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

Fabrice Ardhuin[a,*], Justin Stopa[a,b], Bertrand Chapron[a], Fabrice Collard[c], Madison Smith[d], Jim Thomson[d], Martin Doble[e], Byron Blomquist[f], Ola Persson[f], Clarence O. Collins III[g], Peter Wadhams[h]

[a]Univ. Brest, CNRS, IRD, Ifremer, Laboratoire d'Océanographie Physique et Spatiale (LOPS), IUEM, Brest, France
[b]LHEEA, Ecole Centrale de Nantes, France
[c]OceanDataLab, Brest, France
[d]University of Washington, Seattle, USA
[e]PolarScientific Ltd., Appin, UK
[f]NOAA/Earth System Research Laboratory, CIRES, University of Colorado Boulder, Boulder, CO, USA
[g]Oceanography Division, Naval Research Laboratory, Stennis Space Center, Hancock County, MS, USA
[h]Cambridge Polar Consultants Ltd., Cambridge, UK

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ABSTRACT

Measurements of wave heights in marginal ice zones are limited to very few in situ data. Here we revisit the linear and quasilinear theories of Synthetic Aperture Radar imaging of waves in the particular case of waves in sea ice. Instead of only working with spectra, we have developed an iterative nonlinear algorithm to estimate phase-resolved deterministic maps of wave-induced orbital velocities, from which elevation spectra can be derived. Application of this algorithm to Sentinel 1A wave mode images in the Southern Ocean shows that it produces reasonable results for swells in all directions except when they propagate at a few degrees off the range direction. The estimate of wave parameters is expected to work best when the shortest wave components, those which cause a pixel displacement of the order of the dominant wavelength in azimuth, can be neglected. Otherwise short waves produce a blurring of the image, increasing exponentially with the azimuthal wavenumber and reducing the estimated wave amplitude. Given the expected spatial attenuation of waves in ice-covered regions, our deterministic method should apply beyond a few tens of kilometers in the ice, without any correction for short wave effects. In situ data collected around the ice edge as part of the 2015 SeaState DRI cruise in the Beaufort confirm the progressive image blurring caused by such short waves, and the apparent reduction in the wave modulation. When short waves propagate from the open ocean towards the ice, this blurring can produce an unrealistic apparent increase of wave height, from the open ocean up to a few tens of kilometers inside the ice.

1. Introduction

A knowledge of wave parameters in sea ice is critical for navigation safety as well as for the understanding ocean currents and mixing near the ice (e.g. Rascle and Ardhuin, 2009) and the evolution of the ice edge (e.g. Davis et al., 2016). A quantitative estimation of wave height from satellite remote sensing would greatly augment the amount of available data in the marginal ice zones, where only few experiments have been performed (e.g. Wadhams et al., 1986; Kohout et al., 2014; Doble et al., 2015; Sutherland and Gascard, 2016; Smith and Thomson, 2016; Rogers et al., 2016). With their all-weather capabilities and unprecedented coverage, the high resolution modes of the Sentinel 1 constellation provides an extensive set of Synthetic Aperture Radar (SAR) images of the ice-covered ocean.

There have been many contributions to the quantitative analysis of waves in the open ocean using analyses of the image spectrum (e.g. Hasselmann and Hasselmann, 1991), and further adjustments in the spatial domain using the autocorrelation function (Collard et al., 2005). In ice-covered regions, patterns in SAR imagery due to ocean wave have also been reported by Lyzenga et al. (1985) among others. When such patterns are present, the dominant peak in the power spectrum of the image intensity yields the dominant wavelength and wave direction (e.g. Liu et al., 1991; Shulz-Stellenfleth and Lehner, 2002). Also, using the observed attenuation of waves and change of wavelength Wadhams et al. (2004) proposed to determine the ice

* Corresponding author.

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thickness. Such an application, however, requires a good understanding of the relationship between wave heights and patterns in the SAR image. This understanding is the main topic of the present paper.

The apparent modulation of the radar backscatter is expected to be caused by the velocity bunching effect. Velocity bunching is a displacement along the direction of motion of the radar antenna (the azimuth) of the scatterers in the SAR image. This displacement is due to the fact that both the position in azimuth and the scatterer velocity towards the radar contribute to the Doppler shift received by the radar. Hence, a homogeneous roughness with a spatial variation of velocities creates patterns in the SAR scene. A more complete interpretation of SAR scenes in the ice-covered ocean was proposed by Vachon et al. (1993) who also included tilt effects. Given the generally weak large-scale variation of radar backscatter with incidence angles over the ice, weaker than over water, in this work we will neglect here the tilting of the icy surface.

Because the velocity bunching can result in a highly nonlinear transformation of wave patterns into an image, the spectrum of the image can have a very different shape from the surface elevation spectrum. Consequently, the image contrast is not a monotonic function of the wave amplitude (e.g. Liu et al., 1991), which complicates a quantitative analysis of wave properties from SAR imagery.

Lyzenga et al. (1985) also showed how the velocity bunching transformed straight lines, like the ice edge, into oscillating contours. That idea was extended by Ardhuin et al. (2015) to the analysis of wave patterns within the ice pack, and the estimation of wave heights in the presence of two swell systems.

The expected displacement of targets in the azimuth direction is given by their velocity multiplied by the ratio of distance R to the satellite velocity along its orbit V. The target velocity can be decomposed into a vertical component w, and a horizontal component u, giving the displacement

$$\delta_A = (w\cos\theta_i + u\sin\theta_i)\,R/V, \tag{1}$$

where θ_i is the incidence angle, and $Z = R\cos\theta_i$ is the satellite altitude above the target, with R the radar-target distance. In ice-covered conditions, Ardhuin et al. (2015) further neglected the horizontal ice motion giving

$$\delta_A \simeq wZ/V. \tag{2}$$

The in situ data from SWIFT drifters (Thomson, 2012), discussed in Section 3, instead show that the vertical and horizontal motions have nearly equal amplitudes. In the particular event analyzed here, this applies within 4 km of the ice edge, and wave frequencies up to 0.2 Hz. Those data were taken within 4 km of the ice edge, and in wave frequencies below 0.2 Hz; it not clear how general this property may change with ice thickness and ice floe sizes. To include the u component we define the velocity v such that

$$\delta_A = vZ/V = (w + u\tan\theta_i)\,Z/V. \tag{3}$$

Because ocean waves are random, v and δ_A are random. All wave components traveling in the azimuth direction and with a wavelength shorter than the typical value of δ_A are blurred by the random displacements (Alpers and Rufenach, 1979). This effect is known as the azimuthal cut-off (e.g. Kerbaol et al., 1998). Because it is a prominent feature of spectra of SAR images, the cut-off has also been used to measure the root mean square orbital velocity of surface gravity waves (Stopa et al., 2015).

In ice-covered water, the short waves are quickly attenuated by their interaction with the ice (e.g. Squire et al., 1995), so that the blurring is weak. Instead the pixel displacement δ_A enhances coherent long waves propagating in azimuth. In many cases there is a simple relationship between the modulation in the image intensity and the rate of change of the vertical velocity along the azimuth direction. As already described by Hasselmann et al. (1985) and illustrated here in Fig. 1, the imaging of surface waves by the velocity bunching is exactly analogous to the mapping of the surface elevation by light patterns at the bottom of a pool. It is noteworthy that this optical technique has been used by Cox (1958) and Jähne and Riemer (1990). The main difference is that SAR imagery over the ice-covered ocean produces focusing only in the azimuth direction, and no such focusing in the range direction. Range bunching that is common in SAR images over land with mountain ranges correspond to cases when the ground or sea surface slope is comparable to the incidence angle.

The difference here is that the displacement in the image is not proportional to the surface slope but, as given by Eq. (1), it is proportional to the surface velocity. As a result, the SAR image is brighter where $-\partial v/\partial y$ is maximum, with y the azimuth direction.

Here we discuss how wave elevation spectra can be derived from various patterns in SAR images over sea ice using amplitude images. We particularly wish to take advantage of the sampling and coverage of the wave mode of the Sentinel-1 constellation. This wave mode extends the previous capabilities of ERS 1/2 and Envisat, and is ideally designed to map the large-scale evolution of wave properties across ocean basins (Collard et al., 2009; Hasselmann et al., 2012).

Our general objective is to define a level-2 processing to determine ocean wave spectra in ice-covered regions, as is currently done in open water (Chapron et al., 2001; Johnsen et al., 2006; Johnsen and Collard, 2009). A method is proposed in Section 2, using brightness patterns and spectral shapes. Following Hasselmann and Hasselmann (1991) our method uses the complete nonlinear SAR transformation, because nonlinear features are very common in SAR scenes over sea ice and the quasi-linear approach of Chapron et al. (2001) is not sufficient. Because short wind seas can often be neglected, our method is particularly adapted to the narrow wave spectra generally found in sea ice. The same method applies to both wave mode and interferometric wide (IW) swath images from Sentinel-1, as illustrated in Section 3. With that example we also use in situ wave measurements acquired near the ice edge during a 2015 field experiment in the Beaufort Sea (Wadhams and Thomson, 2015), in order to evaluate the wave estimates from our method, including the effect of short unresolved waves, with in-situ observations. Perspective and conclusions follow in Section 4.

2. Proposed method

Since the 1950s, with a turning point at the 1960 Ocean Wave Spectra conference (e.g. Longuet-Higgins et al., 1963), properties of ocean waves have been characterized routinely by spectra, estimated from time series, pictures or movies. This approach benefits from linear relationships between the wave elevation and measured variables (accelerations, pressure, slopes, etc.). Here, because the SAR transformation can be strongly nonlinear, we will first attempt to estimate a plausible surface velocity field that can explain observed patterns in SAR image, instead of estimating a wave spectrum. It is thus a deterministic approach in the sense that we resolve the phases of the waves and their detailed shape. We still use a spectral analysis but as a first guess and for final verification of the image properties. In this section we will neglect the blurring effect due to short wave components. That effect may be important close to the ice edge, as will be discussed in Section 3.

We have analyzed over 35000 wave mode images from two satellite missions Sentinel 1A and Sentinel 1B that contain wave patterns in sea ice. A visual inspection reveals that in all these cases, the wave field is dominated by one or two narrow swell systems. We have thus developed a two-step algorithm which aims at