Oil spill detection and classification in hybrid-polarimetric SAR images

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Earth observation research activities at Norwegian Computing Center

Monitoring of **cryosphere** (snow cover, snow-water equivalent, snow properties, sea ice, avalanches, …)

**Object detection** (vehicles, cultural heritages, seals, …)

Monitoring of **vegetation** (tropical forests, mountain vegetation, nature types, forest health, …)

Automatic **oil spill** detection, characterization, multi-sensor approaches. Collaboration with KSAT.
The primary scattering mechanism for SAR imaging of ocean waves with ripples (capillary waves) is Bragg resonance.

The *normalized radar cross section* is proportional to the spectral energy density of the sea waves having wavelength $\lambda_s$ and obeying the Bragg resonance condition:

$$\lambda_s = \frac{\lambda_r}{2 \sin \theta}$$

The backscatter intensity increases with increasing wind speed.
Oil spills appear as dark spots in the SAR image since oil dampens the ripples.
The challenge is that several conditions result in dark slicks

- Low wind
- Biogenic materials
- Wave wakes
Polarimetric SAR provides improved analysis

- It has been demonstrated that the use of polarimetric SAR
  - increases the oil spill detection performance
  - makes it possible to discriminate oil slicks from biogenic slicks (Migliaccio et al., 2009)

- Preferable with coherent VV and HH channels
  - E.g. the co-polarized phase difference (CPD) have shown to provide additional discrimination (Migliaccio et al., 2009).

Challenges:

- Limited spatial coverage of SAR images with coherent VV and HH
  - Radarsat-2 quad-pol has a swath of 50 km!

- No polarimetric SAR images with coherent VV and HH channels suitable for large-scale operational oil spill monitoring
Compact polarimetry

- The goal of compact polarimetry is to realize many benefits of quad-pol, without the reduced swath width.
- In ocean applications, HH and HV (and VV and VH) are almost uncorrelated, which makes compact polarimetry even more suitable.
- Many compact polarimetric schemes exist (Raney, 2011)
  - $\pi/4$-mode, circular, hybrid

**Aim of this work**

Demonstrate that compact polarimetric SAR data can be used to detection and classify oil spills.
Hybrid-polarimetric SAR data

- Transmit circular polarization, receives in H and V
- Received single-look complex (SLC) pixel values in H- and V-channels

\[
\mathbf{r} = \begin{bmatrix} E_H \\ E_V \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \begin{bmatrix} 1 \\ -i \end{bmatrix}
\]

- For the horizontal (H) and vertical (V) polarizations in the two-scale model (Valenzuela, 1978) the backscattering coefficients may be expressed as (Iodice et al., 2011)

\[
\mathbf{S} = a_s \mathbf{R}(\phi) \begin{bmatrix} B_{HH}(\theta_i) & 0 \\ 0 & B_{VV}(\theta_i) \end{bmatrix} \mathbf{R}^T(\phi)
\]

\(B_{XX}:\) Bragg scattering coefficients
Hybrid-polarization coherency matrix

Propose to consider the quantities:

\[
E_H + iE_V = \frac{1}{\sqrt{2}}(S_{HH} + S_{VV}) = \frac{a_s}{\sqrt{2}}(B_{HH} + B_{VV}),
\]

\[
E_H - iE_V = \frac{1}{\sqrt{2}}(S_{HH} - S_{VV} - 2iS_{HV}) = \frac{a_s}{\sqrt{2}}(B_{HH} - B_{VV}) \exp(i2\phi),
\]

Corresponding covariance matrix:

\[
D = \begin{bmatrix}
    D_{11} & D_{12} \\
    D_{12}^* & D_{22}
\end{bmatrix}
\]

\[
D_{11} = \langle |E_H + iE_V|^2 \rangle = \frac{1}{2} \langle |a_s|^2 |B_{HH} + B_{VV}|^2 \rangle
\]

\[
D_{22} = \langle |E_H - iE_V|^2 \rangle = \frac{1}{2} \langle |a_s|^2 |B_{HH} - B_{VV}|^2 \rangle
\]

\[
D_{12} = \langle (E_H + iE_V)(E_H - iE_V)^* \rangle
= \frac{1}{2} \langle |a_s|^2 (B_{HH} + B_{VV})(B_{HH} - B_{VV})^* \exp(-i2\phi) \rangle,
\]

\(D_{11}\) and \(D_{22}\) only depend on \(B_{HH}\) and \(B_{VV}\)

\(D_{12}\) only depend on \(\phi\) via the average of complex exponentials
The features are based on the hybrid-polarimetric coherency matrix

According to Minchew et al. (2012) the tilt angles may be assumed to be constant over the neighborhood considered in the spatial averaging, i.e.

\[
D \approx |a_s|^2 \left[ |B_{HH} + B_{VV}|^2 \right. \\
\left. e^{i2\phi}(B_{HH} + B_{VV}^*)(B_{HH} - B_{VV}) \right]
\]

Features applied

- \( D_{11} \)
- \( D_{22} \)
- \( |D_{12}| \)

An interesting feature combination for oil spill detection and lookalike suppression is the correlation coefficient between \( E_H + iE_V \) and \( E_H - iE_V \) (Salberg et al., 2014):

\[
Coh = \frac{|D_{12}|}{\sqrt{D_{11}D_{22}}}
\]
Domain adaptation

▶ There is a need to compensate for the effect the wind has on the backscatter intensity

▶ **Idea:** Transform the test image such that the clean sea intensity distribution matches the training image clean sea intensity distribution.

Proposed scheme:
Domain adaptation

► Find clean sea samples
  ▪ Find *N clean sea* samples using the $D_{11}$ image. Assumption: main mode is clean sea and has high intensity.
  ▪ May also apply SAR wind (e.g. from CMOD5)

► Estimate transform function
  ▪ For each feature ($x$) and at clean sea locations, compute estimate the cumulative distribution (using a Parzen density framework)

$$F_{CS}(x) = \int_{-\infty}^{x} f(\xi) \, d\xi = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}\sigma} \exp \left( \frac{\|\xi - x_n\|^2}{2\sigma^2} \right) \, d\xi$$

► Transform the data of each feature to standard normal $N(0,1)$

$$t(x) = F_N^{-1} (F_{CS}(x))$$

▪ A similar strategy was applied by Storvik at al. (2009) for multisensor fusion of optical and SAR images.
To classify the data we apply a Random Forest classifier

► Benefits
  ▪ Very good of-the-shelf classifier
  ▪ Provides an out-of-bag error estimate. May skip cross-validation during training.
  ▪ No data distribution assumptions.
  ▪ Outputs class probabilities.

► Many implementations exist, we applied `randomForest` in R
  ▪ `nTree=10000`, `mTry = 2`, and equal class weights
  ▪ Stratified sampling in which each tree is built with a number of samples equal to 80% of the smallest class

► Class probabilities are used as confidence measures
The proposed ocean slick classification system

Hybrid-polarimetric coherency matrix.

Hypothesis: SAR image contains a large portion of clean sea pixels.

Matching of the test and training images.

Random forest classifier. Confidence is set to the probability of the selected class.
The training image contains four different slicks

- Oil-on-water experiment outside Norway, June 2011.
- Wind speed between 3 – 4 m/s
- Incidence angle 35°
The OOB confusion matrix shows good performance

<table>
<thead>
<tr>
<th></th>
<th>Clean sea</th>
<th>Low wind</th>
<th>Plant oil</th>
<th>Emulsion</th>
<th>Crude oil</th>
<th>Class. error</th>
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</thead>
<tbody>
<tr>
<td>Clean sea</td>
<td>1164</td>
<td>285</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.20</td>
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<td>Low wind</td>
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<td>416</td>
<td>46</td>
<td>0</td>
<td>0</td>
<td>0.17</td>
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<td>Plant oil</td>
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<td>65</td>
<td>2</td>
<td>4</td>
<td>0.16</td>
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<td>Emulsion</td>
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<td>1</td>
<td>5</td>
<td>17</td>
<td>20</td>
<td>0.60</td>
</tr>
<tr>
<td>Crude oil</td>
<td>0</td>
<td>2</td>
<td>9</td>
<td>72</td>
<td>103</td>
<td>0.44</td>
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<table>
<thead>
<tr>
<th></th>
<th>Clean sea</th>
<th>Plant oil</th>
<th>Mineral oil</th>
<th>Class. error</th>
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<tbody>
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<td>46</td>
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<td>0.024</td>
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<tr>
<td>Plant oil</td>
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<td>65</td>
<td>6</td>
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<tr>
<td>Mineral oil</td>
<td>3</td>
<td>14</td>
<td>212</td>
<td>0.074</td>
</tr>
</tbody>
</table>

Merging the emulsion and crude oil class, and clean sea and low wind class.
The results show that we can separate clean sea, mineral oil and plant oil.
Spill edges tend to be classified as plant oil. Plant oil is classified with lower confidence.
For the oil-on-water 2012 experiment, a larger part of the spill is classified as plant oil.
Also the edges of the Deepwater Horizon spill is classified as plant oil.
The results are the same for the oil-on-water 2013 experiment image.
The $Coh$ measure suppresses lookalikes

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The $Coh$ measure suppresses lookalikes

$D_{11}$ image  

$Coh$ image
The Coh measure suppresses lookalikes

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\[ D_{11} \text{ image} \]

\[ \text{Coh image} \]
We conclude that hybrid-polarimetric SAR can provide new analysis results for operational oil spill services

► Hybrid-polarimetric SAR can discriminate some surface slicks.

► Unclear how the backscatter is related to the oil type. (Edges are classified as plant oil.)

► Confidence about the decision obtained directly from the classifier output.

► We expect that SAR systems providing compact polarimetry modes will have a high impact on operational oil slick monitoring in the future.
Acknowledgements

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