Radar signatures of internal solitary waves – revisited

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The conventional radar imaging theory (Alpers, Nature 1985) explaining the radar signatures of internal waves, which is based on weak hydrodynamic interaction theory and Bragg scattering, has only limited application and is inadequate to describe the radar signatures of strong internal waves.

Strong internal waves or internal solitary waves (ISWs) are often associated with bands of breaking waves on the sea surface, as described already in a book by Mauray (1861), who observed roughness bands in Andaman Sea:

"The ripplings are seen in calm weather approaching from a distance, and in the night their noise is heard a considerable time before they come near. They beat against the sides of a ship with great violence, and pass on, the spray sometimes coming on deck; and a small boat could not always resist the turbulence of these remarkable ripplings."

There is now much experimental evidence that breaking surface waves contribute significantly to the radar signature of strong internal waves.
Principal result of the conventional radar imaging of internal waves:

\[
\frac{\delta \sigma}{\sigma_0} = \frac{\delta N}{N_0} = \frac{\delta E}{E_0} = -(4 + \gamma) \tau_r \frac{\partial U_x}{\partial x}
\]

- \( \frac{\delta \sigma}{\sigma_0} \) = modulation depth
- \( \frac{\delta N}{N_0} \) = modulation depth
- \( \frac{\delta E}{E_0} \) = modulation depth
- \( \tau_r \) = relaxation time

Relaxation time: 10-100 wave periods

- The modulation depends on azimuth angle \( \phi \).
- Modulation is maximum for range travelling internal waves and zero for azimuthally travelling waves.

These theoretical predictions often do not comply with observations.
Low wind speed case

Sentinel-1A VV SAR image acquired on 9 Feb 2017 at 06:19 UTC over the Strait of Gibraltar

Wind on 9 February 2017 at 0000 UTC: 4 m/s from 85 deg
High wind speed case

Sentinel-1B VV SAR image acquired on 2 July 2017 at 0621 UTC

Wind on 2 July at 0000 UTC: 12 m/s from 75 deg
Internal waves can be imaged even when there is no wind

Sentinel-1A VV SAR image, 27 July 2017 at 1908 UTC  
VH SAR image shows no modulation

Modulation depth: up to 6 dB

NRCS scan along the transect inserted Panel A

Much too large to be explainable by weak hydrodynamic interaction theory/Bragg scattering theory!
Sentinel-1A VV SAR image, 13 May 2017 at 1016 UTC
VH SAR image shows no modulation

Internal wave packets in the South China Sea

Modulation depth: up to 3 dB
What is the scattering mechanism causing these large radar signatures?

Experiments aimed at answering this question have been carried out in the laboratory by Ericson, Lyzenga, and Walker (1999), who studied radar backscatter from stationary breaking waves generated by a flow passing over a submerged inclined hydrofoil.

**Result:**

- It is caused by non-coherent, backscatter from small-scale roughness generated by breaking waves.
- The backscatter is predominantly non-polarized and shows very little dependence on azimuth angle.
- The theory which describes best the scattering at breaking wave crests is the Kirchoff Approximation (Fung et al. 1992).
This theory has been tested using TerraSAR-X data.

TerraSAR-X StripMap image, HH pol. 17 August 2009, 06:29: 59 UTC, ID: dims_op_oc_dfd2_513403606_1

Polarization ratio HH/VV

Non-polarized contribution to radar backscatter
Contrast in linear units
Wave breaking has to be taken into account

$$\sigma_0^p = \sigma_{\text{Bragg}}^p + \sigma_{\text{wb}}$$

Kudryavtsev et al. 2009

Percentage of \textbf{Bragg} & \textbf{non-Bragg} backscatter components

Transect along- internal solitary wave profile
Optical image taken by the Multispectral Instrument (MSI) on-board the Sentinel-2A satellite showing sea surface signatures of an internal wave packet generated in the Strait of Gibraltar. Note the irregular bright spots which are white caps generated by breaking surface waves.
Photo taken from a ship showing sea surface signatures of an internal wave. Note that the band of enhanced sea surface roughness also includes breaking waves.

Photo taken by Guozhen Zha in the South China Sea on 27 April 2018.
TerraSAR-X image showing internal waves in the southwest Tropical Atlantic near the Amazon river mouth

Streaks anti-parallel to flight direction
When a target has a velocity component $v_r$ in range direction, then the target is shifted in azimuth direction by

$$\Delta y = \frac{R}{V} v_r$$

$R = \frac{H}{\cos \theta}$ is the target range (81 s$^{-1}$)
$H$ the satellite height (514 km)
$\theta$ the incidence angle (33.5°)
$V$ the speed of the satellite (7.6 km/s)

$\Delta y = 120$ m $\quad v_r = 1.48$ m/s

Scatterers ("sea spikes") have a velocity in look direction of the antenna of $v_r = 1.48$ m/s

Contribution from "downward plunging" and advection in wave propagation direction

Multipath scattering

$\sigma_0(HH) >> \sigma_0(VV)$

Grazing incidence angles

Moderate incidence angles
Experimental results reported by Plant et al. (2010) on radar backscattering from internal waves:

1) Shipborne measurements in the South China Sea (X-band, VV, HH):

- Scatter velocities at HH polarization frequently exceed 1 m/s, sometimes 2-3 m/s.
- $\sigma_0(\text{HH}) \gg \sigma_0(\text{VV})$ by 5 -10 dB.

2) Airborne measurements in Atlantic Ocean off the New Jersey coast (X-band, VV, HH):

- $\sigma_0(\text{HH}) \approx \sigma_0(\text{VV})$  Non-Bragg scattering is important
Conclusion

- The conventional theory of radar imaging of internal waves based on weak hydrodynamic interaction theory and Bragg scattering theory cannot explain the observed strong radar signatures of internal solitary waves.

- In addition to Bragg scattering, also no-polarized scattering from breaking “intermediate-scale surface waves” with wavelengths of the order of meters contributes to the radar signature of internal solitary waves.

- At intermediate incidence angles \(20^\circ < \theta < 70^\circ\): \(\sigma_0(HH) \approx \sigma_0(VV)\).

- At grazing incidence angles \(\theta > 85^\circ\): \(\sigma_0(HH) \gg \sigma_0(VV)\) by 5 - 10 dB.

- Sea spikes in the modulation pattern resulting from breaking of intermediate-scale surface waves have values typically of 1-2 m/s.

Thank you for your attention