Retrieval of the dielectric properties of oil slick using SAR via a Polarimetric Two-Scale Model

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Oil spills appear as **dark patches** in SAR images primarily because of the dampening of capillary waves responsible for the radar backscattering.

Low backscattered area.

This situation is typical for many other features referred to as **look-alikes**:

- Natural biogenic slicks
- Low wind areas
- Coastal fronts and eddies
- Grease sea ice
- Ship wakes
Motivation

Physical parameters affected by the presence of oil on the water surface:

- **Surface roughness**
- **Dielectric properties**

Information about geophysical parameters of oil/ocean surfaces may help:

- solving ambiguities related to look-alikes
- improving operational services
Objectives

- Implement a procedure that will allow an estimation of the permittivity of oil slick

\[ \varepsilon = \varepsilon' - j\varepsilon'' \]

Oil : 2.3 – j 0.02

Sea water : 80 – j 70

[T=20 C, f=1 GHz]
Objectives: Dielectric properties of crude oil

\[ \varepsilon = 2.3 - j0.02 \quad f=1 \text{ GHz} \]

The dielectric properties of the scattering surface can change due to the presence of oil

New dielectric medium

\[ \varepsilon_{mix} \approx \varepsilon_{sw} + \varepsilon_{oil} \]

\[ \varepsilon_{mix} = \varepsilon_{oil} \cdot \omega_0 + \varepsilon_{water} \cdot (1 - \omega_0) \]

Linear mixing model
Polarimetric Two-Scale Model (PTSM)

- In order to determine the permittivity of the scattering surface an appropriate scattering model is required.
- PTSM models the ocean surface as a superposition of randomly orientated, slightly rough, tilted facets.

Iodice et. al. & references therein
Deviation from X-Bragg model

In X-Bragg:

• the random incidence angle variation $\Delta \nu$ is ignored

• the incidence plane angle of rotation $\beta$ is heuristically assumed to be uniformly distributed in an interval $(-\beta_1, \beta_1)$

In PTSM

• These simplifying assumptions are removed

• We assume that facet slopes, $a, b \sim N(0, \sigma^2)$

Iodice et al. & references therein
We can construct a set of equations that model the Normalized Radar Cross Sections (NRCS) in both VV and HH polarimetric channels from a single facet:

\[
\sigma_{HH}^0 = \frac{4}{\pi} k^4 \cos^4 \nu_l s^2 W_n (2k \sin \nu_l) |F_H(\nu_l)\cos^2 \beta + F_V(\nu_l)\sin^2 \beta|^2
\]

\[
\sigma_{VV}^0 = \frac{4}{\pi} k^4 \cos^4 \nu_l s^2 W_n (2k \sin \nu_l) |F_V(\nu_l)\cos^2 \beta + F_H(\nu_l)\sin^2 \beta|^2
\]

Local incidence angle:
\[
\cos \nu_l = \frac{\cos v + b \sin v}{\sqrt{1 + a^2 + b^2}}
\]

\(a, b\) : facet slopes

Small-scale roughness variance

Power spectral density

Bragg coefficients Functions of \(\varepsilon\)

Global incidence Plane shift
\[
\tan \beta = \frac{a}{-bcos + sinv}
\]
Polarimetric Two-Scale Model (PTSM)

We can average over the slopes of the randomly tilted facets $a$ and $b$ and employ a MacLauren expansion for simplification

$$
\langle \sigma_{HH}^0 \rangle_{a,b} = \frac{4}{\pi} \left[ C_{0,0}^{HH} + C_{2,0}^{HH} + 2 \frac{\text{Re}\{C_{0,0}^{HV}\} - C_{0,0}^{HH}}{\sin^2 \psi} + C_{0,2}^{HH} \right] \sigma^2
$$

$$
\langle \sigma_{VV}^0 \rangle_{a,b} = \frac{4}{\pi} \left[ C_{0,0}^{VV} + C_{2,0}^{VV} + 2 \frac{\text{Re}\{C_{0,0}^{HV}\} - C_{0,0}^{VV}}{\sin^2 \psi} + C_{0,2}^{VV} \right] \sigma^2
$$

Expansion coefficients: $C_{k,n-k}^{pq} = \frac{1}{n!} \binom{n}{k} \frac{\partial^n (k \cos \nu)^4 WF_p F_q^*}{a^k b^{n-k}} \bigg|_{a=b=0}$
Polarimetric Two-Scale Model (PTSM)

• The trick: employ the co-polarization ratio
• This ensures that dependence on small scale roughness is eliminated and we are left with a function that depends only on \( \varepsilon \) (dielectric properties) and \( \sigma \) (large scale roughness)

\[
\frac{\sigma_0^{(1)}(v_l)_{VV}}{\sigma_0^{(1)}(v_l)_{HH}}
\]

• Then find \(|\varepsilon|\) that minimises

\[\|\text{copol}_{\text{from data}} - \text{copol}_{\text{from theory}}\|\]
Datasets: Norwegian oil spill Experiments

NOFO - The Norwegian Clean Seas Association for Operating Companies

Each year NOFO conduct an oil-on-water clean up exercise

- 2011
  - I.A. 46°
  - Wind [m/s]: 1.66-3.3

- 2011
  - I.A. 34°
  - Wind [m/s]: 4

- 2013
  - I.A. 28°
  - Wind [m/s]: 5
Datasets: Norwegian oil spill spill Experiments

Noise Analysis of co-polarization channels

2011
(I.A 46°)

2011
(I.A 34°)

2013
(I.A 28°)
Datasets: Norwegian oil spill spill Experiments

Noise Analysis of cross-polarization channels

2011
(I.A 46°)

2011
(I.A 34°)

2013
(I.A 28°)
A clear implication of the noise analysis is that the cross-polarization channels are too corrupted with noise to be useful for inversion.

Before $|\varepsilon|$ can be estimated the large scale roughness descriptor first $\sigma$ needs to be estimated.

Iodice et al. & references therein

$\sigma = 0.1$

$\sigma = 0.2$

$\sigma = 0.3$

$\sigma = 0.4$
Inversion results: 2011 (I.A. 34°)
Inversion results: 2011 (I.A. 340)

Original 15x15 multilooked VV **crude oil** image vs. image showing $|\varepsilon|$ values
Inversion results: 2011 (I.A. 34°)

Original 15x15 multilooked VV **Plant oil** image vs. image showing $|\varepsilon|$ values
Conclusions

• PTSM can invert for realistic values of $|\varepsilon|$ up to values of approximately 20
Further work

• In-situ data for comparison
• Usefulness in look-alike discrimination e.g. between grease ice, algae
• Continuous monitoring of produced water
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The model requires that $\epsilon$ is a complex quantity.

The assumption made is that the model relies on the quantity $|\epsilon|$. This is done for simplicity.

Can we measure the error incurred by making this assumption?
(PTSM): Model assumptions