S_{HH} ^2 \rangle$
Sigma nought backscatter	$\sigma_{VV}^0 = \langle  S_{VV} ^2 \rangle$
Sigma nought backscatter	$\sigma_{HV}^0 = \langle  S_{HV} ^2 \rangle$
Polarization difference	$PD = \langle  S_{VV} ^2 \rangle - \langle  S_{HH} ^2 \rangle$
Co-polarized ratio	$\gamma_{co} = \frac{\langle  S_{VV} ^2 \rangle}{\langle  S_{HH} ^2 \rangle}$
Cross-polarized ratio	$\gamma_{cross} = \frac{\langle  S_{HV} ^2 \rangle}{\langle  S_{HH} ^2 \rangle}$

### III. EXPERIMENTAL SETUP AND DATA COLLECTION

In this study we use 11 multi-looked complex (MLC) UAVSAR images, see Table II. The UAVSAR images were collected during the OOW 2015 exercise in the North Sea [39], over a crude oil seep in the Gulf of Mexico in 2016, located at the MC-20 site [40], and during a sea ice campaign in Beaufort-Chukchi Seas in 2015 [41]. The images were chosen to cover a range of different IAs, spanning the entire range from  $30^\circ$  to  $55^\circ$ , though not all images contained dark features spanning the entire range. The upper restriction of  $55^\circ$  was set due to the increased influence from cross-talk at the higher IAs in spaceborne SAR systems, even though the UAVSAR has a reliable calibration up to 58 degrees [42]. The MC-20 average slick size (approximately  $14.9 \text{ km}^2$  [43]) and the newly formed sea ice areas were larger than those observed during the OOW 2015 campaign, and therefore a larger number of images were required from the latter campaign to fully cover the same IA range. The UAVSAR images were not corrected for cross-talk [34].

In addition, we use 12 single-look complex (SLC) RS-2 images, separated into 6 different pairs. The oil slick RS-

2 images were collected during four OOW exercises (2011–2013) and one was acquired near-simultaneously with a UAVSAR image over MC-20. RS-2 images with overlapping IAs covering newly formed sea ice were selected from three different sea ice campaigns around Svalbard in 2015 and 2019 respectively, (for more details see [44] and the Research Council of Norway project Nansen Legacy website (<https://arvenetternansen.com>)). The specifics for the UAVSAR and RS-2 data are presented in Table III.

#### A. Oil slick data

The OOW exercises are yearly oil spill response exercises conducted by the Norwegian Clean Seas Association for Operating Companies (NOFO). The exercises took place in the abandoned Frigg field in the North Sea ( $59^\circ 59'N$ ,  $2^\circ 27'E$ ), where controlled releases of mineral oil emulsions and plant oil into the open sea were conducted to test different recovery systems. The amount of oil released in each exercise was  $20 \text{ m}^3$  (2011),  $17 \text{ m}^3$  and  $10 \text{ m}^3$  (2012),  $50 \text{ m}^3$  (2013) and  $43 \text{ m}^3$  and  $35 \text{ m}^3$  (2015). Thickness estimates of 0.1–1.5 mm are given for the OOW2011 [45]. The slicks were thin mineral oil emulsion films with an average water content of 58% – 69%. For further information about the specific mixtures and the exercises in 2011–2013 see, e.g., [45]–[47], and for the 2015 exercise see [39].

The other oil slick dataset was collected in 2016 over a persistent crude oil slick in MC-20. The crude oil slick undergoes emulsification upon surfacing and rapidly spreads as patchy areas of emulsified oil as well as most extensive sheen. Here 4 images from low to medium wind speed conditions are used [40]. *In-situ* data indicate that the crude oil in MC-20 ranged in thickness from sheen to a thickness of 0.02–2 mm [40], [48].

#### B. Newly formed sea ice data

The UAVSAR sea ice data were collected during the Sea State and Boundary Layer field campaign which took place in the Beaufort-Chukchi Seas in October–November 2015 [41]. The thin ice thickness was calculated from skin temperatures measured by two KT-15 infrared thermometers, mounted on the ship and directed towards the sea surface at a distance of 25 m from the side of the ship. Each thermometer viewed an approximately 3 m wide area, with the two areas separated by 24 m. These ice thickness measurements have been validated with other related measurements and are accurate up to a thickness limit of 0.5 m [49]. The thickness measurements from October 6 are plotted on-top of a RS-2 ScanSAR Wide image in Figure 2. The mean thin ice thickness during the day of the UAVSAR flights was 0.16 m and overall during the campaign the thinner sea ice thickness averaged 0.20 m. The air temperature ranged from  $-5$  to  $-10^\circ\text{C}$  from Oct. 4 through Oct. 6, the date of the UAVSAR flight, with Oct. 4 being the date when the time the ship entered the ice field. The water temperature remained below freezing,  $-1.8^\circ\text{C}$  throughout the campaign.

The RS-2 FP images were acquired during three different sea ice campaigns, Norwegian Young sea ICE cruise (N-ICE2015) [44], Fram Strait (FS) observatory cruise 2015 and

TABLE II

UAVSAR AND RS-2 IMAGE DATASETS, WHERE — INDICATES NOT APPLICABLE OR NOT AVAILABLE INFORMATION. FOR 17 NOVEMBER SPATIALLY AND NEAR TEMPORALLY OVERLAPPING UAVSAR AND RS-2 IMAGES WERE USED OVER MC-20. RS-2 IMAGES ARE DIVIDED UP INTO PAIRS (#), WHERE EACH PAIR HAS SIMILAR IA, ONE CONTAINING OIL SLICK AND ONE NEWLY FORMED SEA ICE. AS MC-20 IS A CONTINUOUS SEEP NO AGE OF THE SPILL IS GIVEN. TEMPORALLY OVERLAPPING WEATHER OBSERVATIONS WERE MEASURED ON-BOARD SHIPS THAT PARTICIPATED IN THE OOW AND SEA ICE EXERCISES, THOUGH FOR 15 JUNE 17:48 UTC 2012 WIND SPEED OBSERVATIONS FROM THE CLOSEST PLATFORM IS USED. FOR MC-20 DATA FROM BUOY 42020 FROM NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA) NATIONAL DATA BUOY CENTER ARE USED. DIFFERENCES IN ACCURACY EXIST BETWEEN THE DIFFERENT CAMPAIGNS, WHEN POSSIBLE ONE DECIMAL IS USED.

Datum (UTC)	Sensor and beam	# of images	IA (°)	Pair (#)	Age of spill (h)	Wind speed (m/s)	Air temp (°C)
<b>OOW</b>							
08 Jun 2011 05:59	RS-2 FQ28	1	46.1–47.3	5	18	1.6–3.3	11–16
08 Jun 2011 17:27	RS-2 FQ15	1	34.5–36.1	4	9	1.6–3.3	11–16
15 Jun 2012 06:20	RS-2 FQ11	1	30.3–32.0	3	14–22	4	8–9
15 Jun 2012 17:48	RS-2 FQ31	1	48.3–49.5	6	25–29	3	8–9
11 Jun 2013 17:19	RS-2 FQ9	1	28.1–29.8	2	1	5	9–11
09 Jun 2015 09:56 - 10:44	UAVSAR	1	29–40	-	3–4	5–7	9
10 Jun 2015 05:32 - 13:18	UAVSAR	3	31–67	-	17–25	9–12	9
<b>MC-20</b>							
15 Nov 2016 13:09 - 13:13	UAVSAR	1	41–52	-	-	5.9–6	22.3
17 Nov 2016 16:30 - 23:20	UAVSAR	2	31–50	-	-	3.9–5.4	23.4
17 Nov 2016 23:49	RS-2 FQW2	1	19.0–22.6	1	-	3.9–5.4	23.4
<b>Beaufort</b>							
06 Oct 2015 18:08 - 20:00	UAVSAR	4	26–64	-	-	4	-8.6
<b>Svalbard</b>							
26 Jan 2015 13:39	RS-2 FQ9	1	28.1–29.8	2	-	2	-31.4
20 Mar 2015 14:33	RS-2 FQ16	1	35.5–37.0	4	-	4	-26.2
30 Aug 2015 18:39	RS-2 FQ30	1	47.6–48.8	6	-	3	-3.4
01 Sep 2015 17:41	RS-2 FQ11	1	30.3–32.0	3	-	6	-3.3
06 Sep 2015 18:35	RS-2 FQ29	1	46.9–48.1	5	-	1	-0.5
02 Dec 2019 12:43	RS-2 FQ 2	1	19.7–21.6	1	-	7	-14.0

TABLE III

SPECIFICS OF THE UAVSAR AND RS-2 DATA USED IN THIS STUDY. RANGE (RG) AND AZIMUTH (AZ) VALUES ARE GIVEN AS NOMINAL VALUES.

Sensor	RS-2	UAVSAR
Operating mode	Spaceborne	Gulfstream-III aircraft
Frequency band	C (5.41 GHz)	L (1.26 GHz)
Acquisition mode	Fine Quad	PolSAR
Polarization mode	Full-polarization	Full-polarization
Resolution, m (Rg x Az)	5.2 x 7.6	1.5 x 0.8
Swath Width, km	25 x 25	22
Incidence angle (IA, °)	19–49	30–70
Noise Equivalent Sigma zero (NESZ), dB	-32.9 ±1.5	-52 to -35

the fourth Nansen Legacy campaign in 2019. The N-ICE2015 and Nansen Legacy campaigns were located north of Svalbard and FS15 close to the east coast of Greenland. During N-ICE2015 the newly formed sea ice observed in leads was in the form of nilas, young grey ice and young white ice [50]. During the 3 weeks of the FS15 campaign, sea ice had just started to form and newly formed sea ice with a thickness up to 4 cm was observed, primarily grease ice and nilas without frost flowers. During the Nansen Legacy campaign north of Svalbard in December 2019 new ice regularly formed during the freezing conditions.

#### IV. METHOD

UAVSAR and RS-2 images, presented in Table II, containing either mineral oil slicks or newly formed sea ice are used to characterise the two types of low backscatter phenomena,

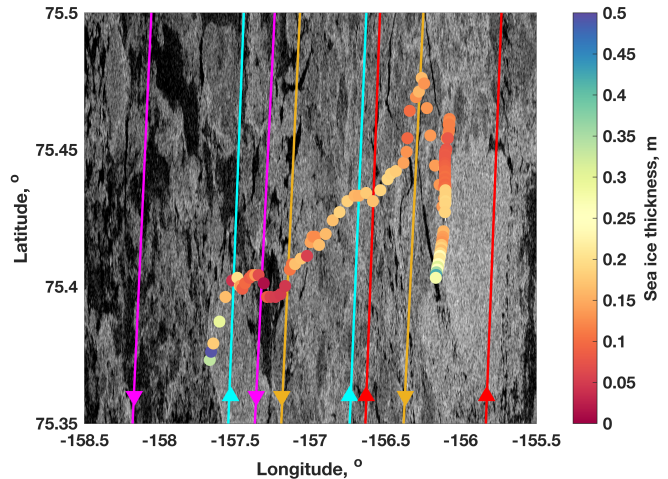


Fig. 2. Measurements of sea ice thickness were either obtained from the Beaufort-Chukchi Seas 2015 campaign, utilising downward-looking radiometers mounted on the ship as it travelled through the sea ice [49]. Sea ice thickness measurements (dots, m) are shown for October 6, which are overlaid on a RS-2 ScanSAR Wide HH-channel image taken on October 6, 2015 at 17:15 UTC. The greyscale on the RS-2 image ranges from -10 to -25 dB. The pairs of coloured lines indicate the swath extent of the four separate UAVSAR acquisitions, and the arrows on the lines the flight direction.

with the aim to establish multi-polarization parameters that can separate the two across a range of IAs. Six multi-polarization features and their response to oil slicks and newly formed sea ice are investigated. A noise analysis is carried out to assess the SAR data quality and to identify potential limitations with



the data for discrimination. The discrimination analysis is performed using the Kolmogorov-Smirnov (K-S) test [51] and finally, the importance of the signal-to-noise ratio and the pixel resolution for the separability are assessed.

#### A. Feature extraction

The multi-polarization features are calculated using the equations outlined in Table I. The UAVSAR images were provided as multi-look complex (MLC) data and were multi-looked by  $3 \times 12$  pixels, with an additional smoothing of  $7 \times 7$  pixels performed to reduce radar speckle. The RS-2 SLC data were multi-looked by  $3 \times 8$  pixels.

Regions of interest (ROI) were manually identified and selected within each of the images to be representative of the mineral oil slicks and the newly formed sea ice areas, with example shown in Figures 3a and 3c. The ROIs for the MC-20 study area correspond to the areas with the highest damping ratios, shown in [52]. Also shown are the PD values for both areas (Figures 3b, and 3d). In the ROI selection the edges of the respective low backscatter areas were avoided to reduce contamination from the surrounding open water and thicker sea ice. Structures such as ships and platforms were also avoided to mitigate effects from side-lobes that might otherwise smear the signal around the target. The UAVSAR images were collected during three separate campaigns and the low backscatter phenomenon covered a significant range of IAs. For this analysis, all pixels within the UAVSAR ROIs were separated into oil slick or newly formed sea ice pixels, and thereafter binned into five different IA ranges, where each range corresponds to  $5^\circ$ . The limited IA range covered by each RS-2 image prevented matching IA groupings with UAVSAR data. Instead, the six RS-2 image pairs, where each pair contained one oil slick and one newly formed sea ice image, were identified with overlapping IAs and all ROI pixels within each image were used for the analysis. The ROIs in the RS-2 images were equally sized for all pairs, though the shape was constrained by the slick or newly formed sea ice geometry and the  $3 \times 8$  pixel multi-look. The same number of pixels was used for each pair, with  $>800$  pixels for sets #1-4. A smaller number of pixels ( $>500$ ) was used for sets #5-6 due to the smaller size of the oil slicks.

To quantify the heterogeneity within the different multi-polarization features the coefficient of variation ( $\widehat{CV}$ ) was calculated for all pixels within each IA range (UAVSAR) or image dataset (RS-2).  $\widehat{CV}$  is defined as;

$$\widehat{CV} = \sigma_X / \mu_X. \quad (2)$$

where  $\sigma$  is the standard deviation,  $\mu$  is the mean value of  $X$ , the polarimetric feature. A low  $\widehat{CV}$  value indicates a largely homogeneous sample and a high value indicates large variations within the sample.

#### B. SAR data quality

The low radar return signal of the investigated mediums implies that the signal-to-noise ratio (SNR) needs to be considered when assessing the robustness of any multi-polarization features. The NESZ is affected by many factors, including the

SAR frequency, the incidence angle and the azimuth resolution [53]. Here we observe a higher NESZ for the RS-2 images than for the UAVSAR images (Table III), controlled primarily by the two different altitudes of the sensors, as well as the increased NESZ with increasing frequency (see eq. 5 in [53]). The higher NESZ for the RS-2 images and corresponding lower SNR has resulted in a lower separability between the ice/oil signatures and the clean ocean using the RS-2 data compared to the UAVSAR data. The effect of SNR on oil slick detection is extensively discussed in, e.g., [28], [33], [54]. The level above the noise floor (NESZ) needed for the NRCS to safely contain a valid signal and be useful for polarimetric scattering analysis varies in the literature, e.g., at least 6 dB [22], 7-9 dB [34] up to 10 dB [19], [33]. When analysing the NRCS values for the respective channels increments of 2 dB above the NESZ are therefore used, as this enables us to capture all three above mentioned ranges. The RS-2 NESZ values are calculated using the beam specified metadata information as well as the local IA [55]. The UAVSAR NESZ profile and further information is found in [42]. As the backscatter signals decrease with increasing IA, thereby reducing the SNR, the IA must also be considered in the analysis.

When comparing discrimination between the oil slicks and the newly formed sea ice and the potential influence of the SNR we define, for either of the two media, the difference ( $\Delta$ ) between the mean value, of the respective backscatter intensities and the NESZ as:

$$\Delta = \mu_X - NESZ \quad (3)$$

#### C. Separability analysis

To investigate the separability between the mineral oil slicks and the newly formed sea ice we use the two sample K-S tests [51]. These tests are based on determining if two probability distributions are from the same distribution or not, by estimating the maximum difference between their cumulative distributions [56]. The test enables comparison between parameters that may not be normally distributed. The K-S test has values between 0 and 1 and here, similarly to [57], [58], we define a K-S value above 0.7 to mean some separability, a value above 0.8 indicates reasonable separability and values above 0.9 represents good separability.

#### D. Effect of additive noise and pixel resolution

This step is only performed on the UAVSAR data, due to the sensors inherently good SNR and high pixel resolution. To test influence of additive noise on the separability measure, we add simulated noise to the UAVSAR measurements, and compare the simulated noise to the true noise floors reported for RS-2 ScanSAR, S-1 Extra Wide (EW) and ALOS-2/PALSAR-2 Stripmap. The noise simulation is performed in the same manner as described in [33], where complex system noise is added to the normalised radar backscatter coefficients. Expressed as;

$$M = S + N \quad (4)$$

where  $M$  is the measured radar cross section,  $S$  is the scattering matrix without noise (Eq. 1), and  $N = [n_{HH}, n_{VH}, n_{HV}, n_{VV}]^T$  represents the complex additive noise. The additive noise is assumed to be complex Gaussian white noise with a mean around zero. From this procedure several new simulated noise floors or NESZ are generated. The separability estimates are thereafter carried out again using the range of new radar cross section values, starting from the polarimetric feature extraction stage.

The importance of the pixel spacing is investigated by varying the speckle filtering window size for the UAVSAR data. The original MLC UAVSAR images have been multi-looked by  $3 \times 12$  pixels, and here a running averaging filter was applied to the images, ranging from a  $1 \times 1$  to a  $20 \times 20$  pixel window size. The averaging will reduce the standard deviation of the values but not significantly affect the mean values. The new effective pixel spacings are also compared with the RS-2 ScanSAR, S-1 EW and ALOS-2/PALSAR-2 Stripmap configurations. The original MLC UAVSAR images have a pixel spacing equivalent to the SLC RS-2 and ALOS-2 Fine Stripmap multi-polarization data.

## V. RESULTS AND DISCUSSION

In Figure 3a and 3b we observe that there is a good oil-sea contrast in both  $\sigma_{VV}$  and  $PD$  for the UAVSAR data. This high oil-sea contrast for  $PD$  was also observed for three mineral oil emulsions (40%, 60% and 80% volumetric oil fraction) in [34], and moreover,  $PD$  has a reduced dependence on IA for the oil slick compared to the open water. In Figure 3c and 3d, the newly formed sea ice can be detected in the  $\sigma_{VV}$  data though has a lower contrast to the surroundings in  $PD$ . Note that the  $PD$  values for the sea ice areas are lower than for the oil slick and open water areas, though for easier interpretation the same scale-bar is used in both sets of images.

### A. Overall observations

In Figure 4a and 4b, the mean  $\sigma_{HH}$  and  $\sigma_{VV}$  backscatter values for the respective ROIs and the dark slicks are plotted against mean  $PD$ , using the UAVSAR data. A good discrimination between the newly formed sea ice (blue dots) and the oil slicks (red triangles and magenta squares) is provided by  $PD$ . Moreover, the newly formed sea ice has overall lower backscatter, and lower  $PD$  values compared to the mineral oil slicks. Figure 4c shows  $\sigma_{VV}$  plotted against  $\gamma_{co}$ , where a larger variability in the newly formed sea ice  $\gamma_{co}$  values compared to the  $PD$  values (Figure 4b) can be observed. The corresponding results for  $\sigma_{HH}$  and  $\gamma_{co}$  combination are not shown but provide a very similar outlook. The RS-2 data is shown in Figure 4d where mean  $\sigma_{VV}$  is shown against mean  $PD$  values. A lower degree of separability can be observed compared to the UAVSAR data, though note that all ROI's from the different pairs are included and IA is not accounted for. For the RS-2 ice-oil pairs with the highest IAs the values approach the noise floor, and hence a reduced discrimination between the  $\sigma_{HH}$  and  $\sigma_{VV}$  may be expected. Skrunes et al. 2018 [34] found that the  $PD$  values had a large decrease from  $24^\circ$  to  $30^\circ$ , though above this upper range the IA dependency

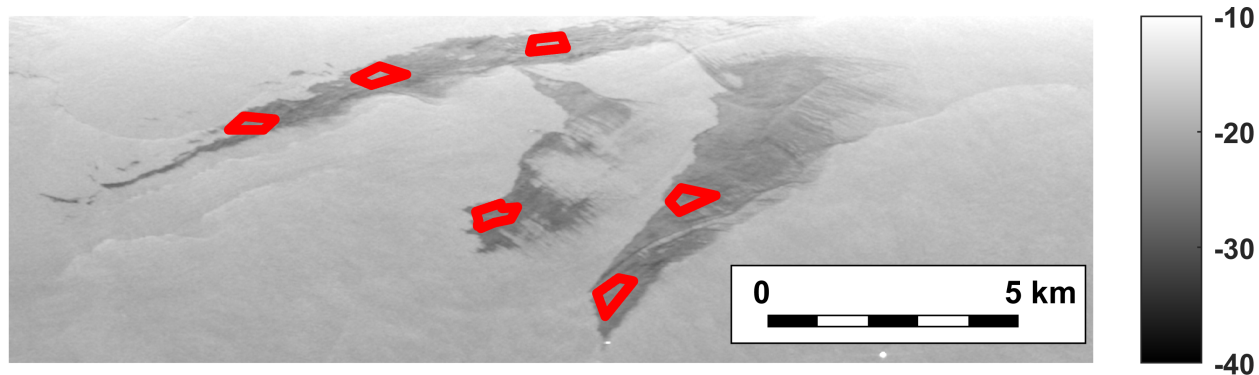
was limited. From this it appears that  $PD$  vs.  $\sigma_{VV}$  gives the overall cleanest separation for the UAVSAR data. Similar trends can be observed for the RS-2 data provided that the data is separated into distinct IA ranges.

There are many different environmental scenarios with respect to varying winds and currents, temperature, ice/oil and water mixtures that need to be examined for the interdisciplinary topic of separating oil slicks from newly formed sea ice. Some of the scenarios are covered within this study, e.g. were SAR images were acquired under low to medium wind conditions. For the RS-2 pairs care was taken to ensure similar wind conditions for the different pairs and also similar incidence angle, though small differences exist between the respective pairs. The air and water temperature variations are larger and may affect the dielectric constant values for the crude oil and oil-ice emulsions [27]. Excellent work has been carried out by e.g. [11]–[14] to investigate the effect on oil spills underneath sea ice. Here we choose to focus on separability between oil slicks and newly formed sea ice, and assume to be located in the vicinity of each other within the marginal ice zone but not yet mixed in. This study is a feasibility study, since multi-polarization SAR images covering both oil slicks and sea ice to the authors knowledge do not presently exist. Moreover, the work presented here requires that the newly formed sea ice and oil slicks have been detected and discriminated from their respective surroundings, and thereafter is the separability between the two assessed. For this we choose to include multi-polarization parameters that [28] found to be suitable for oil spill detection and discrimination, and for sea ice discrimination [32]. Further investigations could be carried out using spaceborne L-band SAR data from e.g. the ALOS-2/PALSAR-2 sensor, as it has both a low NESZ as well as high spatial resolution, though limited data are available overlapping oil spills.

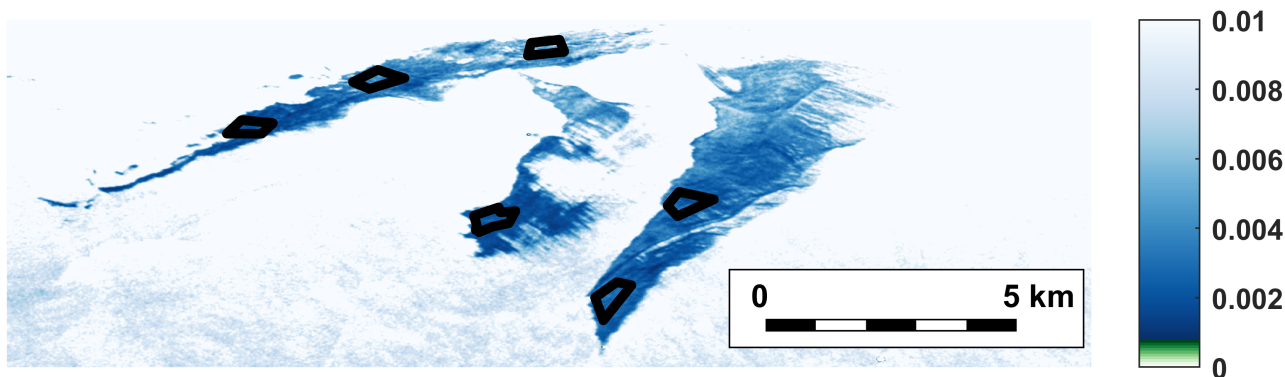
### B. Coefficient of variation

The textural heterogeneity is quantified using  $\widehat{CV}$ . The correlation between sea ice thickness, IA and the relative contributions of surface and volume scattering for different IAs, e.g., [18], [57], [59], means that we separate the  $\widehat{CV}$  values for the UAVSAR data into 5 IA ranges, presented in Table IV. The NRCS values for the dark features have low variability with IA, and  $\gamma_{co}$ ,  $\gamma_{cr}$  and  $PD$  have a higher dependency of IA. For all parameters the oil slick values are more homogeneous than the newly formed sea ice values for all IAs except the lowest one. The mineral oil slick in the MC-20 area had less variation with IA than the OOW2015 slicks. A potential reason for this is the higher wind speeds observed during the OOW2015 campaign, or the thinner slick may be more susceptible to breaking up. Skrunes et. al., [34] observed the lowest  $\widehat{CV}$  values for  $PD$  for open water areas under OOW2015, combined with the low IA dependency above  $30^\circ$  indicated that  $PD$  was one of the best operational multi-polarization feature due to the stability under varying imaging geometry.

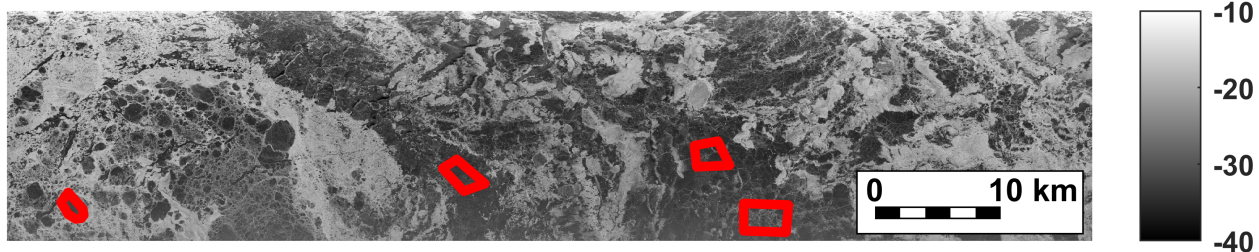
The  $\widehat{CV}$  values for the RS-2 data are shown in Table V. The low values for all NRCS values in pairs #5-6 are likely a



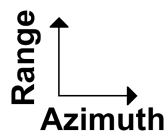
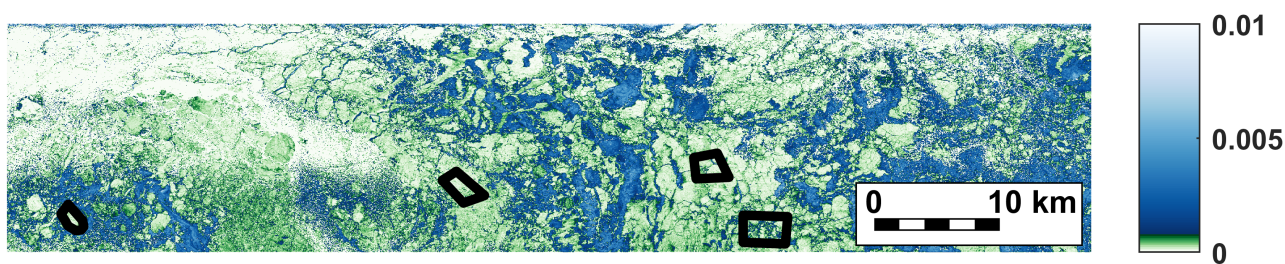
(a) UAVSAR intensity (VV), dB, image from the MC-20 area on November 17 2016 15:10 UTC.



(b) Polarization difference from the MC-20 area on November 17 2016 15:10 UTC.



(c) UAVSAR intensity (VV), dB, image from Beaufort Sea on October 6 2015 18:08 UTC.



(d) Polarization difference from Beaufort Sea on October 6 2015 18:08 UTC.

Fig. 3. Intensity (VV) data in dB for UAVSAR images depicting (a) oil slicks in open water within the MC-20 area in the Gulf of Mexico and (c) newly formed sea ice among thicker sea ice in Beaufort Sea. The red areas indicate the ROIs used. The  $PD$  values for the respective UAVSAR images are shown in (b) for the oil slicks and in (d) for the newly formed sea ice. The same ROIs are here indicated with black polygons. Note that the colorbar is non-linear to enable the same color scale for both images.

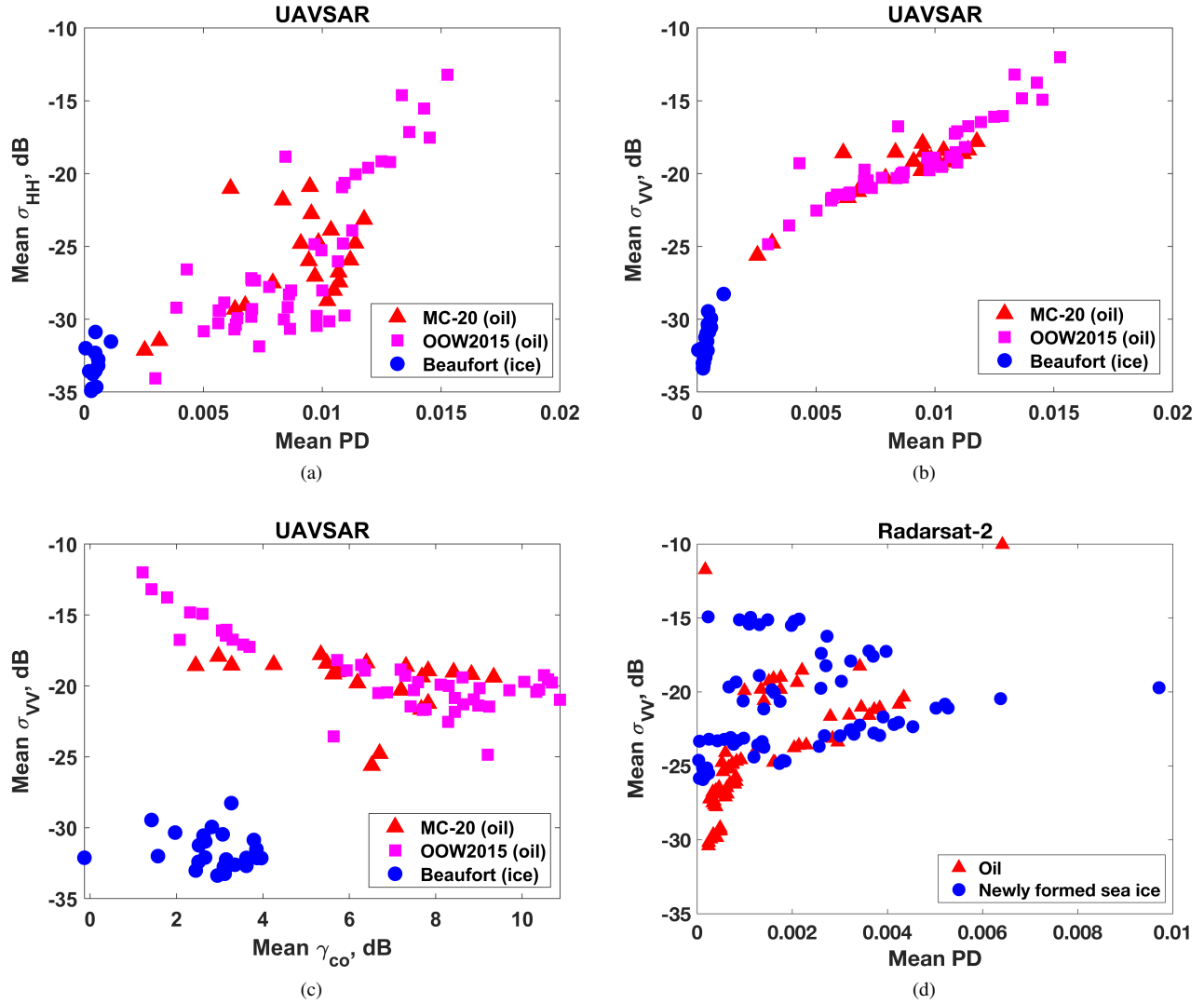


Fig. 4. UAVSAR mean  $PD$  is plotted against (a) mean  $\sigma_{HH}$  and (b) mean  $\sigma_{VV}$ , and in (c) mean  $\sigma_{VV}$  vs. mean  $\gamma_{co}$ . In (d) RS-2 mean  $PD$  against mean  $\sigma_{HH}$ . One marker indicate one individual ROIs, with no consideration for the IA bracket into which it falls.

TABLE IV

$\widehat{CV}$  VALUES FOR THE MULTI-POLARIZATION FEATURES ESTIMATED FROM THE UAVSAR DATA. THE OIL SLICK VALUES ARE HIGHLIGHTED IN LIGHT CYAN AND THE NEWLY FORMED SEA ICE IN WHITE. THE DATA ARE SPLIT INTO IA RANGES OF  $5^\circ$  INCREMENTS.

IA		$\sigma_{HH}$	$\sigma_{VV}$	$\sigma_{HV}$	$\gamma_{co}$	$\gamma_{cr}$	$PD$
OOW2015	30°-35°	0.07	0.09	0.07	0.09	0.51	0.51
MC-20		0.15	0.14	0.06	0.11	0.20	0.27
Beaufort		0.09	0.10	0.04	0.10	0.41	0.54
OOW2015	35°-40°	0.08	0.11	0.07	0.16	0.37	0.47
MC-20		0.08	0.07	0.03	0.12	0.18	0.19
Beaufort		0.18	0.23	0.07	0.19	0.61	0.65
OOW2015	40°-45°	0.06	0.08	0.04	0.07	0.12	0.24
MC-20		0.06	0.05	0.02	0.09	0.15	0.20
Beaufort		0.17	0.27	0.07	0.29	0.72	1.73
OOW2015	45°-50°	0.09	0.13	0.08	0.16	0.27	0.41
MC-20		0.06	0.05	0.02	0.18	0.21	0.17
Beaufort		0.25	0.25	0.15	0.43	0.62	3.68
OOW2015	50°-55°	0.02	0.02	0.01	0.10	0.15	0.10
MC-20		0.06	0.05	0.02	0.16	0.24	0.22
Beaufort		0.22	0.27	0.12	0.45	0.56	1.70

consequence of the low SNR. Notably higher values than for the other parameters were observed for  $PD$ . For pairs #3, 5 and 6 the  $\widehat{CV}(PD)$  values for the newly formed sea ice are higher than for the oil slicks. Common for these three sea ice images is the recent drop in air and sea water temperature [60] and the measured sea ice thickness of 2-4 cm. Whereas for #2 the thickness was estimated to between 10-20 cm and #1 and 4 lacks thickness measurements. Studies by, e.g., [19], [61], [62] identified that when the sea ice thickness exceeds 2-4 cm liquid brine forms at the sea surface, thereby changing the dielectric constant, and also changing the NRCS. The oil slicks studied in pairs #2 and 4 are the youngest slicks (<9 hours), and in pair #1 is the large continuous release in MC-20 studied. The relatively large variability may therefore be an effect of a more contained oil slick and a larger volume. The  $\widehat{CV}$  values may here have been affected by the low SNR and variability within the studied oil slicks and newly formed sea ice areas.

For the UAVSAR data we observe that  $\widehat{CV}$  of multi-



polarization features, e.g.,  $PD$ , may be suitable for oil slick and newly formed sea ice discrimination, provided that the IA is  $>35^\circ$ . Most operational SAR sensors provide data with IAs up to  $47^\circ$ - $50^\circ$ , and hence such restrictions on the use of IAs are certainly possible. The two different UAVSAR oil slick datasets show similar results, this may be a result of the larger volumes of oil released within the MC-20 block, possibly resulting in a more coherent oil slick, or the different wind conditions under which the two slick areas were observed. The RS-2 data show higher  $\widehat{CV}$  values for  $PD$  when the measured sea ice thickness indicate values below 5 cm, though no consistent variability is observed.

TABLE V  
 $\widehat{CV}$  VALUES FOR THE MULTI-POLARIZATION FEATURES ESTIMATED FROM THE RS-2 DATA. THE OIL SLICK VALUES ARE HIGHLIGHTED IN LIGHT CYAN AND THE SEA ICE IN WHITE.

IA	Pair #	$\sigma_{HH}$	$\sigma_{VV}$	$\sigma_{HV}$	$\gamma_{co}$	$\gamma_{cr}$	PD
1	21°	0.16	0.17	0.04	8.07	0.08	6.73
		0.12	0.17	0.06	3.97	0.12	3.95
2	29°	0.10	0.10	0.05	1.68	0.17	1.73
		0.10	0.10	0.06	1.42	0.20	1.52
3	31°	0.08	0.08	0.04	1.53	0.29	1.62
		0.10	0.09	0.06	3.76	0.26	3.78
4	36°	0.07	0.08	0.04	1.48	0.41	1.81
		0.10	0.13	0.05	0.64	0.36	1.38
5	47°	0.04	0.05	0.04	1.02	1.85	1.13
		0.08	0.06	0.05	2.42	0.38	2.51
6	49°	0.05	0.07	0.03	0.51	0.47	0.74
		0.05	0.07	0.04	6.05	0.37	4.77

### C. Noise analysis

Poor SNR may reduce the characterization ability and cause misinterpretations of the data [22], [28], [33]. To assess the data quality, the mean backscatter intensity values are compared to the NESZ at the same IA or range of IAs. In [19], [33] a limit of 10 dB above the NESZ was determined to be at a level when polarimetric scattering properties of the target can be reliably assessed, [34] suggests using 7-9 dB, while [22] sets a value of 6 dB as being needed. In Figure 5a-c, the mean and one standard deviation backscatter values for the combined UAVSAR ROIs separated into  $5^\circ$  IA ranges are shown together with the NESZ values and 2 dB increments above the NESZ, enabling comparison with the three suggested limits.

We observe that for the UAVSAR data the co-polarization channels always meets the  $>NESZ+10$  dB criteria for both the mineral oil slicks and the newly formed sea ice areas. The HV-channel meets this criteria for all the OOW2015 images and for the IA bracket of  $30^\circ$ - $35^\circ$  for the Beaufort images and for the  $40^\circ$ - $45^\circ$  IA for the MC-20 images. The OOW2015 campaign has the highest wind speeds of the included data (see Table II), and this is likely a reason for the reduced effect of the sensor noise on this dataset. The HV-channel may be possible to use for IAs up to  $50^\circ$  as it fulfills the criteria of  $>NESZ+6$  dB for all used datasets, though care must be taken in the interpretation of the results.

The noise analysis result for the RS-2 images are presented in Figure 6. Note that for pair #1 the oil slick data was acquired in Wide Fine Quad-polarimetric beam mode and the

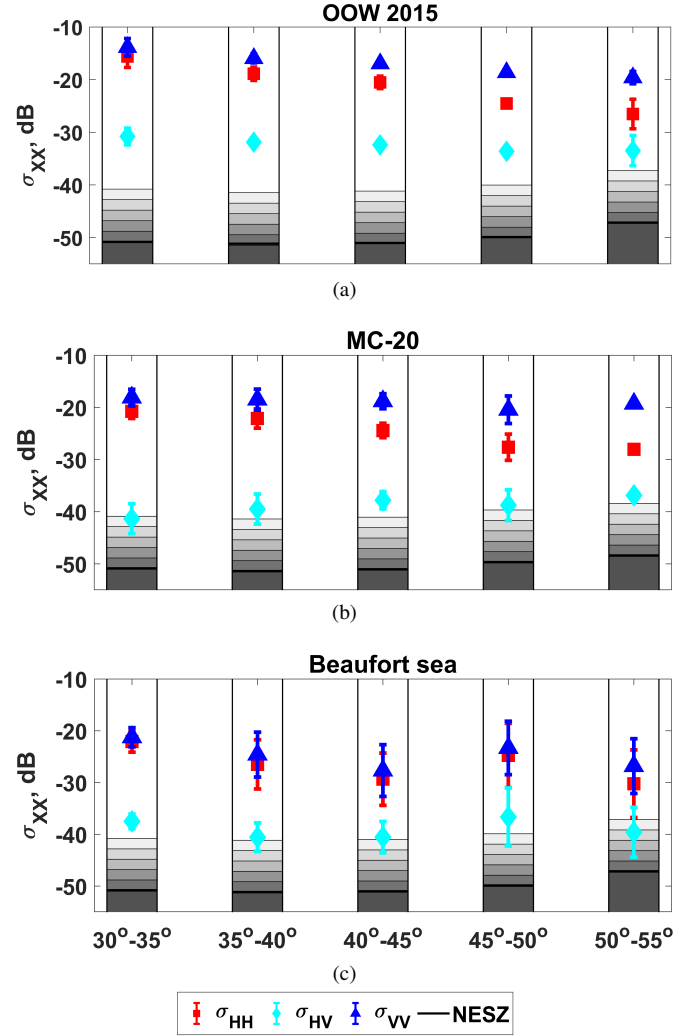


Fig. 5. UAVSAR backscatter  $\sigma_{XX}$  mean  $\pm$  std values plotted together with the NESZ for (a) OOW2015, (b) MC-20 and (c) Beaufort. The NESZ values are illustrated using grey shading, where the darkest colour represents values below the NESZ and white  $>10$  dB above the NESZ. The shading is given in 2 dB increments.

NESZ is therefore significantly higher than for the equivalent Fine Quad-polarimetric beam mode. For image pairs #1-2 both co-polarized channels fulfil the  $>NESZ+10$  dB. When the mean plus one standard deviation fulfils  $>NESZ+10$  dB we define the SNR as good, when the values are below  $NESZ+10$  dB but above NESZ we define the SNR as moderate and when the values are below NESZ as poor. The SNR values were good for the newly formed sea ice in pairs #1-3 and moderate in #4-6, and for the oil slick good in #1-2, moderate in pairs #3 and 6 and poor for pairs #4 and 5. For the cross-polarized channel the values were poor to moderate for all image pairs. The backscatter intensity values for the oil slicks in pair #6 are relatively high despite the high IA, this is possibly an effect of the age (25-29 h) of the observed oil slicks that may therefore have undergone more emulsification than the other slicks. In [35] they argue that the IA should, if possible, be kept below  $35^\circ$  to ensure a sufficient SNR for newly formed sea ice areas, and the results here corroborate those findings.

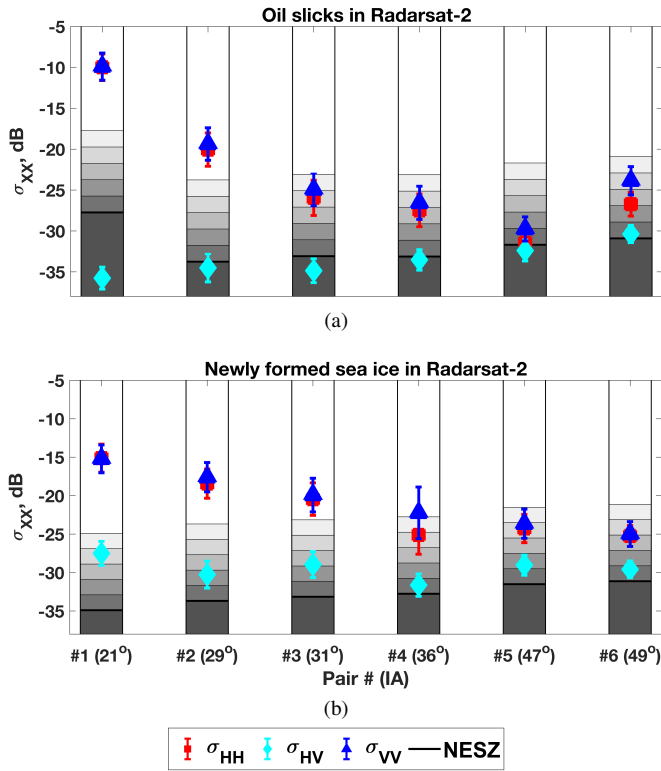


Fig. 6. RS-2 backscatter  $\sigma_{XX}$  mean $\pm$ std values plotted together with the NESZ for (a) oil slicks and (b) newly formed sea ice. The NESZ values are illustrated using grey shading, where the darkest colour represents values below the NESZ and white  $>10$  dB above the NESZ. The shading is given in 2 dB increments.

From this section, we conclude that the UAVSAR data have sufficiently good SNR for the co-polarization channels (due to the lower NESZ), though care must be taken when interpreting the result for the RS-2 images when the IA is  $>30^\circ$ . For both the C- and the L-band data used here part of the cross-polarization data lie below the recommended limit of 10 dB set by [19], [22], [33]. The low SNR for the cross-polarized data in RS-2 limits the usability of the  $\sigma_{HV}$  and  $\gamma_{cr}$  features. A detailed scattering analysis is not the objective of this study, and a lower SNR may be acceptable. However, the proximity to the noise floor and possible effects on the results should always be kept in mind when analyzing this type of data.

#### D. Kolmogorov-Smirnov test - discrimination of oil and new ice

To investigate separability between the mineral oil slicks and the newly formed sea ice, the K-S test for each IA range in the UAVSAR data is calculated (Table VI.) For the MC-20 and Beaufort datasets the best separability was found using the  $PD$  and  $\gamma_{co}$  values. For both combinations of mineral oil slicks and newly formed sea ice, UAVSAR data  $PD$  provides good separability with only one value (0.77) below 0.9. It should be noted that the Beaufort and MC-20 data had similar wind speeds and that during the OOW2015 campaign the wind speeds were higher. The two highest IA bands ( $45^\circ$ - $50^\circ$  and  $50^\circ$ - $55^\circ$ ) for the Beaufort and MC-20 data are dominated by data with slightly higher wind speeds,

approximately 6 m/s compared to 4 m/s. In these two cases we also observe lower K-S values for the single channel based parameters.  $\sigma_{VV}$  and  $\sigma_{HV}$  overall provide some ( $>0.7$ ) to good ( $>0.8$ ) separability for the Beaufort and OOW2015 data. For both datasets  $\sigma_{HH}$  and  $\gamma_{cr}$  was found to be less suitable for discrimination between mineral oil slicks and newly formed sea ice, which is similar to findings in [28].  $\sigma_{HH}$  had better overall separability in the OOW2015 and Beaufort dataset compared to the MC-20 and Beaufort dataset. The lower separability in  $\gamma_{cr}$  is important as most operational SAR sensors acquire wide-swath coverage images in the HH/HV mode in an Arctic Ocean context, and based on the findings here these images may not be suitable for discrimination between oil slicks and newly formed sea ice considering only the backscatter intensity values. For a discrimination using these type of images, such as S-1, inclusion of textural and spatial information is necessary.

TABLE VI  
K-S TEST BETWEEN THE MINERAL OIL SLICKS AND THE CORRESPONDING NEWLY FORMED SEA ICE FOR THE UAVSAR DATA. WE ADOPT THE SEPARABILITY MEASURES FROM [57], [58] WHERE A K-S VALUE ABOVE 0.7 MEANS SOME SEPARABILITY (LIGHT GREEN), A VALUE ABOVE 0.8 INDICATES REASONABLE SEPARABILITY (MID-GREEN) AND VALUES ABOVE 0.9 HAVE GOOD SEPARABILITY (DARK GREEN).

#### Beaufort and OOW2015

IA	$\sigma_{HH}$	$\sigma_{VV}$	$\sigma_{HV}$	$\gamma_{co}$	$\gamma_{cr}$	PD
$30^\circ$ - $35^\circ$	0.84	0.92	0.90	0.67	0.16	1.00
$35^\circ$ - $40^\circ$	0.93	0.99	0.99	0.61	0.51	1.00
$40^\circ$ - $45^\circ$	0.90	0.97	0.95	0.80	0.45	1.00
$45^\circ$ - $50^\circ$	0.34	0.61	0.58	0.87	0.68	1.00
$50^\circ$ - $55^\circ$	0.63	0.74	0.79	0.74	0.35	0.97

#### Beaufort and MC-20

IA	$\sigma_{HH}$	$\sigma_{VV}$	$\sigma_{HV}$	$\gamma_{co}$	$\gamma_{cr}$	PD
$30^\circ$ - $35^\circ$	0.35	0.66	0.72	0.99	0.90	0.99
$35^\circ$ - $40^\circ$	0.49	0.71	0.34	0.81	0.54	0.93
$40^\circ$ - $45^\circ$	0.58	0.85	0.73	0.99	0.58	0.94
$45^\circ$ - $50^\circ$	0.52	0.32	0.44	0.99	0.27	0.77
$50^\circ$ - $55^\circ$	0.62	0.82	0.75	1.00	0.32	1.00

The RS-2 data K-S distance is presented in Table VII. It can be observed that for some of the multi-polarization features the K-S values are  $>0.7$  for certain IAs, though no individual parameter was found to work for all datasets. The difference in separability compared with the UAVSAR data might be explained by the difference in SNR. In Figures 7a and 7b the K-S values for the different image pairs are plotted against  $\Delta$  (Eq. 3) for the two different mediums, and in Figure 7c the differences in  $\Delta$  between the two different mediums are plotted against the K-S values. In the cases with the highest separability the  $\Delta_{ice}$  values fulfils the criteria of at least NESZ + 6 dB. This may indicate a discrimination between a signal in the newly formed sea ice data and the higher noise component in the oil slick data. For the HV-data the  $\Delta_{oil}$  values indicate that the oil slicks are close to or below the NESZ. Even though the  $\Delta_{ice}$  values do not always have values of at least NESZ + 6 dB, they are higher than the  $\Delta_{oil}$  values, again likely indicating a separation between a higher signal component due to a higher noise component.

$PD$  can be used to reliably separate the investigated mineral oil slicks and newly formed sea ice using UAVSAR images, though for the RS-2 images the discrimination is hampered by

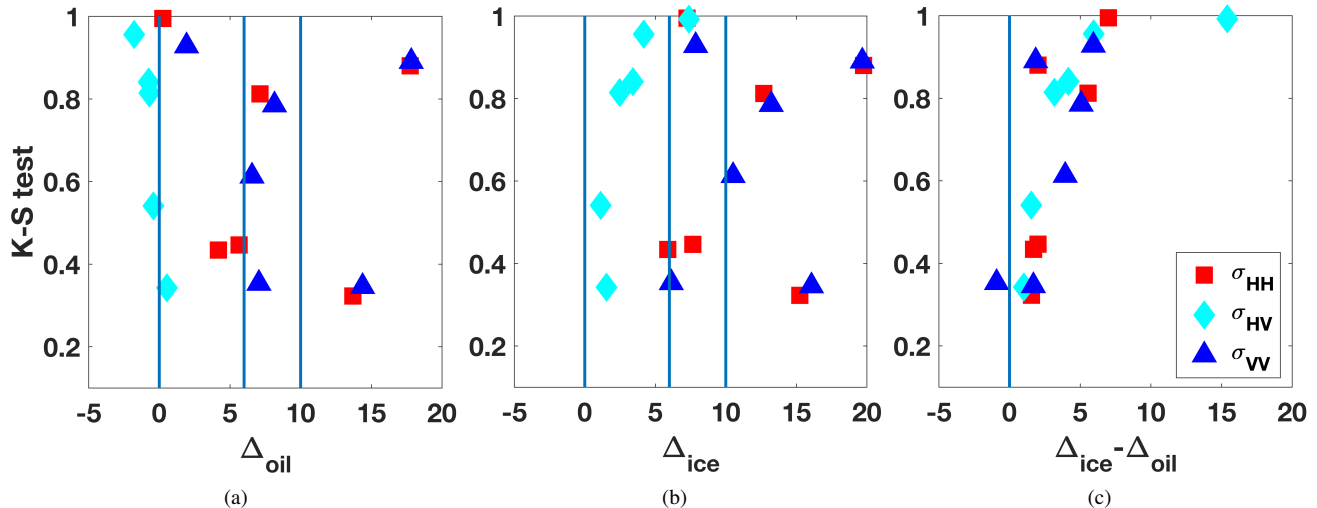


Fig. 7. RS-2 data K-S test values for  $\sigma_{HH}$  (red squares),  $\sigma_{HV}$  (cyan diamonds) and  $\sigma_{VV}$  (blue triangles) plotted versus  $\Delta$  in dB for oil slicks (a), newly formed sea ice (b) and the difference in  $\Delta$  for the newly formed sea ice and oil slicks (c). The vertical lines represent 0dB, 6dB and 10dB above the NESZ respectively.

TABLE VII

K-S TEST BETWEEN THE MINERAL OIL SLICKS AND THE CORRESPONDING NEWLY FORMED SEA ICE FOR THE RS-2 DATA. IA IS THE MEAN IA. WE ADOPT THE SEPARABILITY MEASURES FROM [57], [58] WHERE A K-S VALUE ABOVE 0.7 MEAN SOME SEPARABILITY (LIGHT GREEN), A VALUE ABOVE 0.8 INDICATE REASONABLE SEPARABILITY (MID-GREEN) AND VALUES ABOVE 0.9 HAVE GOOD SEPARABILITY (DARK GREEN).

Pair #	IA	$\sigma_{HH}$	$\sigma_{VV}$	$\sigma_{HV}$	$\gamma_{co}$	$\gamma_{cr}$	PD
1	21°	0.71	0.73	0.91	0.21	0.96	0.21
2	29°	0.32	0.35	0.84	0.07	0.43	0.20
3	31°	0.81	0.79	0.96	0.15	0.10	0.32
4	36°	0.45	0.61	0.54	0.47	0.12	0.62
5	47°	0.99	0.93	0.81	0.29	0.72	0.32
6	49°	0.43	0.35	0.34	0.63	0.23	0.58

the low SNR.  $PD$  has a high correlation with  $\gamma_{co}$  though the advantages with the reduced imaging geometry dependency of  $PD$ , the lower false alarm detection rate for oil slicks [28], the reduced dependency on additive noise [33] and the reduced influence of the wind to sensor direction [34] means that  $PD$  is preferable for discrimination between mineral oil slicks and newly formed sea ice for both datasets used here. However, the lower contrast between newly formed sea ice and thicker sea ice may limit the possibility of using  $PD$  for their discrimination, but  $\gamma_{co}$  has been proven to be useful for separating thinner sea ice from thicker sea ice [16], [18], [19], [32], [63]–[65]. Using a linear mixture model, [15] demonstrated that for L-band SAR the  $\gamma_{co}$  values for young ice are closer to the values for oil-ice emulsions than to open water values, and that newly formed sea ice have  $\gamma_{co}$  values higher than crude oil and oil-ice emulsions at  $-20^\circ\text{C}$ . This was partially attributed to the higher dielectric constant for the newly formed sea ice. Using five complex permittivity mixture models [27] found that the temperature was very important for the dielectric constant values for crude oil and oil-ice emulsions and at  $-1.8^\circ\text{C}$  the real permittivity values were similar to those for the newly formed sea ice. The dielectric

loss factor was on the order one magnitude smaller than for the newly formed sea ice in [27] though one order of magnitude larger than modelled in [15].

Following the findings in this study, we suggest that a fully automatic detection and discrimination algorithm should first identify low  $\sigma_{HH}$  and  $\sigma_{VV}$  values, and thereafter do an assessment of the  $PD$  and  $\gamma_{co}$  values, similar to the discrimination presented in [32] where two thresholds were set for  $\gamma_{co}$  to separate the thin ice from open water ( $<2.8\text{ dB}$ ) and from thicker sea ice types ( $>1.3\text{ dB}$ ).

#### E. Additive noise

The overall good separability using  $PD$  in the UAVSAR data meant that we select this parameter for further studies regarding the effect of additive noise to the NRCS values. In Figure 8 the K-S test vs. the simulated noise floors are shown for the Beaufort and MC-20 data. The results are comparable for the discrimination between the Beaufort and the OOW2015 data (not shown). The NESZ values for RS-2 multi-polarization data, RS-2 dual-polarimetric data and for S-1 EW are indicated with vertical lines, even-though these sensors are C-band sensors, as they are commonly used for operational ocean surveillance, and the NESZ values for the L-band ALOS-2/PALSAR-2 Stripmap high resolution mode are indicated for the HH-channel. When the simulated additive noise is approximately at the same level as the NESZ for S-1 EW the K-S discrimination is starting to be negatively affected by the additive noise. From this we conclude that significant noise levels can be added to the UAVSAR data before the discrimination between the newly formed sea ice and the oil slick is compromised. To ensure good separability and low false alarm rates in the detection of dark features the NESZ should if possible be below  $-24\text{ dB}$ . The backscatter values for the oil slicks and the newly formed sea ice will be affected by the frequency, and hence the sensitivity to the additive noise should be investigated for the different

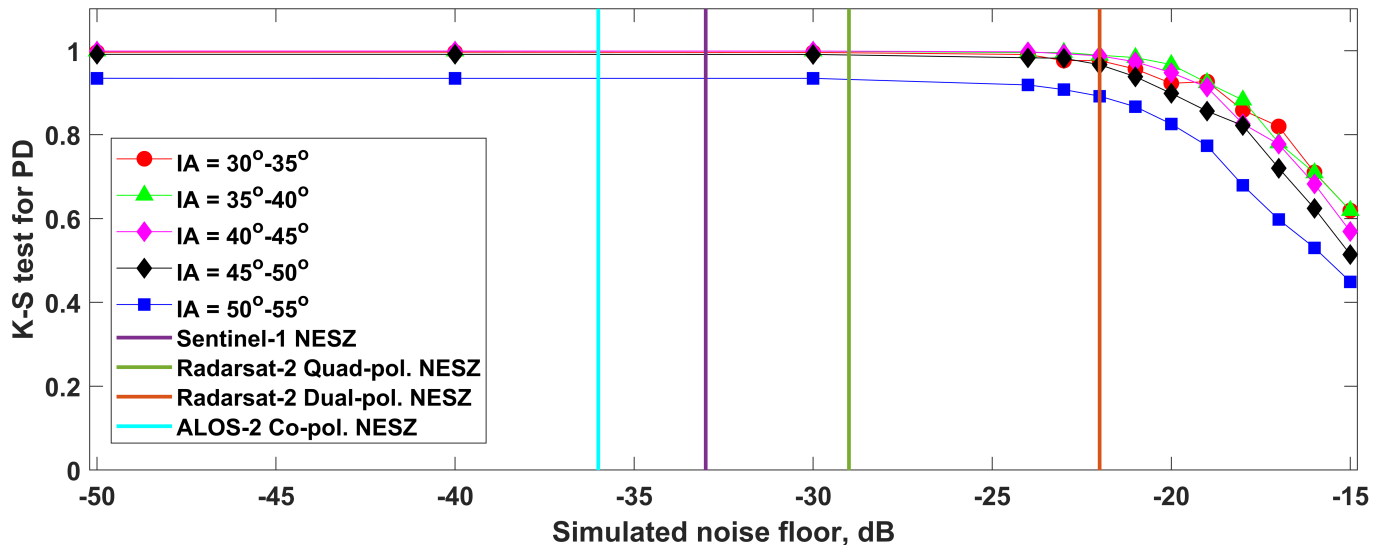


Fig. 8. K-S test for the Beaufort (ice) and MC-20 (oil) backscatter values with additive noise. The different colours represent different IA ranges. The x-axis shows the simulated noise floor levels that are derived from the UAVSAR measurements after Gaussian white noise is added to the measured signal. The original NESZ levels for the multi-polarization and dual-polarimetric RS-2 modes, S-1 EW and ALOS-2/PALSAR-2 Stripmap are indicated with vertical lines.

frequencies, particularly the commonly used C-band. Ideally such an investigation should therefore be carried out using a multi-frequency platform.

In addition to RS-2 and Sentinel-1, other current SAR satellites that are regularly used for ocean and sea ice surveillance include TerraSAR-X (NESZ = -17 dB [66]), ALOS-2 (NESZ for HH and VV = -36 dB, NESZ for HV = -46.0 dB [67]) and RADARSAT Constellation Mission (NESZ = -19 dB to -25 dB). The PALSAR-2 sensor onboard the ALOS-2 satellite has already been shown to have good potential for improved sea ice characteristics [68], [69]. Upcoming missions also include the NASA-ISRO SAR (NISAR) mission that will have sea ice coverage but also the capability to cover oil slicks, and offers both L- and S-band frequencies with NESZ of -25 dB [70].

Comparing the simulated additive noise level with the mean co-polarization backscatter values, shown in Figure 5, we observe that the mean backscatter values for the OOW2015 and MC-20 datasets are between -30 dB and -10 dB, whereas the Beaufort dataset has backscatter values between -18 dB and -33 dB. This seems to indicate that a good discrimination can be achieved as long as one of the two investigated media has backscatter values above the noise floor, whereas when both media have values approaching the noise floor discrimination may be impaired. This is similar to the results for the RS-2 data shown in Figure 7. The required backscatter values to separate low backscatter signatures including oil spills and newly formed sea ice (6-10 dB [19], [22], [33]) will vary in each these systems, depending on the on the NESZ, available polarizations, and incidence angle examined.

#### F. Averaging filter size

The K-S test show a slight improvement for  $PD$  when the smoothing window size increases, though separability between 0.7–0.9 was found for all window sizes. The  $\overline{CV}(PD)$  values

in Figure 9 indicate that the newly formed sea ice values remain similar once the window size is  $5 \times 5$  or larger, whereas the oil slick values are stable regardless of window size. The pixel spacing corresponding to those of the RS-2 dual-polarimetric mode ( $6 \times 6$ ), S-1 EW mode ( $4 \times 4$ ) and ALOS-2 ScanSAR mode ( $5 \times 5$ ) and should therefore enable good separability provided sufficient SNR.

From this we conclude that for discrimination between oil slicks and newly formed sea ice, SNR is the most important parameter, and for our dataset a pixel size similar to the one from S-1 EW did not hamper the discrimination.

## VI. CONCLUSIONS

We observe that  $PD$  can be used to reliably separate the investigated mineral oil slicks and newly formed sea ice using UAVSAR images, though low SNR hampers the separability in the RS-2 images used. The recently launched RADARSAT Constellation Mission (RCM) provides low resolution, high areal coverage acquisitions using both the co-polarization channels as well as a dual polarization option, i.e., HH/HV, VV/VH and HH/VV. Moreover, it has a compact polarimetry SAR mode where the 2nd component of the Stokes vector is similar to  $PD$  assuming reflection symmetry and reciprocity. The HH/VV ScanSAR option might be suitable for large scale discrimination, and the compact polarimetric SAR mode is very promising for the detection and separation case of newly formed sea ice and oil slicks.

The high oil-sea contrast for  $PD$  in both the UAVSAR and RS-2 data indicates that it can be used both to detect oil slicks and separate them from the surroundings. However the lower newly formed sea ice and thicker sea ice contrast may limit the possibility of using  $PD$  both for detection and discrimination of oil slicks and newly formed sea ice.  $PD$  has a high correlation with  $\gamma_{co}$  though the advantages with the reduced imaging geometry dependency and the reduced



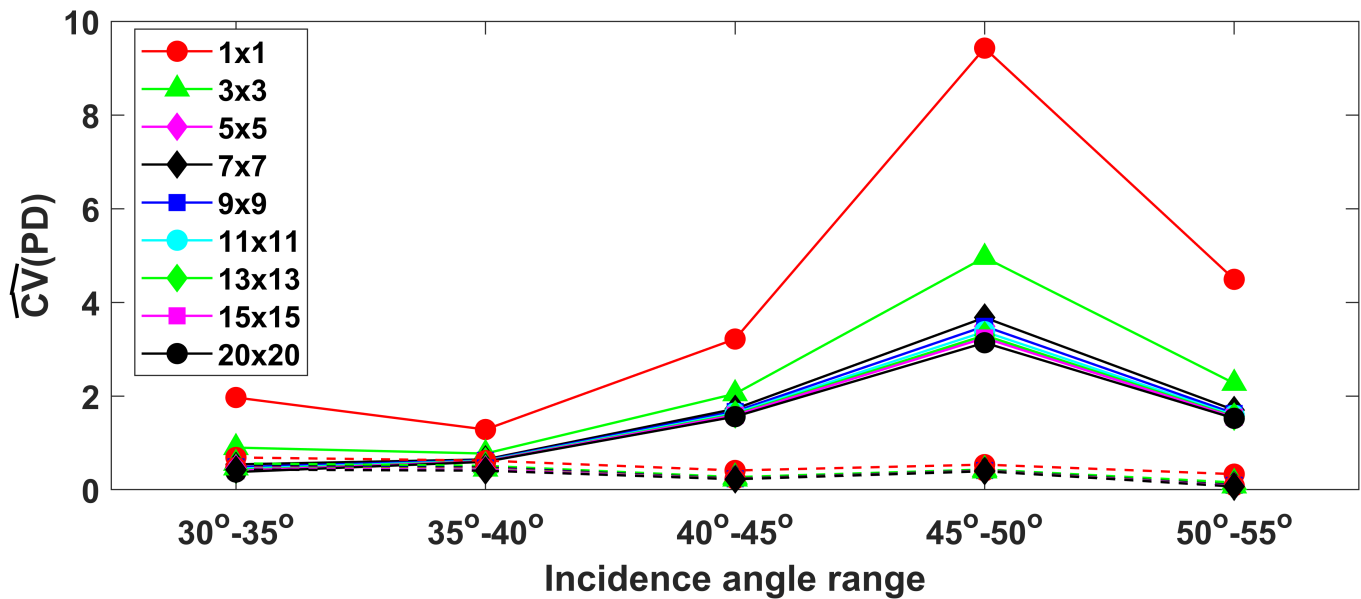


Fig. 9.  $\widehat{C_V}$  values for  $PD$  for newly formed sea ice Beaufort (ice, solid lines) and MC-20 (oil, dashed lines) data with different sized averaging window. The different coloured lines represent different smoothing window size. The x-axis show the different IA ranges.

dependency on additive noise means that  $PD$  is preferable for the discrimination. Simulated noise floors were generated by adding white Gaussian noise to the UAVSAR data, with the results indicating that discrimination between the two low backscatter phenomena was possible until the new noise floor reached  $-24$  dB. The pixel resolution had limited effect on the separability.

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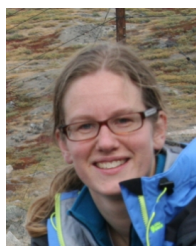
agreement 2011, 2012, 2013 and 2019. UAVSAR data can be downloaded from [uavsar.jpl.nasa.gov](http://uavsar.jpl.nasa.gov) or from the Alaska Satellite Facility ([www.asf.alaska.edu](http://www.asf.alaska.edu)).

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