OIL SPILL CHARACTERIZATION WITH MULTI-POLARIZATION C- AND X-BAND SAR

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ABSTRACT

Single-polarization (VV or HH) C-band synthetic aperture radar (SAR) sensors have conventionally been utilized in remote sensing of marine oil pollution. This paper examines the capability of combining the complex VV and HH channels in C-band and X-band SAR for oil spill characterization and for discrimination between mineral oil spills and biogenic slicks. The two frequency bands are evaluated from a theoretical point of view and subsequently experimentally compared using a truly unique data set, consisting of quasi-simultaneous Radarsat-2 and TerraSAR-X data acquired during the June 2011 oil-on-water exercise in the North Sea. Multi-polarization features for the two frequencies are compared based on classification results. A potential for discriminating biogenic films from mineral oil slicks is found. The analysis shows that some slicks have internal zones that correlate well with expected thickness variations.

Index Terms—SAR, oil spill, characterization

1. INTRODUCTION

Over the last decades, satellite borne C-band SAR sensors have been the backbone in operational oil spill detection and monitoring services. Recently, several new SAR satellites operating in X-band are emerging, e.g. TerraSAR-X and Cosmo-SkyMed. Due to less operational experience and research on X-band SAR for oil spill monitoring, more knowledge on the capability and performance of X-band versus C-band for oil spill purposes is still needed.

In this paper, we address this issue through a large scale oil-on-water exercise conducted in Norwegian waters in June 2011 by the Norwegian Clean Seas Association for Operating Companies (NOFO). In this exercise, a unique data set was obtained, including one quad-polarimetric Radarsat-2 and one dual-polarization TerraSAR-X scene, acquired only 16 minutes apart. Both images contain the same three slicks with different chemical properties; crude oil, plant oil, and oil emulsion. Here, we compare the C- and X-band SAR data both with respect to (i) theoretical potential for oil spill detection and characterization, and (ii) in terms of an experimental investigation of the information content in multi-polarization features extracted from the two different quasi-simultaneous sensor acquisitions. A K-means classification is applied to the features, and the characterization potential and power to discriminate between biogenic and mineral oil films is investigated. The analysis shows a potential for discrimination, and within-slick zones are revealed, correlating very well with expected thickness variations.

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2. THEORETICAL POTENTIAL OF C- AND X-BAND SAR SENSORS

An oil spill on the sea surface will dampen the waves and hence reduce the surface roughness. The oil covered areas will show up as dark spots in the SAR image due to the reduced backscatter level. Many parameters influence the capability of a satellite borne SAR sensor to detect oil spills. Oil properties and environmental conditions are important, but also the sensor properties, i.e. frequency, polarization, resolution, sensor noise floor, incidence angle etc. We are here interested in the potential of C-band (~ 5 cm) and X-band (~ 3 cm) SAR with respect to:

- detection of slicks (including monomolecular biogenic films and hydrophobic hydrocarbon slicks)
- characterization of slick properties
- discrimination between different types of slicks

One challenge in oil spill monitoring by SAR is that other phenomena, e.g. natural biogenic slicks, have similar appearance in the images. Mineral oils and biogenic slicks form two different types of films on the sea surface. Biogenic slicks produce a very thin film, only one molecule thick (~ 2.4-2.7 nm), a so-called monomolecular film. Mineral oil spills on the other hand, produce films with thicknesses orders of magnitudes larger than the monomolecular films (µm -mm, in some cases cm) [2]. The two slick types will have different viscoelastic properties, and induce different damping on the ocean waves. Discrimination between mineral oil films and...
biogenic slicks is highly desirable, and this is experimentally investigated for real SAR measurements in section 3.

It is generally accepted that the dominating mechanism for generating ocean backscatter is a type of Bragg resonance. The Bragg wavelength of ocean waves resulting in resonance depends on the radar wavelength, the incidence angle $\theta$, and the angle $\phi$ between the radar look direction and the direction of wave propagation. The relationship is illustrated in Fig. 1 for the radar wavelengths of Radarsat-2 and TerraSAR-X. The Bragg resonance waves of TerraSAR-X and Radarsat-2 are of wavelengths $\sim 2 - 5 \text{ cm}$ and $\sim 3 - 9 \text{ cm}$ ($\phi = 90^\circ$) depending on $\theta$. Since the damping of the Bragg resonant waves is expected to be more efficient at shorter wavelengths, radars of higher frequencies may be more efficient for oil spill detection than radars with longer wavelengths [3]. However, other factors may counterbalance this advantage of the higher frequencies. Very heavy rain can attenuate the signals of high frequency SAR sensors, producing artifacts in the images. This is a larger problem at X-band than at C-band.

The noise equivalent sigma zero (NESZ), which is the background noise in the SAR system, is another important factor affecting oil spill characterization. The NESZ must be lower than the measured normalized radar cross section (NRCS) to make sure that the signal is not corrupted by noise. The NESZ of TerraSAR-X lies between -19 dB and -26 dB, depending on the incidence angle, with an average of -21 dB [1]. Radarsat-2 shows large variations in NESZ between the modes. For dual-polarization modes, NESZ vary from -22 dB to -31 dB, while quad-polarization modes have NESZ values in the range -27.5 dB to -43 dB [6]. As oil slicks have very low backscatter, the noise floor, especially for TerraSAR-X, may limit the detection and characterization ability.

The accuracy of damping ratios is determined from the relative radiometric accuracy of the SAR data [3]. For TerraSAR-X dual-pol Stripmap products, the relative radiometric accuracy (i.e. the standard deviation of the radiometric error of known targets within one data take, i.e. over range and within 220 sec. [1],) is 0.3 dB. This implies that oil spill detection is possible even for low-density oil and low wind conditions. Slight spatial variations in damping ratios, possibly related to slick properties such as density and thickness variations, could be observed [3].

3. EXPERIMENTAL RESULTS

Oil spill detection has conventionally been performed on single channel co-polarization multi-look intensity or amplitude SAR imagery. In this study, Radarsat-2 and TerraSAR-X single-look complex data containing oil spills are evaluated through the investigation of multi-polarization features. Only co-polarization channels are used in the analysis.

3.1. Data set

From 6-9 June 2011, NOFO conducted their annual oil-on-water exercise in the North Sea. During the controlled discharges of oil at sea for the purpose of equipment and procedure testing, three different slicks, i.e. oil emulsion, crude oil and plant oil, were formed and imaged by SAR. One quad-polarization Radarsat-2 scene and one dual-polarization ($S_{HH}$, $S_{VV}$) TerraSAR-X scene were acquired with a temporal difference of only $\sim 16$ minutes. Both scenes contain all three slicks. Properties of the images are given in Table 1. Wind speeds of $\sim 1-3 \text{ m/s}$ were measured in conjunction with the acquisitions. Intensity images are seen in Fig. 2.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>TerraSAR-X</th>
<th>Radarsat-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>08.06.2011</td>
<td>08.06.2011</td>
</tr>
<tr>
<td>Time</td>
<td>17:11</td>
<td>17:27</td>
</tr>
<tr>
<td>Frequency</td>
<td>9.65 GHz (X-band)</td>
<td>5.41 GHz (C-band)</td>
</tr>
<tr>
<td>Mode</td>
<td>Stripmap</td>
<td>Fine Quad</td>
</tr>
<tr>
<td>Polarization</td>
<td>HH, VV</td>
<td>Quad</td>
</tr>
<tr>
<td>Incidence angle</td>
<td>19.9° - 21.7°</td>
<td>34.5° - 36.1°</td>
</tr>
<tr>
<td>Resonant wavelength (cm) ($\phi = 90^\circ$)</td>
<td>4.2 - 4.5</td>
<td>4.7 - 4.9</td>
</tr>
<tr>
<td>Resolution (Rg x Az) [m]</td>
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<td>3.2 x 7.6</td>
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<tr>
<td>Pixel spacing (Rg x Az) [m]</td>
<td>0.9 x 2.4</td>
<td>4.7 x 4.8</td>
</tr>
</tbody>
</table>

* nominal value for Fine-Quad mode [6]

(a) X-band (b) C-band

Fig. 1: Bragg wavelength of sea waves in resonance with X-band and C-band radar wavelength, as function of angles $\theta$ and $\phi$ (in degrees).

Fig. 2: Intensity images in VV polarization.

(a) Radarsat-2 scene. RADARSAT-2 Data and Products ©MDA LTD. (2011) - All Rights Reserved.
(b) TerraSAR-X scene. Copyright ©2011 DLR.
oil, released ∼ 13 hours before image acquisitions, and untouched after discharge. In the middle are remains of the emulsion released ∼ 29 hours before image acquisitions. Most of this spill was recovered mechanically after release, but the remains are clearly visible. To the right is the crude oil, released ∼ 9 hours before the satellite passes. Dispersion of the slick is going on at the time of image acquisitions.

3.2. Polarimetric properties

Three multi-polarization features are extracted from the scenes in Fig. 2, including covariance scaling factor, μ, standard deviation of the co-polarized phase difference, σ_{eCO} [4] [7], and the real part of the correlation between S_{HH} and S_{VV}, r_{CO} [5]:

\[
\sigma_{eCO} = \sqrt{\langle (\phi_{HH} - \phi_{VV})^2 \rangle - \langle \phi_{HH} - \phi_{VV} \rangle^2}, \quad (1)
\]

\[
\mu = (\det(C))^{1/d}, \quad (2)
\]

\[
r_{CO} = \Re(\langle S_{HH} S_{VV} \rangle), \quad (3)
\]

where \( \phi_{HH} \) and \( \phi_{VV} \) are the phases of the co-polarization measurements \( S_{HH} \) and \( S_{VV} \), \( C \) is the covariance matrix with dimension \( d \times d \) (with \( d = 2 \) in this case), \( \Re \) is the real part, * is the complex conjugate, and \( \langle \cdot \rangle \) denotes ensemble averaging. A neighborhood of \( 9 \times 9 \) pixels is used in all computations. \( \sigma_{eCO} \) and \( r_{CO} \) have previously been found useful for slick detection and discrimination [4] [5] [7]. Fig. 3 shows the three features extracted from the scenes. Visual inspection of the features in Fig. 3 show variations, both between different regions within the slicks and also between the three different oil types. The oil covered areas have lower \( \mu \) than the sea, due to the reduced surface roughness. The differences between slick-free and slick-covered areas in \( r_{CO} \) and \( \sigma_{eCO} \) reflect the reduced correlation between the two co-polarization channels when an oil spill is present [4] [5]. The most pronounced differences between the plant oil and the two mineral slicks seem to appear in \( \sigma_{eCO} \) and \( r_{CO} \) for Radarsat-2 (Fig. 3(c) and 3(e)). \( \mu \) distinguishes all three slicks very well from the ocean background (Fig. 3(a)). To further investigate the potential of slick type discrimination, a classification is performed, based on these three features.

3.3. K-means classification

Initial classification is done using standard K-means method. Classifications into 3 and 4 classes, using all three multi-polarization features are presented in Fig. 4.

The Radarsat-2 classifications (Fig. 4(a) and 4(c)) show that most of the crude oil and emulsion is classified as red with a green zone along the edges, while most of the plant oil is green, with some internal red areas. Also for the TerraSAR-X classification (Fig. 4(b) and 4(d)), the two mineral oil slicks are dominated by the same class (red), however, the discrimination of these from the plant oil is not as apparent as for Radarsat-2. As the emulsion have been on the surface for the longest amount of time, it is interesting to see that it’s properties are more similar to the crude oil than to the plant oil. This may indicate that the differences we see are related to the type of slick (mineral vs biogenic) and the properties they have, e.g. monomolecular vs thicker layer etc..

Further investigation of the characterization abilities are performed on the Radarsat-2 scene, as this looks the most promising. For the Radarsat-2 co-polarization channels, the signal lies above the system noise floor for both oil and water, hence enabling an investigation of the information content of the oil slick measurement. Various K-means classifications are performed on the segmented slicks. The classifications into 2, 3 and 4 classes are seen in Fig. 5. It is interesting to see the zones that appear around the edge of the crude oil and oil emulsion. For the 2-class image we see one edge zone (green), while the 3-class image produces two zones (green and blue). The 4-class image exhibit an inwards change between 4 different classes. For all cases studied, the outmost zones of the mineral slicks correspond to the classes present in the plant oil slick. The zones could be related to slick thick-
ness, which is expected to be low for the plant oil and to decrease towards the edges of the mineral oils.

4. CONCLUSION

A comparison of C- and X-band SAR for oil spill characterization and discrimination is performed. The Bragg wave damping in X-band may theoretically provide a larger slick-to-sea contrast, however this is not evident in our data set. The noise floor of TerraSAR-X is higher than for Radarsat-2, which may give the latter an advantage in oil spill applications. Experimental data from the oil-on-water exercise in June 2011, including quasi-simultaneous multi-frequency data, are investigated. Three different features, all combinations of the two co-polarization channels, are compared. Variations in the features are seen, both within the individual slicks, and between the different types of oil. These findings are especially pronounced in the Radarsat-2 data. A classification is performed on the feature set, and a potential in discriminating between biogenic and mineral oils is found for Radarsat-2. The classification results also reveal slick zones correlating very well with expected thickness variations. The preliminary results of the analysis indicate that multi-polarization C-band might possess a larger potential for slick characterization and discrimination than X-band.

5. REFERENCES