An Experimental Study on Oil Spill Characterization by Multi-Polarization SAR

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Abstract

During the Norwegian oil-on-water exercise in June 2011, a unique and comprehensive data set was acquired, containing multi-sensor data of oil slicks on the sea surface and corresponding ground truth information. The data set includes multi-polarization SAR data from Radarsat-2 and TerraSAR-X, acquired under calm to moderate sea and wind conditions. Two of the scenes each contain slicks from three different oil types, i.e. plant oil, crude oil and oil emulsion. Several polarimetric quantities are extracted from the multi-channel SAR data set, and many of the studied features show good detection performance. Some internal variations in the power of the features within the individual slicks and between the various types of oil are seen. These variations indicate that some of the features, alone or in combination with others, may allow discrimination between the different types of slicks, and hence confirm the added value of utilizing multi-polarization measurements in oil spill monitoring.

1 Introduction

Oil spills, both deliberate discharges and accidents, are an important environmental problem. Remote sensing methods have become valuable tools for oil spill detection and monitoring, with Synthetic Aperture Radar (SAR) being the most efficient satellite sensor. Over the last years, more advanced commercial SAR sensors have become available, providing us with dual-and quad-polarization data which yield more information than single-channel SAR data.

Studies done over the last years have found multi-polarization SAR data useful for oil spill monitoring. The polarimetric features entropy ($H$) and mean scattering angle ($\alpha$), have been evaluated for oil spill detection in e.g. Migliaccio et al. [2]. In [2], the entropy was found to be the most useful quantity, and the authors found that $H$ could distinguish the oil-free sea surface from oil-covered areas, and in some cases biogenic slicks could be distinguished from anthropogenic film. In [3], the co-polarized phase difference (CPD) was investigated with respect to oil spill detection and ability to discriminate between oil spills and look-alikes. It was found that for C-band data under low to moderate wind conditions, the standard deviation of the CPD would emphasize oil slicks, while biogenic look-alikes were de-emphasized. In [4], the CPD feature was found to be useful also for X-band data.

The objective of this paper is to further investigate the potential of polarimetric features (see section 2) with respect to their ability to detect and characterize oil slicks on the ocean surface. During the annual Norwegian oil-on-water exercise, which took place at the Frigg natural gas field in the North Sea in the beginning of June 2011, a truly unique data set, consisting of quad-polarimetric Radarsat-2 imagery and dual-polarization TerraSAR-X imagery, was acquired. Three different types of oil were released into the sea, i.e. oil emulsion (50/50 mixture of oil and water), crude oil and plant oil. Two of the multi-channel SAR acquisitions, one polarimetric C-band image and one dual-polarization X-band acquisition, recorded only few minutes apart, captured all three oil releases within the same scene. In addition to these SAR images, data from other satellites, including COSMO Skymed, Envisat and Aqua (Modis data) was obtained, together with ground truth information.

The paper presents early results from this investigation. It is organized as follows: section 2 gives a brief introduction to SAR polarimetry and oil spill characterization by multi-polarization SAR, including the methods used in this paper. The experimental setup and the data acquired are described in section 3, while section 4 shows some preliminary results. Section 5 concludes the paper.

2 Multi-polarization features

The full scattering matrix is given as

$$ S = \begin{bmatrix} |S_{HH}|e^{i\phi_{HH}} & |S_{HV}|e^{i\phi_{HV}} \\ |S_{VH}|e^{i\phi_{VH}} & |S_{VV}|e^{i\phi_{VV}} \end{bmatrix} $$

(1)

where the matrix elements represent the measured complex scattering coefficients, and the first and second subindices refer to the polarization of the sent and received signal respectively, where H denotes horizon-
tal and V vertical polarization. From S, the Lexicographic scattering vector, \(1 = [S_{HH} S_{HV} S_{VH} S_{VV}]^T\) (for quad-polarization), \(1 = [S_{HH} S_{VV}]^T\) (for dual-polarization) and the Pauli scattering vector \(k = \frac{1}{2} (S_{HH} + S_{VV} S_{HH} - S_{VH} 2S_{HV})^T\) can be extracted. The \(d \times d\) covariance matrix \(C_d\), and the \(3 \times 3\) polarimetric coherency matrix \(T_3\) is produced from \(I\) and \(k\) respectively:

\[
C_d = \frac{1}{L} \sum_{i=1}^{L} I_i I_i^T \quad (2)
\]

\[
T_3 = \frac{1}{L} \sum_{i=1}^{L} k_i k_i^T \quad (3)
\]

where \(d = 2\) or \(4\) for dual- and quad-polarization respectively, \(I_i\) and \(k_i\) are SLC measurements, \(L\) is the number of samples and \(*\) is the complex conjugate transpose. \(T_3\) can also be written as \(T_3 = U \Lambda U^{-1}\), where \(\Lambda\) is a \(3 \times 3\) diagonal matrix whose elements, \(\lambda_1, \lambda_2\) and \(\lambda_3\), are the real non-negative eigenvalues of \(T_3\) and \(U = [e_1 e_2 e_3]\) is a \(3 \times 3\) unitary matrix in which \(e_n\) are the eigenvectors of \(T_3\) given in [1]. The features investigated in this study are given in Table 1.

### Table 1: Multi-polarization features.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entropy</td>
<td>(H = -\sum_{i=1}^{d} p_n \log_2 p_n)</td>
</tr>
<tr>
<td>Mean scattering angle</td>
<td>(\alpha = p_1 \alpha_1 + p_2 \alpha_2 + p_3 \alpha_3)</td>
</tr>
<tr>
<td>Std of CPD</td>
<td>(\sigma_{\phi} = std(\phi_{HH} - \phi_{VV}))</td>
</tr>
<tr>
<td>Mean radar backscatter</td>
<td>(\mu = \langle \delta(\mathbf{C}) \rangle)</td>
</tr>
<tr>
<td>Cross-polarization ratio</td>
<td>(r_x = \frac{\langle S_{HH} \rangle \langle S_{VV} \rangle - \langle S_{HV} \rangle \langle S_{VH} \rangle}{\sqrt{\langle S_{HH} \rangle} \sqrt{\langle S_{VV} \rangle}})</td>
</tr>
<tr>
<td>Co-polarization ratio</td>
<td>(r_c = \frac{\langle S_{HH} \rangle \langle S_{VV} \rangle + \langle S_{HV} \rangle \langle S_{VH} \rangle}{\sqrt{\langle S_{HH} \rangle} \sqrt{\langle S_{VV} \rangle}})</td>
</tr>
<tr>
<td>Correlation magnitude</td>
<td>(\rho_m = \max \left(\frac{\langle S_{HH} \rangle \langle S_{VV} \rangle - \langle S_{HV} \rangle \langle S_{VH} \rangle}{\sqrt{\langle S_{HH} \rangle} \sqrt{\langle S_{VV} \rangle}}\right))</td>
</tr>
</tbody>
</table>

In Table 1, \(std\) denotes standard deviation, \(det(\cdot)\) is the matrix determinant, \(d\) is the dimension of the complex scattering vector and \(p_n = \lambda_n / (\lambda_1 + \lambda_2 + \lambda_3)\).

## 3 Experimental setup and data acquisitions

From 6-9 June 2011, the Norwegian Clean Seas Association for Operating Companies (NOFO) conducted their annual oil-on-water exercise in the North Sea. The controlled discharges of oil at sea for the purpose of equipment and procedure testing provided a unique opportunity to acquire satellite images of oil spills with corresponding ground truth information such as oil type, volume of the oil releases and weather conditions known. Data were collected from several sensors during the exercise. In this paper we limit our discussion to the SAR data acquired by Radarsat-2 and TerraSAR-X, operating in the C-band and X-band respectively. Three different slicks, i.e. oil emulsion, crude oil and plant oil were imaged during the exercise. A summary of the data set is given in Table 2.

### Table 2: Properties of the SAR scenes. The letters following "Spills" indicate which of the emulsion (E), plant oil (P) and crude oil (C) are visible in the relevant scene. Under "Mode", FQ denotes Fine Quad-polarimetric, SC denotes ScanSAR and SM Stripmap. Weather observations were made at the platform Heimdal.

<table>
<thead>
<tr>
<th>Image</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>07.06</td>
<td>08.06</td>
<td>08.06</td>
<td>08.06</td>
<td>08.06</td>
</tr>
<tr>
<td>Time</td>
<td>17.28</td>
<td>05.38</td>
<td>06.23</td>
<td>17.11</td>
<td>17.27</td>
</tr>
<tr>
<td>Sensor</td>
<td>FSX</td>
<td>KS2</td>
<td>FSX</td>
<td>TSX</td>
<td>TSX</td>
</tr>
<tr>
<td>Mode</td>
<td>SC</td>
<td>FQ</td>
<td>SM</td>
<td>SM</td>
<td>FQ</td>
</tr>
<tr>
<td>Polarization</td>
<td>VV</td>
<td>Quad</td>
<td>HH, VV</td>
<td>HH, VV</td>
<td>Quad</td>
</tr>
<tr>
<td>Spills</td>
<td>E*</td>
<td>E</td>
<td>P</td>
<td>E</td>
<td>E, C</td>
</tr>
<tr>
<td>Wind speed</td>
<td>2 m/s</td>
<td>6 m/s</td>
<td>6 m/s</td>
<td>1-3 m/s</td>
<td>1-3 m/s</td>
</tr>
<tr>
<td>Wave height</td>
<td>0.5 - 1 m</td>
<td>1 m</td>
<td>1 m</td>
<td>1.5 m</td>
<td>1.5 m</td>
</tr>
</tbody>
</table>
* to be confirmed

![Figure 1: Intensity images in VV polarization containing all three slicks.](image)

Image # 4 and # 5, which are X-band dual-polarization and C-band quad-polarimetric scenes respectively, contain all three slicks, facilitating both multi-polarization and multi-
frequency analysis. The temporal distance between the two acquisitions is \( \sim 16 \) minutes. Intensity images are seen in Figure 1. Furthest to the left is the plant oil, released \( \sim 13 \) hours before image acquisition, and untouched after discharge. In the middle are remains of the emulsion released \( \sim 29 \) hours before image acquisition. Most of this spill was recovered mechanically after release, but the remains are clearly visible. To the right is the crude oil, released \( \sim 9 \) hours before the satellite pass. Dispersion of the slick are going on at the time of image acquisition. The slicks are clearly visible, despite the low wind speed of 1-3 m/s (see Table 2).

![Image](image1.png)

**Figure 1:** The locations of the oil slicks at the time of image acquisition.

### 4 Results and discussion

In this section, a preliminary analysis of multi-polarization features calculated based on Image # 4 and Image # 5 is given. The features discussed in section 2 are calculated for one or both of the images, depending on the polarimetric information required. The most interesting results are shown in Figure 2 and Figure 3. A sliding window of size \( 9 \times 9 \) pixels are used in the calculations of the features, and the \( \mu, r_x \) and \( r_c \) have been log transformed for visualization purposes.

![Image](image2.png)

**Figure 2:** Multi-polarization features calculated based on C-band data (Image # 5 in Table 2).

By visually inspecting the features presented in Figure 2 and 3, we get an impression of enhancement variations between the three different oil slicks. Particular regions within individual slicks are also more pronounced than other regions of the same slick. However, a more in-depth statistical analysis, also taking into account weather, chemical and sensor characteristics information, is needed and will be pursued in further work.

In Cloude and Pottier [5], the \( H-\alpha \) space, representing all random scattering mechanisms, is described. A \( H-\alpha \)-plot for selected regions within the slicks and an ocean area in Image # 5 is seen in Figure 2(h). We see that the ocean, plant oil and crude oil regions lie next to each other, with a little overlap. The emulsion pixels overlap with crude and plant oil. The zones of different scattering mechanisms given in [5] are indicated in Figure 2(h), and it is seen that water and plant oil mainly lie in Z9: Low Entropy Surface Scatter, while crude oil and emulsion are found in Z6: Medium Entropy Surface Scatter, and Z5: Medium Entropy Vegetation Scattering. The different age of the slicks, different chemical properties and thickness variations are possible reasons for the different distributions in...
the H-α-space.

As the oil slicks are low backscatter areas, a signal to system noise analysis is performed where the backscatter level is compared to the noise floor, \( \sigma_{NE} \). In Figure 4, the mean and standard deviation of selected regions within the slicks in Image # 4 and Image # 5 are shown together with the noise floor of the respective scene as function of incidence angle. Each bar represents the results based on a box of 50 \( \times \) 50 samples within the region of interest.

The results presented in Figure 4 reveal that the co-polarization signal in both scenes lie mostly above the noise floor. Only the bar for the crude oil measurements are seen to slightly cross the noise floor. The cross-polarization signal for Image # 5 show fluctuations about the noise floor, hence some of the information content in this channel is hidden below the noise floor, making it less useful for oil slick characterization purposes than the co-polarization signal.

## 5 Conclusions and further work

A preliminary analysis of a unique data set composed of multi-polarization and multi-frequency SAR scenes is presented. An evaluation of the data with respect to improved detection and characterization of three oil slicks with different chemical properties have been initiated. Multipolarization features calculated for two of the scenes show interesting variations within the individual slicks and between the different oil types. These variations indicate that discrimination between the different types of slicks may be possible. A signal-to-noise analysis indicates that the co-polarization signal are in most cases not affected by the noise floor. The co-polarization channels are more reliable for oil spill characterization than cross-polarization channels for which the signal is often hidden below the noise floor.

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### References


