Azimuthal variations of X-band medium grazing angle sea clutter

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ONERA ACTIVITIES – Sea surface radar imagery

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…)

- EM modeling of the sea clutter

- Detection/characterization/quantification of marine pollutants. (POLLUPROOF project)

- Inversion of ocean surface parameters (wind/wave heights/ocean currents…)

Collaborative work:

- ONERA – Research labs (MIO, DSTO …)
- ONERA – Industrial organizations (TOTAL)
Various challenges:

- Modeling of the HH and HV returns
- The variability of the NRCS
- The directional wave number spectrum of the short waves

The purpose:

Recent progresses toward the depiction and simulation of some of these phenomena.
FULLY-POLARIMETRIC X BAND RADAR SYSTEM MAINTAINED & OPERATED WITHIN THE « DEFENCE SCIENCE & TECHNOLOGY ORGANISATION »

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<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>
</tr>
</tbody>
</table>

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

**Circular spotlight mode collection for the INGARA data (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>Wave Height (m)</th>
<th>Wave Direction (deg)</th>
<th>Period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCTM4</td>
<td>F33</td>
<td>9/8/04</td>
<td>10.2</td>
<td>248</td>
<td>4.9</td>
<td>220</td>
<td>12.3</td>
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<td>F34</td>
<td>10/8/04</td>
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<td>3.5</td>
<td>205</td>
<td>11.8</td>
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<td>210</td>
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<tr>
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<td>12/8/04</td>
<td>13.6</td>
<td>0</td>
<td>3.2</td>
<td>293</td>
<td>8.8</td>
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<td>16/8/04</td>
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<td>2.5</td>
<td>160</td>
<td>9.7</td>
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<tr>
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<td>9.5</td>
<td>315</td>
<td>3.0</td>
<td>234</td>
<td>11.4</td>
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<tr>
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<td>12.5</td>
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<tr>
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<td>F2</td>
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<td>112</td>
<td>3.1</td>
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<tr>
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<td>35</td>
<td>2.6</td>
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<tr>
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<td>4.0</td>
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<tr>
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<td>10.2</td>
<td>124</td>
<td>1.21</td>
<td>128</td>
<td>4.6</td>
</tr>
</tbody>
</table>

**Wind and wave ground truth for the Ingara data (reproduced from [1])**

A vanishing of the secondary downwind maximum is observed with the HH pol at lowest grazing angle (as modelled in the empirical GIT mean backscattered model). This directional asymmetries are shown to be polarization-dependant and follow non-monotonic variations with respect to the grazing angle.

For the lower grazing angle, the SNR (particularly at HH pol) is low and an accurate denoising procedure is of primary importance to correct retrieval of the NRCS.
Azimuthal variation of the NRCS: Maximum Likelihood estimation

Model: Truncated Fourier series
\[
\sigma_0^{\text{model}}(\phi_n) = \sigma_0(\phi_n) + b(\phi_n)
\]

\[
\sigma_0(\phi_n) = a_0 + \sum_{k=1}^{4} a_k \cos(k(\phi_n - \delta_k))
\]

Log-Likelihood:
\[
\mathcal{L} = -\frac{1}{2} \sum_{n=1}^{N_u} \log(2\pi \sigma_0^2) - \sum_{n=1}^{N_u} \frac{1}{2\sigma_0^2} \left[ \sigma_0^2 \sigma_{\alpha}(\phi_n) - \left( \sigma_0(\phi_n) + \sigma_{\beta}^2 \right) \right]^2
\]

\[
\frac{\partial \mathcal{L}}{\partial a_k} = 0, \quad \frac{\partial \mathcal{L}}{\partial \phi_k} = 0 \ldots \quad a_k, \; \phi_k
\]
Angular variation of the denoised NRCS: grazing variations

Run day 9
- Upwind
- Crosswind
- Downwind
- Noise floor

VV: upwind ~ downwind > crosswind
HH: downwind ~ crosswind at the lowest grazing angle

Denoised NRCS is up to 10 dB lower than the noise floor
Angular variation of the denoised NRCS: azimuthal variations

Run day 9
Grazing 45°
Grazing 35°
Grazing 25°
Grazing 16°

Moderate grazing angle: commonly observed pattern of a sinusoidal variation

As the grazing angle is decreased in HH pol, we observe a progressive shift from two local maxima at upwind and downwind directions to a unique and pronounced maximum in the upwind direction

=> physical modeling of this peculiar behavior is not established
Model/data comparison

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

### Spectral models
- Omni-directional spectra
  - Elfouhaily [5]
  - Bringer [6]
- Spreading functions
  - Elfouhaily [5]
  - Yurovskaya [7]

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**Run day 9 – grazing 42°**

![Graph showing significant improvement brought by the use of improved spectral models](image)

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Significant improvement brought by the use of the improved spectral models

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Relations between the different polarizations:  
**Polarization difference – Grazing and azimuth behavior**

\[ PD = VV - HH \text{ (linear unit)} \]

PD is proportional to the wave number spectrum taken at the Bragg frequency, it is therefore more sensitive to the small scale features of the sea surface rather than the larger scale which are responsible for the unpolarized portion of the NRCS.

PD doesn’t exhibit the UDA asymmetry seen with the HH & VV pol  
=> the UDA asymmetry is likely to be contained in the non-polarized part and presumably linked to the large scales of roughness.
Relations between the different polarizations: 
*Polarization ratio – Grazing and azimuth behavior*

PR = VV/HH

The PR is a decreasing function of grazing angle

PR\(_{\text{experimental}}\) < PR\(_{\text{Bragg}}\)

PR has a strong azimuthal dependency with a sharp maximum in the downwind direction

=> Can allow removing the usual ambiguity encountered between upwind and downwind directions
Polarization ratio of asymmetric wave profiles

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

$$PR_{\text{Bragg}} = \frac{|B_{VV}|^2}{|B_{HH}|^2} = f(\theta_{loc}, \varepsilon)$$

Wind direction

Downwind

Upwind

At local incidence angles:

$$PR_{loc} = PR(\theta_{loc}), \quad \theta_{loc} = \begin{cases} \theta_{i} - \alpha & \text{downwind} \\ \theta_{i} - \beta & \text{upwind} \end{cases}$$

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

Study of the slope influence

- Based on Bragg theory, the slope influence is significantly more pronounced at HH than VV polarization.

- **Taylor expansion** with respect to the slope:

\[
\sigma_{pp}^{0\text{Bragg}}(\theta_{loc}) = \sigma_{pp}^{0\text{Bragg}}(\theta_L, \alpha) = \sigma_{pp}^{0\text{Bragg}}(\theta_L, 0) + \Delta \sigma_{0}^{1}(\theta_L) \alpha + \Delta \sigma_{0}^{2}(\theta_L) \frac{\alpha^2}{2} + \ldots
\]

- **Two scale-Model**

\[
\sigma_{0}(\theta_{loc}) = \int_{-\infty}^{+\infty} p(\alpha) \sigma(\theta_L, \alpha) d\alpha
\]

\[
= \sigma_{\text{Bragg}}(\theta_L, 0) + \Delta \sigma_{0}^{1}(\theta_L) \int_{-\infty}^{+\infty} \alpha p(\alpha) d\alpha + \Delta \sigma_{0}^{2}(\theta_L) \int_{-\infty}^{+\infty} \alpha^2 p(\alpha) d\alpha
\]

\[
\text{UDA} = \frac{\sigma_{\text{Bragg}}(\theta_L, 0) + \Delta \sigma_{0}^{1}(\theta_L) M_{1}^{+} + \Delta \sigma_{0}^{2}(\theta_L) M_{2}^{+}}{\sigma_{\text{Bragg}}(\theta_L, 0) + \Delta \sigma_{0}^{1}(\theta_L) M_{1}^{-} + \Delta \sigma_{0}^{2}(\theta_L) M_{2}^{-}}
\]
Study of the slope influence

**Long waves (LF waves $\lambda > 3cm$) − $U = 8m/s$**

- Anisotropic long waves: waves strongly aligned with the wind direction.
- Asymmetry of positive and negative slopes → Asymmetric slope distribution.

$contours = 1 \times 10^{-8} \times [0.1 \ 1 \ 2 \ 3 \ 4 \ 5 \ 6]$
Study of the slope influence

Short waves (HF waves $\lambda \leq 3cm$) – $U = 8m/s$

- Isotropic short waves.
- Slight difference between positive and negative slopes.

$contours = 1.10^{-8} \times [0, 1, 2, 3, 4, 5, 6]$
Conclusions & perspectives

Conclusions

• Empirical/physical model for the azimuthal repartition of radar sea clutter.
• Study of the UDA, PD, PR and other parameters.
• Data/model comparison: Improvement of the co-polarized simulated NRCS brought by the use of improved spectral models.


• Evaluation of slope influence on the NRCS.

Perspectives

• Quantification of the UDA using asymmetric slope distribution inferred from wave-trank measurements.
• Diffraction by non-linear wave fields including gravity-capillarity waves and their parasitic capillaries (Project in collaboration with V. Schira from the NOAA).
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

VV (upper dots) and HH (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 HH pol and at smaller wind speeds.