High-Fidelity Numerical Simulations of Range-Resolved, Time-Varying Radar Backscatter from a Sea Surface with Floating Targets

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Introduction

“Numerical Experiment” Approach:
- use first-principles solution for backscatter from a given boundary
- the sea-like surface+target profile generated using physical models
- produce range-resolved, coherent time-varying echoes
- accumulate Monte Carlo ensembles

Limitations:
- 2-D space (care with interpretation, no cross-pol HV or VH)
- High computational cost of direct scattering solution

Benefits:
- Highly controlled conditions (e.g. can adjust wind speed at will)
- Flexibility
- Applicability at all incidence geometries, including low grazing angles
- Benchmark for approximate scattering models
Tapered plane wave incident field at $\theta_i$
- Surface with wind-driven spectrum
- Conducting round floating targets
- Scene evolves with time (20 s)
- Simultaneous, coherent VV and HH

Two aspects of the problem:
- Hydro part: model surfaces and targets
- E/m part: evaluate scattered field

$f_0 = 10$ GHz
$\delta r \geq 0.34$ m
$\theta_{gr} = 90^\circ - \theta_i$:
  - $5^\circ .. 70^\circ$
Wind speed:
  - 5, 7, 10 m/s
Scattering simulations: Problem set-up

- Tapered plane wave incident field at $\theta_i$
- Surface with wind-driven spectrum
- Conducting round floating targets
- Scene evolves with time (20 s)
- Simultaneous, coherent VV and HH

Two aspects of the problem:
- Hydro part: model surfaces and targets
- E/m part: evaluate scattered field

Embedded targets parameters:

<table>
<thead>
<tr>
<th>#</th>
<th>Diameter $d$, m</th>
<th>Location $x$, m</th>
<th>Center depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>0</td>
<td>$d/3$</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>35</td>
<td>$d/3$</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>-30</td>
<td>$d/3$</td>
</tr>
</tbody>
</table>
1. At a given frequency, surface electric current is found exactly by solving boundary integral equation (iterative “Forward-Backward” technique with accelerations).

   Backscattered field is then found as the radiation effect of that current.

2. Calculations repeated at 2048 frequencies covering a 1.25-GHz band ($f_0 = 10$ GHz).

3. Range-resolved surface radar response is synthesized in Fourier domain.

4. Procedure is repeated for 10,000 “frozen” surface profiles.

In (1), exact technique can be replaced by an approximate model (Small Slope Approximation, Bass-Fuks 2-scale, etc.)
Scattering simulations: Surface model

1. Generate a realization of Gaussian random process with power spectral density given by Elfouhaily spectrum

2. Propagate each harmonic independently with the dispersion relation

\[
\Omega(K) = \sqrt{gK[1 + (K/K_m)^2]}, \quad K_m = 363 \text{ rad/m}
\]

"Linear" surface

3. At each time step, apply Creamer transform \( \to \) inter-harmonic interaction

\[
\zeta(K, t) = \frac{1}{|K|} \int e^{-jKx}[\exp\{jK\zeta_{0H}(x, t)\} - 1] \, dx
\]

- ripple enhancement at crests
- modified dispersion relation
- no wave breaking

<table>
<thead>
<tr>
<th>( U_{10}, \text{ m/s} )</th>
<th>Rms height ( \zeta_{rms}, \text{ m} )</th>
<th>Peak wave length ( \Lambda_p, \text{ m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.16</td>
<td>23.3</td>
</tr>
<tr>
<td>7</td>
<td>0.32</td>
<td>45.5</td>
</tr>
<tr>
<td>10</td>
<td>0.65</td>
<td>92.4</td>
</tr>
</tbody>
</table>
Scattering simulations: Targets

MODEL:
• a round body whose submerged center follows orbital current (no inertia)
• in the broached region surface roughness is replaced by the target contour
• otherwise, no disturbance of the ambient wave field
Results: Range-time records

Backscatter magnitude: range resolution 0.34 m, wind speed 7 m/s

Grazing angle: 50°
Results: Range-time records

Backscatter magnitude: range resolution 0.34 m, wind speed 7 m/s

Grazing angle: $30^\circ$
Backscatter magnitude: range resolution 0.34 m, wind speed 7 m/s

Importance of time dimension

Grazing angle: 30°
Results: Range-time records

Backscatter magnitude: range resolution 0.34 m, wind speed 7 m/s

Grazing angle: $10^\circ$

Ground range, m

<table>
<thead>
<tr>
<th>$d$</th>
<th>HH</th>
<th>$d$</th>
<th>VV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 m</td>
<td><img src="image1" alt="HH" /></td>
<td>1.0 m</td>
<td><img src="image2" alt="VV" /></td>
</tr>
<tr>
<td>1.5 m</td>
<td><img src="image3" alt="HH" /></td>
<td></td>
<td><img src="image4" alt="VV" /></td>
</tr>
</tbody>
</table>

-20 dB
Results: Range-time records

Backscatter magnitude: range resolution 0.34 m, HH

Impact of wind speed

Grazing angle: 30°

Ground range, m

7 m/s

5 m/s

d=1.5 m
d=1.0 m
d=0.5 m
Results: Doppler spectra

Doppler spectrogram at $x_g = 34.5$ m: 7 m/s, range resolution 1 m, HH

(sliding 0.5-s Hann window)

$\theta_g = 30^\circ$
Results: Doppler spectra

Average Doppler Spectrum vs range: 7 m/s, range resolution 0.34 m

Spectrograms averaged over 20 s

Grazing angle: 30°
Results: Doppler spectra

Average Doppler Spectrum vs range: range resolution 0.34 m, HH

Grazing angle: 30°
Results: Doppler spectra

Average Doppler Spectrum vs range: range resolution 0.34 m, HH, 7 m/s

\[ \theta_{gr} = 20^\circ \]

\[ \theta_{gr} = 40^\circ \]
Summary

• Modelled round targets visible at moderate grazing angles

• Time dimension is important for detection

• Differences of Doppler spectra of targets and background: similar orbital motions but different scattering mechanisms

• More elaborate model for floating bodies desired

• Numerical experiment: control and flexibility

• Integral-equation scattering solution – may be overkill at medium and high grazing angles, but always works

• Simulated data - benchmark for detection algorithms