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Newly-formed sea ice distinction near the oil platform Prirazlomnaya in the Pechora Sea using polarimetric Radarsat-2 SAR observations

Dmitry V. Ivonin[a], Andrey Yu. Ivanov[a], Malin Johansson[b], Camilla Brekke[b]
[a] Shirshov Institute of Oceanology RAS, 36, Nakhimovsky av., Moscow, Russia
[b] UiT The Arctic University of Norway, Tromsø, Norway

Abstract

A polarimetric approach developed to discriminate oil slicks and look-alikes was used to study the polarimetric properties of newly-formed ice (NFI) observed near the Prirazlomnaya oil platform. This approach is based on the multi-polarization parameter called Resonant to Non-resonant signal Damping (RND), which is related to the ratio between the ice damping and the short wind waves and wave breakings. Fully-polarimetric Radarsat-2 images containing NFI were analyzed. The RND parameter indicates that in many cases the damping of the resonant and non-resonant electromagnetic signals in NFI is significantly different from oil slicks and that the RND parameter can distinguish them.

1 Introduction

The Arctic is a dynamically economically developing region in the world, where ship traffic and the oil and gas sites are growing rapidly. The Arctic environment is challenging and synthetic aperture radar (SAR) images are one of the most convenient ways to monitor the state of the sea surface. This is especially true for the conditions of the Arctic with frequent cloud cover and polar night. In the SAR images, the contaminations on the sea surface are displayed as dark features with reduced scattering from the sea surface, due to the suppression of capillary-gravitational ripples and wave breaking [1]. At the same time, other areas of reduced scattering, such as wind shadows, and hydrodynamic smoothing of the surface, etc, are also present in the SAR images. Thinner ice types, such as nilas, grease ice, and newly-formed ice, also form areas with reduced scattering [2], which only a specialist can distinguish from oil pollutions in SAR images. When processing large volumes of SAR images processing for oil pollution segmentation, the problem becomes more challenging, and Barents and Kara Sea are areas with a high degree of grease ice formation [3]. Should an oil spill occur in the Arctic ocean it is therefore important to be able to separate if from newly-formed sea ice.

Recently, a polarimetric method, which is based on the model of the electromagnetic scattering on the sea surface proposed by Kudryavtsev et al. in [6], and tested in [4,5]. The method uses amplitudes of the co-polarization channels (VV and HH) in the SAR images. It was demonstrated in [4,5] that mineral oil slicks could be discriminated from the other type of slicks, such as plant oil (used as a proxy for monomolecular biogenic films), natural oil seeps, and biogenic films, when applied to Radarsat-2 [4] and TerraSAR-X [5] images.

In this work, we test the polarimetric method on Radarsat-2 SAR data collected near the oil platform Prirazlomnaya in the Pechora Sea and that contains newly-formed ice patches.

2 Polarimetric Approach

According to the normalized radar cross section (NRCS) model for scattering from the sea surface [6], the dual co-pol scattering at the incidence angles greater than ~25° (when the Kirchhoff specular reflections from the slopes of long waves can be neglected) consists of two terms: (1) σ_B is the conventional two-scale resonant Bragg scattering from the short gravity-capillary wind waves (i.e., Bragg waves superposed on long waves), (2) σ_n is the non-polarized scattering due to a non-resonant scattering from the rough surface patches caused by wave breaking:

$$\sigma^p = \sigma_B^p + \sigma_n \quad (1)$$

where the subscript p denotes either H (horizontal) or V (vertical) polarization. The Bragg scattering term without taking into account the tilts of long waves is defined as follows

$$\sigma_B^p \approx 4\pi k_r \cos^4\theta \left|g_{pp}(\theta,\varepsilon)\right|^2 W(k_b) \quad (2)$$

where $k_b = 2k_r \sin\theta$ is the Bragg wavenumber, $k_r = 2\pi f_r/c$ is the SAR wavenumber (f_r is the radar frequency and c is the speed of light), θ is the radar incidence gle, $W(k_b)$ is the spectral density of the short gravity-capillary waves evaluated at k_b, and g_{pp} is the reflectivity coefficient [6] depended on θ and the sea water relative dielectric constant ε.

The ratio of σ_B^H to σ_B^V is called the co-polarization ratio P_B for the resonant Bragg scattering:

$$P_B = \sigma_B^H/\sigma_B^V \quad (3)$$

or

$$P_B = |g_{HH}(\theta,\varepsilon)|^2/|g_{VV}(\theta,\varepsilon)|^2. \quad (4)$$

The non-resonant term σ_n is described as the fraction q of the sea surface covered by wave breaking (in generally, expressed through the short wind wave spectrum $W(k_b)$) and some mechanism of specular reflections from wave breakers $\sigma_{0n}(\theta)$ (see full details in [6])

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$$\sigma_n = q \cdot |R(\varepsilon)|^2 \sigma_{0n}(\theta) \quad (5)$$

where R is the Fresnel reflection coefficient at normal incidence.
According to the definition of the NRCS model (1) and (4), the following expressions for the resonant and non-resonant parts of the backscattered signal can be obtained:

$$\sigma_B \approx \frac{\sigma^V - \sigma^H}{1 - P_B}; \ \sigma_n \approx \frac{\sigma^H - P_B \sigma^V}{1 - P_B} \quad (6)$$

Tracking the relative changes $\tilde{\sigma}_B$ and $\tilde{\sigma}_n$ of the Bragg scattering and the non-resonant scattering within the slick (dark areas on SAR images) with respect to clean water

$$\tilde{\sigma}_B = \frac{\sigma_{B,slick}}{\sigma_{B,water}}; \ \tilde{\sigma}_n = \frac{\sigma_{n,slick}}{\sigma_{n,water}} \quad (7)$$

(where subscript indexes refer to the slick and clean water respectively) one can estimate relative damping of the Bragg scatters and the wave breaking scatters within the slick. A ratio of these relative damping's is defined as *RND* (meaning Resonant to Non-resonant signal Damping) parameter [4]

$$RND = \frac{1 - \tilde{\sigma}_n}{1 - \tilde{\sigma}_B} \quad (8)$$

Applications of the *RND* parameter to the separation of mineral oil slicks from plant oil ones using Radarsat-2 and TerraSAR-X co-polarized images is reported in [5,7].

3 The Prirazlomnaya Oil platform

The Prirazlomnaya offshore oil-production platform was built in 2013 specifically for the development of the Prirazlomnoye oil field in the Pechora Sea, the south-east part of the Barents Sea **(Figure 1)**. It is located in the sea 55 km offshore at 69°15′57″ N, 57°17′09″ E. The platform is operated by Gazpromneftshelf (a subsidiary of Gazpromneft). The first batch of ARCO (blend of Arctic oil) was shipped in April 2014. The platform is used for all oil production operations including drilling, extraction, storage, treatment and offloading. As it was designed for the Arctic Region, Prirazlomnaya can be used in extreme weather conditions; it meets the most stringent safety and environment requirements and can withstand the highest ice loads. The Prirazlomnaya platform conducts their drilling operations without releasing polluting drilling waste to the environment. Drilling and production waste is either delivered onshore or, pre-treated before, injected into the seabed and the formation layer[1].
The part of the sea in which the platform is located, freezes every year, and is under the ice for 7-8 months a year. For this region a problem of distinguishing between possible oil spill signatures and signatures of newly-formed ice (or melting ice) on SAR images is extremely relevant.

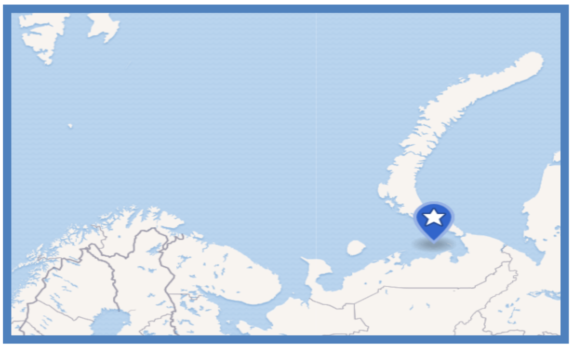

Figure 1 Location of the Prirazlomnoye field in the Pechora Sea.

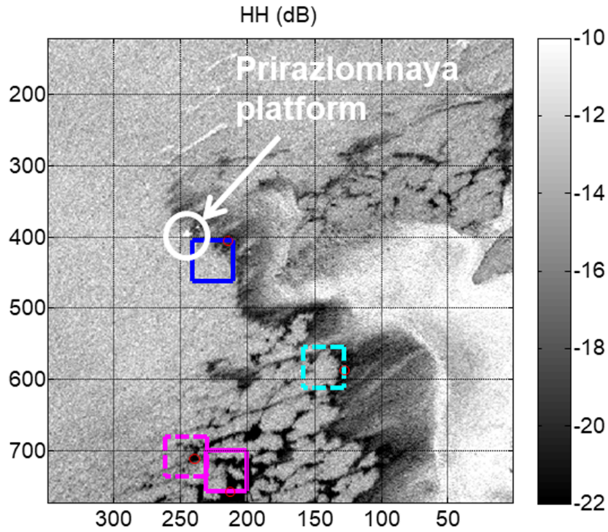

Figure 2 Radarsat-2 HH image 2017, November 28, 02:55 UTC, containing dark features attributed to newly-formed ice. The meaning of different box colours is explained in **Section 4**.

Although, several unknown small oil spills nearby were detected as a result of monitoring using SAR in 2014-2016 [8], direct discharges from the platform (oil, oil products, produced waters, etc.) have not yet been detected and the overall environment situation remains favorable.
Similar to all oil platforms in the Arctic sector, the Prirazlomnaya is an object of high environmental concern and is closely monitored by various environmental and scientific organizations. During a Norwegian-Russian joint project funded by RCN and RFBR in 2018-2019 several Radarsat-2 SAR images in full polarization mode where collected near the Prirazlomnaya platform. Some of them where collected in November and April, at the time of ice formation and melting, and contained dark features, identified by an expert analysist, as newly-formed ice (outlined by square boxes in **Figure 2)**.

[1] https://www.marinetechnologynews.com/blogs/prirazlomnaya-rig-details-e28093-part-2-700440

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4 Radarsat-2 image

The Radarsat-2 C-band (5.4 Gz) image (**Figure 2**) was acquired in the beam mode FQ13 (Fine Quad Polarization). The incidence angles span from 32.44° to 34.08°. The noise level is -35 dB. The NRCS values range between -25 dB and -10 dB, therefore, the noise could negligibly influence the data.

The main gray background (**Figure 2**) at a level of about minus 14 dB (the right and upper parts of the image) containing characteristic wind streaks is formed by scattering from a clean water surface. In the lower right part, there is a relatively bright spot associated with an increased level of scattering [2] from newly-formed ice, such as pancake ice, lite nilas and gray ice (possibly containing so-called frost flowers). Extensive areas of reduced scattering are present in the gaps between water and bright spots of sea ice (outlined by magenta boxes). In the center of the figure, dark areas are observed between areas of open water. Based on the analysis of similar SAR images observed in the Arctic, it seems most likely that the dark areas in such images are due to low radio signal scattering features of grease ice and dark nilas [2], which have not yet transitioned to older first-year ice. The Prirazlomnaya oil platform is located at the junction between clear water and dark spots of grease ice and dark nilas (outlined by a blue boxe), which, in principle, can be interpreted as possible discharges of oil and waste waters. A transitional zone from water with grease ice or dark nilas to lite nilas or gray ice with an increased level of scattering is outlined by a cyan box.

5 Results

According to the technique described in [4,5], four areas with the dimensions of 2200 × 2200 m^2 (outlined by cyan, magenta and blue boxes in **Figure 2**) were selected, containing both clean water and dark slicks. As a result, it was possible to estimate the relative changes $\tilde{\sigma}_B$ and $\tilde{\sigma}_n$ of the Bragg scattering and the non-resonant scattering within the slick using equation (7), compute corresponding RND distributions for these three areas (see **Figure 3**).

Two of these RND distributions (magenta lines) are obtained for dark features located between the clean open water areas (see **Figure 2**). They show similar behavior with RND centered around 1.1 RND units. The cyan RND distribution taken for the marginal ice zone between clean water and thicker sea ice (most likely, lite nilas or gray ice) is centered around 0.93 units. The blue RND distribution taken in the vicinity of the Prirazlomnaya platform shows more scattered RND values centered around 1.1 RND units. It is seen that it is some kind of mixture of the magenta and cyan RND distributions.

A comparison of the RND_{mean} values for newly-formed ice near the Prirazlomnaya oil platform and the RND_{mean} values reported in [7] for plant and mineral oil spills observed during the NOFO (the Norwegian Clean Seas Association for Operating Companies) oil-in-water exercises in 2011 and 2012 [9,10] is presented in **Figure 4**. The symbols show the RND_{mean} and the RND_{std} (the standard deviation of RND calculated from the RND distributions). The mineral oil zone boundaries $RND_{E,up}$ and $RND_{E,low}$ defined in [6] as

$$\begin{aligned} RND_{E,up} &= 1.130 - 1.27 \cdot 10^{-3} \cdot k_b \\ RND_{E,low} &= 0.994 - 1.27 \cdot 10^{-3} \cdot k_b \end{aligned} \quad (9)$$

are shown in **Figure 4**. Here $k_b = 2k_r \sin\theta$ is the Bragg wave number, $k_r = 2\pi f_r / c$, where θ is the incidence angle, f_r is the sensor frequency, and c is the light speed.

RND values greater than 1 differ strongly in terms of the polarimetric decomposition (6)-(8) from mineral oils and plant oil. The plant and mineral oil have mean RND values below 1 RND unit [4].

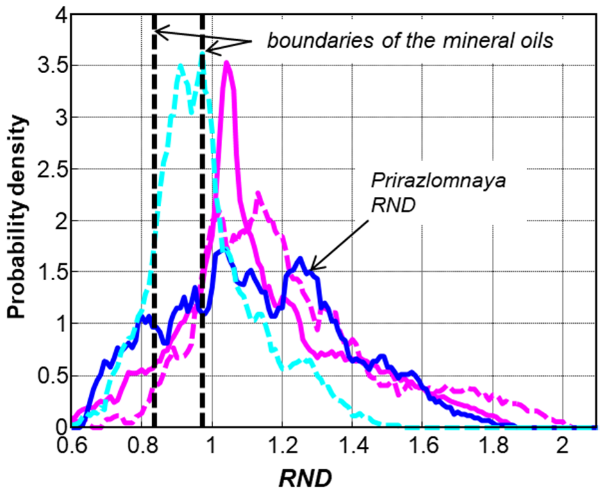

Figure 3 RND distributions for dark features (outlined by squares with corresponding line style and color) in **Figure 2**

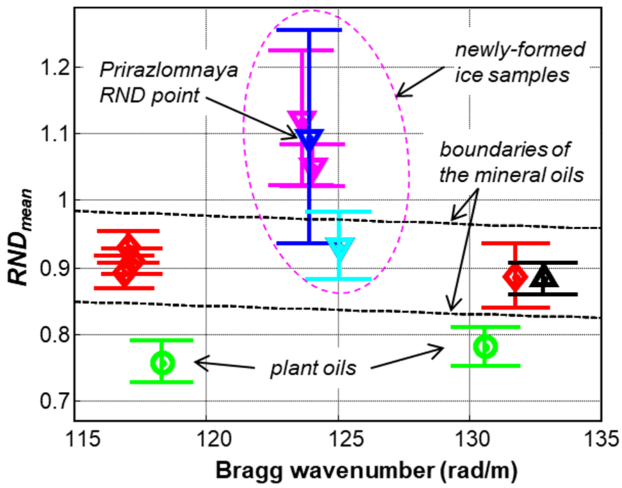

Figure 4 Slick RND_{mean} and RND_{std} (error bar) vs. the Bragg wave number for newly-formed ice and oil spills visible on Radarsat-2 images.

Therefore, a newly-formed ice within the magenta boxes in **Figure 2** (which are most likely grease ice) discriminate well in terms of RND_{std} from the mineral oil slicks (red and black symbols) and plant oil spills (green symbols).

Nevertheless, the transitional zone from water with grease ice or dark nilas to lite nilas or gray ice outlined by the cyan box in **Figure 2**, according to the diagram in **Figure 4,** can be attributed to the type of mineral oils. As it was previously mentioned, a newly-formed ice, outlined in the vicinity of the Prirazlomnaya platform by the blue box, is manifested as some kind of mixture of various newly-formed ice types (probably, grease ice, dark nilas, and lite nilas). Therefore, it appears as a scattered RND distribution with a small part of it lying in the mineral oil zone.

Summarizing, one concludes that the newly-formed ice has complicated behavior with very similar polarization signatures to mineral oil slicks. Though despite this for many cases the RND parameter can successfully separate the newly-formed sea ice areas from the mineral oil slicks.

6 Conclusion

The polarimetic approach developed by authors in previous work [4,5] for mineral and plant oil slicks discrimination was tested for separation of newly-formed ice observed near the oil platform Prirazlomnaya during the remote sensing monitoring of the Prirazlomnoye oil field in 2018-2019. For this, fully polarized Radarsat-2 images were utilized.

The polarimetric approach is based on the model of the electromagnetic scattering on the sea surface developed by Kudryavtsev et al. in [6], which includes as the conventional two-scale resonant Bragg scattering from the short gravity-capillary wind waves, as well as the non-resonant scattering from the rough surface patches caused by wave breaking. The polarimetric approach uses a parameter called RND (ratio of Resonant to Nonresonant signal Damping), which is related to the ratio between the damping within the slick of the short capillary-gravity waves and damping of wave breakings. Different types of slicks dampen these parts of the signals in different proportions and, therefore the RND ratio, in general, is different for different slick types.

The comparison of RND values for newly-formed ice near the Prirazlomnaya oil platform and RND values obtained in previous works for mineral oils and plant oil controlled spills performed during the NOFO oil-in-water exercises in 2011 and 2012 proves that the RND parameter can in some cases (we suppose mostly grease ice cases) separate newly-formed sea ice from mineral oil and plant oil slicks. Nevertheless, sometimes the newly-formed ice areas (we suppose transitional zones from water with dark nilas to lite nilas or gray ice) have very similar polarization signatures to mineral oil slicks and could not be separated from them in terms of the proposed technique. A possible reason for this may be due to differences of the background scattering models for oil in water and various types of newly-formed ice (grease ice, dark nilas, and lite nilas).

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