Investigation of angular variations of radar sea clutter

Guerraou Zaynab$^{1,2}$  Angelliaume Sébastien$^1$  Guérin Charles-Antoine$^2$

1: ONERA, Département Electromagnétisme et Radar
2: Université de Toulon, Mediterranean Institute of Oceanography (MIO)
Improving our knowledge of the EM scattered signal from the sea surface

- Target detection: Developing robust detection methods under difficult sea conditions (Detection of small targets, rough sea state...)
- Sea clutter: Modelling the EM sea surface response
- Detection/characterization/quantification of marine pollutants. (POLLUPROOOF project)
- Inversion of ocean surface parameters (wind/wave heights/ocean currents)

Collaborative work:

- ONERA – Research labs (MIO, IETR, …)
- DEMR (multi-units/multi-sites): Modeling/radar experimentation/system expertise
CONTEXT OF THE STUDY

Various challenges:

• Modeling of the HH and HV returns
• The variability of the NRCS
• Breaking waves, sea spikes
• Azimuthal variations and directional asymmetries
• The directional wave number spectrum of the short waves
• Grazing angle configuration…

The purpose:

Recent progresses toward the depiction and simulation of some of these phenomena.
INGARA SYSTEM

Fully-polarimetric X band radar system maintained & operated within the « Defence Science & Technology Organisation »

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>10.1 GHz</td>
</tr>
<tr>
<td>Grazing angles</td>
<td>15° à 45°</td>
</tr>
<tr>
<td>Range resolution</td>
<td>0.75 m</td>
</tr>
<tr>
<td>Cross-range resolution</td>
<td>62 m</td>
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Circular spotlight mode collection for the INGARA data (reproduced from \[1\])
Fully-polarimetric X band radar system maintained & operated within the «Defence Science & Technology Organisation»

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<tr>
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**INGARA radar and trial parameters (reproduced from [1])**

<table>
<thead>
<tr>
<th>Trial</th>
<th>Flight</th>
<th>Date</th>
<th>Wind Speed (m/s)</th>
<th>Wind Direction (deg)</th>
<th>Height (m)</th>
<th>Wave Direction (deg)</th>
<th>Wave Period (s)</th>
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<td>F33</td>
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</tbody>
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Noise floor and denoising process

Azimuthal variation for HH polarized data for nominal grazing angles of 15° (left panel) and 45° (right panel) for a wind speed of 8.5 m/s

Raw NRCS
Mean noise estimate
Denoised NRCS

Upwind = 0°
Downwind = +/- 180°
Crosswind = +/- 90°
Azimuthal variation of the NRCS: Maximum Likelihood estimation

\[ \sigma_{0}^{model}(\phi_n) = \tilde{\sigma}_0(\phi_n) + b(\phi_n) \]

**Model:** Truncated Fourier series

\[ \tilde{\sigma}_0(\phi_n) = a_0 + \sum_{k=1}^{4} a_k \cos(k(\phi_n - \delta_k)) \]

**Log-likelihood:**

\[ \mathcal{L} = -\frac{1}{2} \sum_{n=1}^{N_a} \log(2\pi \sigma_0^2) - \sum_{n=1}^{N_a} \frac{1}{2\sigma_b^2} \left[ \sigma_0^{data}(\phi_n) - (\tilde{\sigma}_0(\phi_n) + b) \right]^2 \]

\[ \frac{\partial \mathcal{L}}{\partial a_k} = 0, \quad \frac{\partial \mathcal{L}}{\partial \phi_k} = 0 \ldots \quad \Rightarrow \quad a_n, \phi_n \]
Azimuthal variation of the NRCS: HH peculiar behavior at low grazing angles

Progressive shift from two local maxima at upwind/downwind directions to a unique and pronounced maximum in the upwind direction

Physical interpretation?
Azimuthal variation of the NRCS: Directional asymmetries

Example of the azimuthal variation for a 41° grazing angle, run3

Conclusions:

- UDA and UCA in VV and HH are maximum at moderate grazing angle (30° - 45°)
- \( UDA_{HH} > UDA_{VV} \) & \( UCA_{VV} > UCA_{HH} \) (The maximum UDA in HH is in average about 2 dB higher than the VV counterpart.)

- Upwind/Downwind asymmetry: \( UDA = 10 \log_{10} \left( \frac{\sigma_{up}^0}{\sigma_{down}^0} \right) \)
- Upwind/Crosswind asymmetry: \( UCA = 10 \log_{10} \left( \frac{\sigma_{up}^0}{\sigma_{cross}^0} \right) \)
Relations between the different polarizations: 

**Polarization ratio – Grazing and azimuth behavior**

\[
PR = (\sigma_{VV}^0)_{dB} - (\sigma_{HH}^0)_{dB}
\]

**Conclusions:**

- The PR is a decreasing function of grazing angle
- \( PR_{data} < PR_{Bragg} \)
- PR has a strong azimuthal dependency with a sharp maximum in the downwind direction
Polarization ratio of asymmetric wave
Upwind & downwind

Polarization ratio using Bragg theory for a nominal incidence angle $\theta$

\[
\begin{align*}
B_{VV} &= \frac{\varepsilon - 1}{(q_0 + q'_0)^2} (-q'_0^2 - \varepsilon k_0^2) \\
B_{HH} &= \frac{\varepsilon - 1}{(q_0 + q'_0)^2} K^2
\end{align*}
\]

, With

\[
\begin{align*}
k_0 &= K \sin \theta \\
qu &= K \cos \theta \\
q'_0 &= \sqrt{\varepsilon K^2 - k_0^2}
\end{align*}
\]

\[
PR_{\text{Bragg}}(\theta) = \frac{|B_{VV}|^2}{|B_{HH}|^2} = \frac{|q_0 + q'_0|^4}{|\varepsilon q_0 + q'_0|^4} \left[ \sin^2 \theta (1 - \varepsilon) - \varepsilon \right]^2
\]
Polarization ratio using Bragg theory for a nominal incidence angle $\theta$

$$
\begin{align*}
B_{VV} &= \frac{\varepsilon - 1}{(\varepsilon q_0 + q_0')^2} (-q_0'^2 - \varepsilon k_0^2) \\
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At local incidence angles:

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$$

Wind direction

- Downwind
- Upwind

$\theta_{\text{loc}}^\text{downwind} = \theta_i - \alpha$

$\theta_{\text{loc}}^\text{upwind} = \theta_i - \beta$
Polarization ratio of asymmetric wave
Upwind & downwind

Polarization ratio using Bragg theory for a nominal incidence angle $\theta$

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PR_{loc}(\theta) = \frac{|B_{VV}|^2}{|B_{HH}|^2} = \frac{|q_0 + q'_0|^4}{|\varepsilon q_0 + q'_0|^4} \left[ \sin^2 \theta \left( 1 - \varepsilon \right) - \varepsilon \right]^2
$$

$\alpha$ and $\beta$ angles are in good agreement with slopes obtained in wind-wave tank measurements (Cf Caulliez et al$^{(2)}$)

Relations between the different polarizations:

The polarization difference $\sigma^0_{VV} - \sigma^0_{HH}$

- $\sigma_0 = \sigma^p_0 + \sigma^{np}_0$ (linear units)
- $PD = \sigma^0_{VV} - \sigma^0_{HH}$ removes the non-polarized contribution

Azimuthal variation of the polarization difference $VV$-$HH$ for run days 9 (left) and 12 (right)

Grazing angles
- $25^\circ$
- $37^\circ$
- $42^\circ$

No or weak UDA asymmetry!

Potential Interpretation:

UDA asymmetry is likely to be contained in the non-polarized part and presumably related to the large scales of surface roughness?
Azimuthal variation of the ratio

\[ R = \frac{\sigma_{VH}^0}{\sigma_{VV}^0 - \sigma_{HH}^0} \propto m s s y \]

Spectral models

- Omni-directional spectra
  - Elfouhaily [5]
  - Bringer [6]

Spectral models

- Spreading functions
  - Elfouhaily [5]
  - Yurovskaya [7]

Study of the cross-polarized data

Scattering models

- GOSSA [3] for the two-like polarizations
- SSA2 [4] for the cross-polarized data

Azimuthal variation of the Ratio at 40° grazing angle for run days 3 (left) and 9 (right)

Simultaneous variation of the different polarizations

- Systematic correlation between the HH & HV polarizations ($\rho > 0.9$)
- Poorer correlation between the VV and HV channels ($\rho < 0.8$), albeit following the same trend

*Scatterplot of HH versus HV (left) and VV versus HV (right) for the mean NRCS taken at 37 degrees grazing angle within $\pm 2.5$ degrees from the upwind direction with linear fit shown in red.*
Significant improvement of the simulated HH and VV NRCS brought by the use of the improved spectral models.

*HH (left) and VV (right) NRCS from the INGARA MGA data for run day 9. Superimposed is the simulated NRCS according to the GO-SSA model with Elfouhaily directional spectrum and Bringer-Yurovskaya model.*
Conclusion

- Peciluar azimuthal distribution at low grazing angles for HH-polarized data
- UDA & UCA asymmetries are not monotone functions of grazing angle and reach their maximum at moderate grazing angles (30°-45°)
- $UDA_{HH} > UDA_{VV}$ & $UCA_{VV} > UCA_{HH}$
- PR max at downwind
- $\frac{\sigma_{VH}^0}{\sigma_{VV}^0-\sigma_{HH}^0}$ maximum at crosswind and no or weak UDA for the $\sigma_{VV}^0 - \sigma_{HH}^0$
- Eventual correlation between HH and HV polarized data
- Improvement of the co-polarized simulated NRCS brought by the use of improved spectral models
THANK YOU FOR YOUR ATTENTION

QUESTIONS?
Azimuthal variation of the NRCS: Maximum Likelihood estimation

Robustness of the MLE to the SNR degradation

The RMSE calculated between the noise-free simulated data and the estimated model is found to be significantly low and quite insensitive to the SNR.

Example of NRCS reconstruction at low SNR of -35 dB
Effect of swell

V\textit{V}(upper dots) and H\textit{H} (lower dots) NRCS for the Hwang spectrum with different swell indices for a 4m/s wind speed on the left panel and 10m/s on the right panel.

A slightly more pronounced effect in the H\textit{H} pol and at smaller wind speeds