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Retrieval of the ocean wave spectrum in open and thin ice covered ocean waters from ERS Synthetic Aperture Radar images (*)

G. De Carolis(**)

CNR, Istituto di Tecnologia Informatica Spaziale
Centro di Geodesia Spaziale "Giuseppe Colombo"
Loc. Terlecchia, 75100 Matera, Italy

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Summary. — This paper concerns with the task of retrieving ocean wave spectra from imagery provided by space-borne SAR systems such as that on board ERS satellite. SAR imagery of surface wave fields traveling into open ocean and into thin sea ice covers composed of frazil and pancake icefields is considered. The major purpose is to gain insight on how the spectral changes can be related to sea ice properties of geophysical interest such as the thickness. Starting from SAR image cross spectra computed from Single Look Complex (SLC) SAR images, the ocean wave spectrum is retrieved using an inversion procedure based on the gradient descent algorithm. The capability of this method when applied to satellite SAR sensors is investigated. Interest in the SAR image cross spectrum exploitation is twofold: first, the directional properties of the ocean wave spectra are retained; second, external wave information needed to initialize the inversion procedure may be greatly reduced using only information included in the SAR image cross spectrum itself. The main drawback is that the wind waves spectrum could be partly lost and its spectral peak wave number underestimated. An ERS-SAR SLC image acquired on April 10, 1993 over the Greenland Sea was selected as test image. A pair of windows that include open-sea only and sea ice cover, respectively, were selected. The inversions were carried out using different guess wave spectra taken from SAR image cross spectra. Moreover, care was taken to properly handle negative values eventually occurring during the inversion runs. This results in a modification of the gradient descending technique that is required if a non-negative solution of the wave spectrum is searched for. Results are discussed in view of the possibility of SAR data to detect ocean wave dispersion as a means for the retrieval of ice thickness.

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(**) E-mail: decarolis@itis.mt.cnr.it

1. – Introduction

Since the beginning of the eighties, it has become evident that SAR sensors can image the directional properties of two-dimensional ocean wave fields [1] and the theory that explains the SAR image formation process of ocean surfaces became available soon after as well [2]. Right now, SAR systems operating onboard orbiting platforms are the unique imaging instruments that are able to operate on a regular basis both in space and time under all weather conditions.

SAR imaging of moving surfaces is in general a non-linear process depending on the sea state and the actual imaging geometry of radar acquisition. In particular, the ratio between slant range R and platform velocity V plays an important role in determining the imaging process linearity. Existing orbiting SARs (ERS-1/2, J-ERS, Radarsat) and those planned to be launched in the near future (Envisat) are in fact characterized by R/V as high as 100 seconds, although steep incidence angle ($\sim 23°$ at mid swath for ERS-1/2) and narrow range of incidences ($\sim 7°$ for ERS-1/2) are used. The effect is that azimuth traveling waves having wavelength less than 100 m could not be imaged, almost independently of the sea state condition. Another source of non-linearity lays in the inherent 180° wave propagation direction ambiguity shown in conventional SAR image spectra.

When a closed non-linear mathematical transformation that maps a two-dimensional ocean wave spectrum into a SAR spectrum became available [3, 4], the task of retrieving directional ocean wave spectra from SAR image spectra attracted the interest of the scientific community. In order to provide the missed wave information into SAR spectra, the proposed inversion procedures as those described in [3, 5, 6] make use of *a priori* first guess ocean wave spectrum. First guess ocean wave spectra could be available from wave model predictions or gathered by *in situ* measurements. The major drawback is that they are not generally available all around the world, especially in extreme areas such as the Polar Regions.

Recently, a novel inversion procedure that does not require external wave information has been proposed and tested on airborne SAR imagery [7]. It exploits the property of the cross spectrum between individual look SAR images to retain the wave propagation direction without ambiguity so that the SAR image cross spectrum itself could be supplied as first guess spectrum to the inversion procedure.

This feature is very attractive with respect to the exploitation of ocean SAR imagery from Polar Regions to retrieve and monitor the changes in the wave fields while they propagate into sea ice, according to its physical and rheological properties such as type, extension, concentration and thickness. Although direct ice thickness retrieval remains outside the limits of remote-sensing capability due to the high electrical conductivity of sea ice [8], indirect estimates of ice thickness may be nevertheless envisaged. The analysis could be carried out by revealing the dispersion of the ocean wave field that crosses the interface separating the ice cover from the open-sea area [9, 10].

The objective of this paper is to test the capability of space-borne SAR image cross spectra to detect the dispersion suffered by ocean wave fields after encountering a sea ice cover. SAR image cross spectra can in fact be estimated from full resolution, complex-valued SAR data (SLC, Single Look Complex). The inversion procedure has been thus applied to the SLC SAR image of the Odden Ice Tongue in the Greenland Sea gathered by the radar aboard the European satellite ERS-1 on April 10, 1993 (orbit 9077, frame 1521).

2. – The forward mapping for SAR image cross spectra

The extraction of a sub-look SAR image from a SLC SAR image by means of the application of a band pass filter centered around the azimuth frequency f_0 returns the SAR image of a non-stationary scene centered at the time $t_0 = \mu^{-1} f_0$, where μ is the radar chirp rate. Given a couple of SAR look images $I(\mathbf{x}, t)$ and $I(\mathbf{x}, t+\tau)$ centered at times t and $t+\tau$, respectively, both extracted from the same SLC SAR image, the image cross spectrum is defined as

$$P(\mathbf{k}, \tau) = \lim_{A \to \infty} \frac{A}{4\pi^2} \frac{\langle \tilde{I}(\mathbf{k}, t) \tilde{I}^*(\mathbf{k}, t+\tau) \rangle}{\langle I \rangle^2} - \delta(\mathbf{k}), \tag{1}$$

where $\tilde{I}(\mathbf{k}, \cdot)$ is the spatial Fourier transform of the SAR image intensity $I(\mathbf{x}, \cdot)$ corresponding to the sea surface of extension A and $\mathbf{k}$ is the two-dimensional wave vector; $\delta(\cdot)$ is the Dirac δ-function. For ERS imagery, a pair of azimuth filters could be separated up to $\tau \cong 0.5$ s. According to the velocity bunching model [2], the SAR image intensity at point $\mathbf{x}$ in the image plane can be regarded as the mapping of the Real Aperture Radar (RAR) image intensity at the point $\mathbf{x}'$ in the scene plane displaced by the amount $\zeta(\mathbf{x}')$ along the azimuth direction. The RAR imaging is usually assumed to be a linear wave-radar modulation process for which a Modulation Transfer Function (MTF) can be defined in order to account for the modulation of the Normalized Radar Cross-Section (NRCS) due to range (across-track) traveling ocean waves. In the next sub-sections the problem of defining the RAR MTF in the two cases of SAR imaging in open sea and ice covered sea, respectively, will be addressed. Unlike the RAR image formation process, the velocity bunching process can result highly non-linear. The final expression of the SAR image cross spectrum is in fact given by [3, 4, 7]

$$\begin{aligned} P(\mathbf{k}, \tau) = {} & \frac{1}{4\pi^2} \exp\left[-k_y^2 \frac{R^2}{V^2} \rho^v(\mathbf{o}, 0)\right] \times \int\!\!\int \exp[k_y^2 \rho^v(\mathbf{x}, \tau)] \times \\ & \times \left\{ 1 + \rho^R(\mathbf{x}, \tau) + i k_y \frac{R}{V} \left[\rho^{Rv}(\mathbf{x}, \tau) - \rho^{Rv}(-\mathbf{x}, \tau)\right] + \right. \\ & \left. + k_y^2 \frac{R^2}{V^2} \left[\rho^{Rv}(\mathbf{x}, \tau) - \rho^{Rv}(\mathbf{o}, 0)\right] \left[\rho^{Rv}(-\mathbf{x}, \tau) - \rho^{Rv}(\mathbf{o}, 0)\right] \right\} \times \\ & \times \exp[-i\mathbf{k} \cdot \mathbf{x}] \mathrm{d}\mathbf{x} - \delta(\mathbf{k}), \end{aligned} \tag{2}$$

where R is the slant range of the target, V is the platform velocity and k_y denotes the azimuth component of the two-dimensional wave vector $\mathbf{k}$; finally, $\rho^v(\mathbf{x}, \tau)$, $\rho^R(\mathbf{x}, \tau)$, $\rho^{Rv}(\mathbf{x}, \tau)$ are covariance functions of the orbital velocity, of the RAR image intensity and of the RAR image intensity and orbital velocity, respectively.

For $\tau \neq 0$ the SAR image cross spectrum is a complex-valued function that obeys the condition $P(\mathbf{k}, \tau) = P^*(-\mathbf{k}, \tau)$. This means that its real part is symmetric and its imaginary part is asymmetric with respect to the transformation $\mathbf{k} \to -\mathbf{k}$. The ocean wave propagation direction can thus be retrieved from the imaginary part of the SAR image cross spectrum. In particular, the ocean wave spectrum is located in the spectral domains where the values of the imaginary cross spectrum are positive. Moreover, the cross spectrum estimate is not biased by the contribution due to the speckle noise. In fact, as the speckle noise can be modeled as a white uncorrelated process, the cross correlation (1) greatly reduces the resulting pedestal contribution which acts over the entire wave number space [7].

Finally, it should be pointed out that the exponential term multiplying the integral expression (2) represents the azimuthal cut-off due to the orbital motion of the all-scales ocean waves. It includes the ratio R/V that for ERS imaging is about 110 seconds, thus being a relevant factor for the SAR mapping non-linearity.

2˙1. *RAR imaging in open sea.* – Radar response of waves traveling in the range or near range direction is mainly determined by three modulation processes which form the RAR MTF: tilt, hydrodynamic and range bunching. A theoretical expression for the RAR MTF can be obtained in the framework of the two-scale wave model [3].

Electromagnetic scattering from the sea is usually modeled as a Bragg process in which only those short waves in resonance with the wavelength of the impinging e.m. radiation contribute to the formation of the NRCS. Tilt modulation arises from the variation of the local incidence angle due to long-waves profile. Assuming the wave spectrum is proportional to k^{-4} in the neighbor of the Bragg wave number at incidence angle θ, the analytical expression for VV polarization is

$$R^t \equiv i\,\frac{1}{\sigma^0(\theta)}\frac{\partial\sigma^0}{\partial\theta}\,k_x = 4i\,\frac{\cot\theta}{1+\sin^2\theta}\,k_x, \tag{3}$$

where σ^0 is the NRCS and k_x is the range component of the long wave with wave number $\mathbf{k}$.

Hydrodynamic modulation derives from the interaction of the short waves with the long wave. This latter modulates the short wave spectrum both in energy and wave number. This process is only approximately known through a weak hydrodynamic interaction theory in the relaxation time approximation [11]:

$$R^h = 4.5\,\omega k\,\frac{\omega - i\mu}{\omega^2+\mu^2}\cdot\frac{k_x^2}{k^2}, \tag{4}$$

where μ $(= 0.5\,\mathrm{s}^{-1})$ is the relaxation rate of the Bragg waves and ω is the angular frequency of the long wave.

Finally, the range bunching modulation is due to the change of the backscattering area due to the variation of the slope along the long wave profile. At the first order, it depends only on the incidence angle θ through the expression

$$R^h = \frac{ik}{\tan(\theta)}\,. \tag{5}$$

A validation study conducted by Brüning [12] has shown that the RAR MTF as given by the sum of the three MTFs given above is a reliable expression accounting for ERS-1 SAR imaging of ocean waves.

2˙2. *RAR imaging in sea ice.* – Ice cover affects considerably the high-frequency portion of the wave spectrum. In fact, the sea ice acts as a low-pass filter that dumps out capillary waves [13,14]. This has two effects on SAR imaging: first, Bragg scattering can no longer be assumed as the dominant e.m. interaction; second, short wave-long wave hydrodynamic modulation of NRCS responsible for the Bragg scale waves modifications is greatly reduced [15,16]. The inhibition of the latter mechanism is a direct consequence of the reduced energy spectrum of Bragg waves. It results that the RAR MTF is composed only of the tilt and range bunching contributions. While the range bunching MTF expression (5) is still valid, the tilt MTF has to be estimated. Since the existing scattering e.m. model predictions do not allow a comprehensive and tractable inclusion into the covariance functions included in (2), a direct estimation of the quantity $i((\partial\sigma^0/\partial\theta)/\sigma^0)k_x$ should be carried out on relatively calibrated SAR imagery. This latter approach has been considered in the analysis procedure herein contained.

3. – Inversion procedure and simulated results

The task of retrieving the ocean wave spectrum $S(\mathbf{k})$ from the SAR image cross spectrum $P(\mathbf{k},\tau)$ through the model (2) is an optimization problem that requires the definition of an objective function $\Psi[S]$ to be minimized starting from a feasible guess $S^0(\mathbf{k})$. Due to the physical meaning of $S(\mathbf{k})$, the search of the minimum for the objective function should be constrained to a non-negative solution. Although constrained non-linear programming techniques should be exploited to get the optimal solution $S^*(\mathbf{k})$, we have chosen to adopt the gradient-descending technique [7]. Since the gradient-descending is an unconstrained method of optimization, we have introduced a modification so that only non-negative values of the iterated ocean spectrum are kept at each iteration step. The up-date scheme at n-th iteration step can be thus stated as follows:

$$\left\{\begin{array}{ll} S^n(\mathbf{k}) = S^{n-1}(\mathbf{k}) - \alpha^n W^n(\mathbf{k}) \dfrac{\partial\Psi\left[S^{n-1}(\mathbf{k})\right]}{\partial S^{n-1}(\mathbf{k})}, & \alpha^n > 0\,, \\ \text{if} \quad S^n(\mathbf{k}) < 0, \qquad \text{then} \quad S^n(\mathbf{k}) = 0\,. & \end{array}\right. \tag{6}$$

The objective function has been defined as the error function between the observed SAR image spectrum $P_{\text{obs}}(\mathbf{k}',\tau)$ and the simulated SAR image cross spectrum $P_n(\mathbf{k}',\tau)$ from the n-th iterated ocean wave spectrum $S^n(\mathbf{k})$:

$$\Psi\left[S^n(\mathbf{k})\right] = \int\!\!\int \mid P^n(\mathbf{k}',\tau) - P_{\text{obs}}(\mathbf{k}',\tau) \mid^2 \mathrm{d}\mathbf{k}'\,. \tag{7}$$

The weight function $W^n(\mathbf{k})$ allows spectral increments both to be enhanced, where SAR information is relevant and to be penalized at high wave numbers where SAR information is less reliable. In order to accomplish the task, we chose a bell-shaped form for $W^n(\mathbf{k})$ whose width is recursively searched for every iteration step. The width value for which the objective function takes the minimum value is exploited. Finally, the parameter α^n is computed by first taking the linear contribution of the simulated SAR cross spectrum with respect to α and then minimizing the objective function Ψ with respect to α.

The reason for which the gradient method of optimization with the modification herein introduced has been considered is twofold: the gradient $\partial\Psi/\partial S$ that appears in (6) can be derived in a closed form [7]; the algorithm is easy to implement and gives satisfactory results within an acceptable number of iteration steps, as shall be shown in the next sections. It should be however pointed out that this technique could not return the "true" ocean wave spectrum as observed by SAR imaging because the procedure may get stuck in a local minimum, the latter being a feature common to almost all

Fig. 1. – Inversion results in simulation. First column: simulated ocean wave spectrum including a bimodal sea spectrum with significant wave height 4.1 m. Second column: different first guesses exploited, each one scaled at 3.0 m of wave height. Third column: inverted ocean wave spectra. It can be seen that inversion results were successful in all the cases considered, even if results obtained with asymmetric first guess ocean wave spectra (row 1 and 3) return the lower error between the expected spectrum and the retrieved one.

the deterministic optimization procedures. Nevertheless, stochastic procedures such as genetic algorithms should be exploited to try for getting the global minimum, even if they have to be proven to be effective for operational use.

To test the robustness of the inversion procedure (6) given the cost functional (7) to be minimized, some simulations were carried out with the imaging parameters applicable to the SAR aboard the ERS satellite. We assumed a separation time between the two SAR looks $\tau = 0.5$ s, an incidence angle of 23 degrees and the ratio $R/V = 107$ s. A bimodal ocean wave spectrum with significant wave height of 4.1 m that includes a wind wave system with peak at 130 m and a swell system with peak at 240 m was simulated. The corresponding SAR cross spectrum was computed using (2) and assumed to be the "observed" SAR cross spectrum. The inversions were carried out by exploiting three different first guesses, which were taken from the "observed" SAR cross spectrum as follows: a) the positive imaginary part; b) the real part of the SAR cross spectrum for those spectral domains where the imaginary part takes positive values; c) the modulus of the SAR cross spectrum. Unlike the first two, the third first guess spectrum is a symmetric spectrum. The guess spectra were scaled to a significant wave height of 3 m. Results are shown in fig. 1. The correlation values between the retrieved ocean spectrum and the expected one range from 0.96 for the run c) to 0.98 for run a), thus showing successful retrievals. Besides, the inversion procedure has been able to remove the directional ambiguity included in the first guess spectrum c). The most relevant differences lie in the wave components having wavelengths less than about 100 m. Due to the high R/V ratio imposed, the SAR spectral information is in fact partly missing in azimuth direction. The retrieved ocean spectra thus show distorted shapes at high azimuth wave numbers and the total wave energy is lower than that expected as well. The final significant wave heights are thus underestimated in all the cases, the ratio between the retrieved wave height and the expected wave height being of 0.93, 0.92 and 0.90, respectively for run a), b), c). Finally, the error between the retrieved ocean spectrum and the expected ocean spectrum ranges from 0.08 (run a)) to 0.20 (run c)). Although all the inversion results are in very good agreement with the expected one, it can be concluded that the inversion runs carried out by exploiting an asymmetric guess spectrum returned the best result.

4. – Effects of ice thickness on waves traveling into frazil and pancake ice

Pancake ice is a type of young ice that forms in turbulent waters. Sea surface freezing produces a suspension of small ice crystals (frazil ice), which may aggregate into cakes, typically 1 m across, called pancake ice. Due to the pumping of water or frazil ice onto their edges, the pancakes acquire raised rims. A simple scattering model [17] was developed to describe the propagation of waves in this kind of sea ice. Each ice floe is treated as an elastic-floating raft, which allows wave energy to propagate within itself as a flexural-gravity wave with an altered dispersion relation. Since in pancake and frazil ice the floe size is small in relation to the wavelength, only the ice thickness plays a relevant role. Sea ice can in fact be considered to be a continuum composed of non-interacting mass points, which exerts a pressure upon the water. Based on these assumptions, it results that the wave number k_i for propagation in ice is given by

$$k_i = \frac{k}{1-(\rho_i/\rho_w)chk}\,, \tag{8}$$

where k denotes the wave number propagating in open sea; h is the thickness of the frazil slurry or pancake, c is the average ice concentration and ρ_i/ρ_w is the ratio between ice and water densities. This implies a reduced wavelength $\lambda_i = 2\pi/k_i$ when a wave propagates from open sea to sea ice with the following consequences: 1) according to Snell's law, waves incident obliquely on the ice edge are refracted toward the normal; 2) propagation is not possible for waves whose wave number is greater than or equal to $k_c = (\rho_i/\rho_w)/ch$. This latter feature has implication on SAR imaging of frazil ice. Wadhams and Holt [14] observed on Seasat imagery of frazil ice that Bragg wavelengths

Fig. 2. – ERS-2 SLC SAR image (quadrant 4) acquired on April, 10 1993 (orbit 9077, frame 1521) in the Greenland Sea showing a region of open sea (upper left) along with frazil and pancake ice types mixed with water in the remaining frame. Superimposed is a lat/lon grid and two windows labeled with A and B, in open sea and sea ice, respectively. The windows show the locations where spectral analysis has been carried out (see text).

suffered extreme modifications into the ice so that frazil ice appears dark in SAR imagery. The same argument applies to pancake ice, but it appears bright on SAR imagery because of the raised edges that increase the surface roughness. Since it has been found that ocean waves propagating in pancake icefields and frazil can be imaged by space-borne SAR [10, 14], expression (8) gives a means to get estimates of its thickness by observing the change in wavelength as they cross the ice edge interface. In the next sections this model will be exploited as a physical tool for interpreting the inversion results from SAR imagery of frazil-pancake ice when compared with the ones from open sea region.

5. – The ERS imagery

An ERS SLC SAR image (quadrant 4) of the Odden ice tongue in the Greenland Sea acquired on April, 10 1993 (orbit 9077, frame 1521) was considered as test image. The Odden ice tongue is a sea ice feature, which develops in the region of influence of the Jan Mayen Current (72°-75° N) and it is mostly composed of grease ice like frazil and pancake ice. The selected scene includes both open sea and sea ice so that the spectral changes suffered by the ocean wave spectrum when it propagates from open sea to ice cover (or vice versa) can be detected and analyzed. After a proper spatial resampling to eliminate the stretching effect due to the different pixel and line samplings, the portion of image considered is shown in fig. 2. A grid of lat/long coordinates is also superimposed. The characteristic swirls of pancake ice mixed with open water and probably frazil ice can be

Fig. 3. – The windows extracted from ERS SAR image displayed in fig. 2. The labels A and B are relevant to open-sea region and sea ice region, respectively. It is worth to note how the wave pattern is significantly reduced in open sea due to the low-pass azimuth filtering caused by the random motion of water particles.

recognized in the right and bottom part of the image. The remaining part of the image is composed of open water. A couple of windows was then selected for spectral analysis: the window with label A in fig. 2 includes open sea, while window B in the same figure is mainly composed of pancake ice mixed with frazil ice and water. By visual inspection, backscattering modulation due to ocean wave propagation can be clearly observed in the sea ice region (fig. 3b), while open sea shows an almost homogeneous texture and the modulation pattern due to ocean waves is less evident (fig. 3a). This feature has already been reported in literature [15]. As capillary waves are severely attenuated by sea ice, an increase of the surface coherence that reduces the resolution loss due to SAR azimuth cut-off occurs. As a result, both modulation of long waves and azimuth wave components are enhanced as well. A relative radiometric calibration procedure has been carried out on the SAR image. It includes corrections for range spreading loss, antenna gain pattern and saturation due to analog-to-digital conversion. Absolute calibration was not possible because of the lack of calibration constant for this data set. From each window, two image looks with a time separation of $\tau = 0.45$ s were extracted and the related image cross spectrum was computed with a spectral linear resolution of $\Delta\kappa \cong 40 \times 10^{-4}$ rad/m. This figure includes both the intrinsic resolution limit due to the digital sampling and the smoothing procedure that has been applied to reduce the statistical uncertainty. Both SAR image cross spectra are shown in fig. 4. The open-sea SAR cross spectrum includes a wind sea system propagating toward the ice edge. Some interesting features can be recognized in the SAR cross spectrum relevant to sea ice imaging. In fact, its imaginary part includes a high-frequency peak other than the one due to the dominant wave. It is an image artifact due to the first harmonic contribution, which is frequently seen in sea ice imagery. Moreover, a low-frequency secondary wave system that is not present in the open sea can be seen in the real part of the cross spectrum. In any case, the propagation direction of the dominant wave system traveling in both media has been clearly resolved.

Fig. 4. – Observed ERS-2 SAR image cross spectra for open-sea window (first row) and sea ice (second row). For both spectra, the dominant wavelength is shown in the panel relevant to the imaginary part along with the first harmonic and a probable secondary wave system present in the real part and imaginary part of the sea ice cross spectrum, respectively.

6. – Inversion results and discussion

The inversion procedure described in sect. **3** was applied to the couple of SAR image cross spectra computed in open sea and ice covered sea. In order to evaluate the convergence capability of the inversion procedure, runs exploiting three guess spectra were carried out as for the simulated cases. For each run, it was chosen to terminate the inversion procedure when the cost function decrement between two consecutive iteration steps was less than 5×10^{-4}. The last inverted ocean spectrum is thus retained as the best retrieved spectrum. According to the simulation results, the procedure was able to completely remove the directional ambiguity regardless the first guess spectrum chosen. Figures 5 and 6 show the results for open sea and sea ice imaging, respectively. First guess spectra were scaled to a significant wave height of 2.0 m. This choice has been suggested by independent retrieval results that have been carried out on the PRI product of the same ERS image [10], but exploited through the inversion scheme described in [6].

While the theoretical RAR MTF was considered when inverting the open-sea SAR cross spectrum, the NRCS modulation due to hydrodynamic straining was neglected for the sea ice imaging case. Furthermore, the tilt MTF was estimated from relatively

Fig. 5. – Inversion results applied to the open-sea window. First column: retrieved ocean wave spectrum using first guess ocean wave spectra labeled with A, B, C; first guess spectra were scaled to a significant wave height of 2.0 m (A: positive imaginary part of the observed ERS-2 SAR image cross spectrum; B: modulus of the observed ERS-2 SAR image cross spectrum; C: real part of the observed ERS-2 SAR image cross spectrum at wave number locations where the imaginary part is positive. Second column: real part of the SAR image cross spectrum computed from the corresponding inverted ocean spectrum. Third column: same as column 2, but relevant to the positive imaginary part. Fourth column: evolution of the cost function Ψ(—) and of the significant wave height H_{s} (- - -) as a function of the iteration steps occurred to complete the inversion procedure.

calibrated SAR data of the selected sea ice region (fig. 3b). It was found that the best fit of $(\partial\sigma^0/\partial\theta)/\sigma^0$ with the relatively calibrated SAR data gave a value of 15.

Unlike the retrieved ocean wave spectra in open sea, inversion results from sea ice show a bimodal wave spectrum, as expected. The dominant wave system in sea ice, to be compared with the one showed in the open-sea wave spectrum, results from the wind sea spectrum coming from the open-sea region; the secondary swell system imaged in sea ice is peaking at about 300 m and propagates almost opposite the wind sea spectrum. This wave system is lost in open region due to the noise added by the reduced surface coherency. Moreover, it should be pointed out that the retrieved open-sea spectrum is limited by the intrinsic azimuth cut-off of SAR imagery. As only information from SAR

Fig. 6. – Same as fig. 5 but relevant to the sea ice window.

data has been exploited, the high-frequency part of the ocean spectrum cannot be fully retrieved by the inversion procedure. As a consequence, the inversion scheme tries to recovery the ocean wave energy by enhancing the spectral peak and eventually displacing it towards a lower wave number. These considerations may not apply when retrieving the ocean spectrum in sea ice. Depending on the wind conditions and sea ice properties, the attenuation of capillary-short wave regimes may cause a relevant reduction of the wind sea range of wave numbers such that only "SAR visible" waves can propagate into it.

A spectral partitioning scheme that associates a wave system with a given peak of a wave spectrum has been applied on the retrieved ocean spectra to get the statistical spectral parameters such as the mean wavelength, the mean propagation direction and the significant wave height [18]. Table I reports the results for the corresponding wind wave systems propagating in open sea and sea ice, respectively. The reported uncertainties refer to the averaged values over the three retrieved ocean spectra. The retrieved significant wave heights (H_s and $H_\mathrm{s}^\mathrm{total}$) returned similar values within decimetric figure, thereby the related uncertainty was not reported.

According to Wadhams' wave propagation model, the wind wave system changed its statistical parameters both in propagation direction and wavelength. In particular, the change of the peaks and of the average wavelengths are in the expected direction, *i.e.* the

TABLE I. – *Peak wavelength, mean wavelength, mean propagation direction, significant wave height of the corresponding wind wave system. In the last column, the significant wave height of the entire wave spectrum.*

	λ_{peak} (m)	λ_{ave} (m)	θ_{ave}(deg)	H_{s} (m)	$H_{\text{s}}^{\text{total}}$ (m)
Open sea	176 ± 10	160 ± 14	45 ± 1	1.5	2.6
Sea ice	134 ± 12	132 ± 10	48 ± 1	1.5	2.4

wavelength propagating in sea ice is reduced when compared with the corresponding that travels in open sea. This reduction could be attributed to the ice thickness, although a quantitative and statistically reliable estimation cannot herein be carried out. In order to reduce the underlying statistical error of the estimate, a number of windows into pancake ice and open sea should in fact be considered and the results averaged together. Furthermore, it should be pointed out that estimate of ice thickness from data reported in table I give unreliable value. This could be partly assigned to the misleading peak location of the open-sea spectrum caused by the azimuth SAR cut-off; on the other hand, the inability of the wave model to predict the right change of wavelength should also be accounted for.

7. – Conclusions and outlooks

The task of retrieving the ocean wave spectrum from ERS SAR imagery both in open sea and in ocean waters covered by frazil/pancake ice has been addressed. The possibility offered by SAR image spectra to detect the spectral changes suffered by an ocean wave field when it crosses an interface between the two regions is investigated. As a result, the potential use of SAR imagery to measure thin sea ice properties such as its thickness has also been considered. The scientific relevance is motivated by a number of reasons strictly related to the necessity to map ice composition of polar regions in terms of ice concentration, type and thickness in order to gain insight of the atmospheric and marine processes influencing the global climate. As an example, in 1986 a band of pancake ice 270 km width next to the ice edge was observed in Antarctic during an oceanographic cruise. If the 270 km width is a circumpolar phenomenon, this means that Antarctic pancake in winter could reach 6 million km^2, that is a significant part of the cryosphere. A modified gradient-descending inversion scheme has been proved to capture the major spectral properties of two-dimensional wave spectra by exploiting SAR information only. A drawback is however imposed by the high R/V ratio relevant to ERS illumination geometry. In fact, it may hamper the correct high wave number estimation of wind-generated waves. This effect could not be important for a wind sea generated in open waters when it propagates into sea ice regions. The low-pass filtering imposed by sea ice reduces in fact the wave number spectral range toward the lower frequencies, thus enabling the proposed inversion scheme to estimate the "true" wave spectrum with minor distortions. The detected spectral changes could be suitably used to retrieve ice properties such as the thickness, provided that a reliable wave propagation model is used for proper data interpretation. In order to gain physical insight into the occurring spectral changes, a simple wave propagation model has thus been considered. The model considers the frazil and pancake ice as composed of noninteracting masses which have no rheological or coherency properties but exerting a pressure over the water surface. The major model's prediction is that ocean waves of geophysical interest could reduce their length as they travel from open-sea region. Results on the SAR data set here considered are in accord with model's prediction trend when measuring the length of the dominant wave in either region. Extensive validation should however be carried to get ultimate understanding of wave propagation in grease ice. As improvement of the technique here presented, a refined inversion scheme for wave fields propagating in open sea should be envisaged. It might be based on the exploitation of a wind sea prediction model in which the wind vector is taken as parameter to be fitted.

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