Measuring waves in sea ice using SAR imagery: A quasi-deterministic approach evaluated with Sentinel-1 and in situ data

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Outline

1. Wave patterns in SAR over sea ice: not new
2. Inverting for wave orbital velocities: Ardhuin et al. (GRL 2015)
3. Validation (Ardhuin et al. RSE 2017)
4. Application: from waves to ice properties?
   - Stopa et al. (JGR in press), Ardhuin et al. (JGR in press)
   - Stopa et al. (PNAS, in press)
Velocity bunching effects:

- waves in **azimuth** create bright lines in SAR image
1. Wave patterns in SAR over sea ice

Velocity bunching effects:

For monochromatic waves

For random waves:

→ harmonics are so strong, a spectral transform does not work

→ low values of intensity are good indicator of image nonlinearity

\[
I_{\text{max}} = \frac{1}{|1 - C|}
\]

\[
C = a\omega k H / V
\]

\[
I_{\text{min}} = \frac{1}{1 + C}
\]

Fig. 4. (a) Variation of the normalized image variance and normalized minimum intensity in the case of a monochromatic wave of amplitude \( a \) traveling along the azimuth direction, as a function of the SAR mapping nonlinearity parameter \( \sigma_k \).

(b) Similar variation but for a Gaussian wavenumber spectrum \( B(k) \propto \exp\left(-\frac{(k - k_0)^2}{\alpha_k^2}/2\right) \), with \( \sigma_k \) defined from the r.m.s. wave amplitude. \( I_{5\%} \) is the mean intensity of the 5\% least intense pixels, shown with dashed lines.

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Velocity bunching effects:

→ waves in **range**

make anything « wavy »: here is an example with 2 swells

Ardhuin et al. (GRL 2015)
2. Inverting wave orbital velocities

Our algorithm is supposed to handle 2 swells
- needs some supervision for the 2nd swell
- runs automaticall for a single swell
... in cases with homogeneous scenes

Further refinements (for non-homogeneity) are described in Stopa et al. (JGR, in press)

Ardhuin et al. (RSE 2017)
2. Inverting for wave orbital velocities

separate processing of each range line:
- linear estimate of \( v_1 \)
- adjustment of \( v_1 \) to get low intensities
- change of \( v_1 \) to shift peak positions along azimuth

After these 3 steps: check image spectrum
if not good: try a lower linear estimate

NB: small change in orbital velocity give large change in intensity
3. Validation

Using in situ buoys from the ONR DRI « Sea State & BL physics in the emerging Arctic »
Courtesy of Martin Doble, Peter Wadhams, Jim Thomson, Allison Kohout.
... and IW mode imagery thanks to ESA & Copernicus

Buoys are close to the ice edge …
still a bit of short wave energy
→ azimuthal cut-off
knowing the short wave energy (buoy)
we can correct for it…
Can we estimate it from the image ?
3. Validation

Other IW image from S1A: October 12, 2015
http://tiny.cc/S1AOct12

(Stopa et al., JGR in press)
3. Validation

Orbital velocity:
- OK near ice edge
- Too large farther
  (but Hs is OK because cut-off negligible there)

(Stopa et al. JGR in press, Ardhuin et al. JGR in press)
We can now map the ocean wave heights and learn a lot about wave attenuation.

Ardhuin et al. (JGR in press)
We can now map the ocean wave heights and learn a lot about wave attenuation.

**Multi-layered:** pancakes, frazil

**Single layer:** fractured ice

**Single layer:** solid ice

**Wave heights**

**Maximum floe diameter:** ice broken by waves

Ardhuin et al. (JGR in press)
And with S1A + S1B in wave mode: we have tons of data in Southern Ocean: A wide range of wave attenuations … from a few km to 100s of km …

**Strong and highly variable push of ocean waves on Southern Ocean sea ice**

Justin E. Stopa\(^a,1\), Peter Sutherland\(^a\), and Fabrice Ardhuin\(^a\)  

(Stopa et al., PNAS in press)

Over 2000 wave mode images have been analyzed to estimate wave decay …
When waves are attenuated they push the ice:

$$0.0000008 < \text{Decay rate} < 0.09 \text{ per meter} \rightarrow \text{stress of } 0.003 \text{ to } 1 \text{ Pa}$$

This stress is comparable to the wind stress over 50 km. Very **strong decay** (and stress) is presumable caused by very **thick ice** …

(Stopa et al., PNAS in press)
4. Applications

Green: wind stress
Blue: average wave stress
Over 50 km

(Stopa et al., PNAS in press)
5. Conclusion and Perspectives

• Wave patterns in SAR imagery over ice gives wave heights

• Wave heights are not easy to estimate right at the edge (cut-off), but more simple far inside the ice (in absence of leads, large floes …)

• Unique measurements of wave attenuation obtained from IW image in Arctic

• Wave mode data in Southern Ocean is a goldmine of amazing waves, ice & iceberg patterns

• Highly variable wave attenuation points to varying ice properties (thickness …)