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Wave and wind retrieval from SAR images of the ocean

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Abstract

Over the past few years, recognition of the importance of the coastal zone has led to the establishment of international programmes for monitoring the coastal zone environment and its change. The European programme MARSAIS is part of this effort. One important component of such actions aims to better predict the sea surface wind and wave dynamics in these vulnerable regions where most economic marine activity is taking place.

Indeed, ocean surface wind and wave observations serves both oceanographic and meteorological communities and have direct applications for driving ocean circulation models, numerical predictions and short term forecasts, but also for advancing in the physical understanding of the complex interactions that take place at the ocean-atmosphere interface. As now well recognised, satellite data and particularly the weather independent radar remote sensing data present potential advantages and applications to achieve these requirements. Nowadays, sea surface remote sensing techniques are rapidly developing throughout the world and need some kind of assessment. Altimetry and scatterometry are well proven techniques, which result in recognised operational applications. Synthetic Aperture Radar (SAR) missions have not enjoyed such successes. However numerous space borne radar images of the ocean surface have revealed a wealth of information on different dynamical processes and SAR images of the ocean surface very often reveal a remarkable range of signatures on the uppermost layers of the sea. These data have resulted in numerous quantitative scientific findings and theoretical advances in upper-layer and lower atmosphere dynamics. In this review, the main different techniques developed to retrieve surface wave and wind information are recalled. Illustrations are given for ENVISAT wave mode products.

Key words: Remote sensing, Land observation satellite, Oceanographic survey, Surface state, Sea state, Wind, Synthetic aperture radar, Inverse problem.

ESTIMATION DU VENT ET DES VAGUES À PARTIR D'IMAGES RSO DE LA SURFACE DE L'OCÉAN

Résumé

Depuis quelques années la reconnaissance de l'importance de la zone côtière a conduit à l'établissement de programmes internationaux pour la surveillance de l'environnement et ses changements. Le programme européen MARSAIS fait partie de cet effort. Une composante importante de telles actions a pour but de mieux prédire la dynamique du vent et des vagues à la surface des océans dans ces régions vulnérables où la plus grande partie de l'activité marine a lieu.

En effet, les observations du vent et des vagues à la surface de l'océan servent aussi bien les communautés d'océanographie que de météorologie et ont des applications directes pour forcer les modèles de circulation des océans, dans les modèles de prédiction numériques et les prévisions à court terme, mais aussi pour aider à comprendre les interactions complexes qui prennent place à l'interface océan-atmosphère. Ainsi qu'il est actuellement bien admis, les données satellitaires, et particulièrement celles provenant d'acquisitions par radar non affectées par les conditions météorologiques, présentent un potentiel d'avantages et d'applications pour répondre à ces besoins. De nos jours, les techniques de télédétection de la surface des océans se développent rapidement dans le monde et il est nécessaire de les évaluer. L'altimétrie et la diffusiométrie sont des techniques bien établies qui donnent des résultats en applications opérationnelles reconnues. Les missions Radars à Synthèse d'Ouverture (RSO) n'ont pas eu un tel succès. Cependant de nombreuses images de l'océan par radars satellitaires ont révélé une grande richesse d'information sur différents processus dynamiques et ont très souvent montré une remarquable étendue de signatures des couches les plus proches de la surface. Ces données ont permis des découvertes scientifiques quantitatives et des avancées théoriques

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sur la dynamique des couches supérieures de l'océan et de la basse atmosphère. Dans ce papier, les principales techniques développées pour retrouver les informations de vents et vagues de surface sont rappelées. Des illustrations sont données pour les produits « vagues » du prochain satellite ENVISAT.

Mots clés : Télédétection, Satellite observation Terre, Observation océanographique, État surface, État mer, Vent, Radar ouverture synthétique, Problème inverse.

Contents

I. INTRODUCTION

Synthetic Aperture Radar (SAR) instruments are advanced imaging system in which dedicated Doppler processing of the signal can be used to achieve very fine along-track (azimuth) resolution. For a SAR, this azimuth resolution is solely specified as one-half of the antenna length. This improved resolution making the SAR so peculiar is simply achieved by tracking the individual phase and amplitude of individual return signals during a given integration time interval. This is used to simulate the so-called synthetic aperture, a distance much longer than the effective length of the instrument antenna. The SAR process directly uses the recorded individual Doppler shift in the backscatter signal to determine the exact position of the scatter in the azimuth position. In contrast, the across track resolution is simply obtained through standard range discrimination using the radar chirp (frequency modulation) principle.

It can then be easily understood that the Doppler analysis is greatly affected when the observation is made over a random time-varying surface such as the sea surface. Sea surface radar echoes will have their phases locally modified by the underlying sea surface motion to blur the true ocean-wave field scene. As further controlled by the range-to-velocity ratio, such a problem is almost systematically observed for SAR instruments on board high altitude polar orbiting platforms. As probed by a SAR instrument, the ocean surface represents a collection of random moving scatterers leading to a systematic distortion of the imaged spectrum. In most cases, the random blurring is so strong that the shortest wave components are filtered out.

As theoretically recognized, Doppler shifts and associated misregistrations in azimuth (along track) are mostly associated with the random orbital motions leading, among other effects, to a measurable cut-off in the azimuth direction. The shortest detectable azimuth wavelengths are limited to about 200 meters in the case of the ERS Wave Mode products. Furthermore, purely non-linear coupling effects between wave spectral components at different frequencies have also been clearly identified for high orbiting SARs. Therefore, the possible sea-state cases for which space-borne SAR products alone can be simply inverted and used are appreciably limited. In recent years, several methods have then been proposed and developed to overcome these difficulties for extracting the directional ocean wave spectrum from SAR data and valuable retrieved information have now been proved to be routinely extracted from ocean SAR products. In particular, with the successful ERS missions and their so-called SAR Wave Mode products, wave modellers can, for the first time, obtain continuous global information. Unlike conventional buoy measurements mainly located near shore, satellite data are available in the open ocean where waves are generated and propagate. The SAR Wave Mode dataset acquired by the ERS satellites since 1991 comprises a unique set of about 5 million ocean wave spectral observations distributed over the world seas and oceans. Such a sensing device will continue to be implemented in space in the near future (ENVISAT), and it is presently the only source of data that potentially provides directional information on the presence of swell. Several remaining problems must still be solved or clarified but, it can already be stated that, in the swell part of the spectrum, the SAR measurements properly carry the necessary information.

Parallel to these efforts, it has further become clear that a SAR instrument can provide measurements on more local phenomena, especially in coastal areas. The SAR is actually an imaging scatterometer. Once radiometrically calibrated, SAR images offer unique opportunities to analyse high-resolution (about 1 km) radar cross-section measurements to potentially infer mesoscale wind measurements that were never possible before. Potential applications of such a capability are numerous and will help to validate fine resolution state-of-the-art meteorological and ocean circulation models. These data can in particular complement the coarse-scale (20-50 km) wind information obtained from standard wind scatterometer. In that sense, the high resolution aspects of SAR do also indicate promise for wind stress analysis at spatial scales within the synoptic, providing information on specific local phenomena associated with marine boundary layer transformations, current patterns, oceanic fronts and eddies... Under low wind conditions, the analysis can be extended to surface slicks detection and shallow-water bathymetry. Such a vivid source of information is currently not operationally used to derive local climatology, but it can be anticipated that much attention will be devoted to such developments in the near future where large swath SAR systems will be operated (ENVISAT, RADARSAT).

Finally, the knowledge of the local wind characteristics (magnitude and direction) has also been recognised to be one of the major factor to improve our ability to properly retrieve the directional spectrum of ocean surface waves. It is now commonly suggested that it will help to better define local imaging modulation transfer functions as well as to better determine an a priori improved first guess wind sea spectrum to start a complete inversion algorithm.

Difficulties clearly encountered with the SAR technique to map perfectly ocean surface waves have been, somehow, compensated by innovative signal processing analysis. These works cover a large range of subjects: processing methods of the SAR data, improved formulation of the transfer function relating the SAR image spectra to the wave spectra, image pixel statistical analysis, retrieval algorithms to obtain wave spectral properties, and wind.

Hereafter, we will present an overview of the current knowledge concerning the SAR imaging process over the ocean, that can be used to estimate waves and wind properties, and report on the main wave retrieval algorithms. In particular, we report the recent version of the SAR inversion algorithm (developed by NORUT-No, and IFREMER-Fr) chosen by the European Space Agency to deliver the so-called « level 2 » products from the wave mode of ENVISAT. We also recall the capabilities of SAR measurements to estimate the wind vectors.

II. SAR IMAGING PROCESS OF SURFACE WAVES

The SAR is a two-dimensional imaging system that can produce images of the ocean surface with an extremely high spatial resolution (e.g., about 20×16 m^2 for the ERS-SAR instruments).

Close to the range direction (across track), the wave imaging process is the same as for a real aperture radar (RAR). It is dominated by the modulation in backscatter due to the long wave induced varying surface tilt (local relative orientation) and straining (local roughness modulation). In that sense, the imaging of ocean waves by a very high resolution radar instrument (SAR, RAR) is commonly described on the basis of a two-scale model: waves shorter than the resolution cell mostly contribute to the composite Bragg resonant backscattering mechanism, ride on a weakly random sea of much longer waves. The short waves (waves within the resolution cell) are only described through their statistical average properties (elevation and slope variances, elevation spectrum amplitude and directionality). They directly contribute to the wind dependent mean radar cross section over the scene.

These shortest components are usually wind-generated waves and ride over more deterministic modulating longer waves to produce measurable local contrasts. These observed modulations are supposed to be linear and small compare to the mean radar cross section.

II.1. Tilt modulation

As pictured, the longer waves will locally modify the exact plan of incidence, producing a local change in cross section (following the geometrical characteristics of the instrument). This so-called **tilt modulation** is thus linearly related to the slope of the long waves with a proportionality coefficient which is related to the derivative of the relative cross section as function of the incidence angle. So far, this derivative has been determined according to a given scattering model (Bragg) or through a direct estimation based on an empirical model (CMOD, see e.g. Stoeffelen et Anderson, 1993). The former estimation has been originally introduced by Hasselmann and Hasselmann, 1991 in their seminal work on the non-linear mapping of the ocean surface wave spectrum by a SAR instrument. The latter estimation has been mainly promoted by Mastenbroek and De Valk, 2000 in their semi-parametric algorithm to retrieve ocean wave spectra from SAR. This technique is sought to avoid uncertainty associated with the use of a pure-Bragg scattering model, and do certainly offer an efficient alternative for C-band VV polarised SAR data.

II.2. Hydrodynamic modulation

Longer waves are also known to govern part of the dynamics of the local shorter wave spectrum. As commonly observed, the roughness distribution is inhomogeneous along a longer wave profile. Such a physical phenomenon will then introduce an additional so-called **hydrodynamic modulation** to describe the radar wave imaging process. Current parameterisations are still subject of on-going active research efforts and usually follow weakly non-linear theory solutions, (see e.g. Hasselmann and Hasselmann, 1991). Actual inversion algorithms solely rely on the weakly non-linear formulation mainly describing the orbital straining effects.

II.3. Velocity bunching effect

To complete the SAR imaging mechanism, the induced Doppler shifts, mainly associated with the longer wave orbital velocity field, must be considered as a very crucial mapping process. The motion effects do influence strongly the SAR imaging mechanism by affecting the complex backscatter signals. Doppler shifts associated with the longer wave orbital velocities can also potentially contribute to an additional constructive modulation mechanism, (see e.g. Alpers and Ruffenach, 1979). In such a case, the so-called **velocity bunching** mechanism may help to image swell wave components in the along-track direction. This constructive mechanism is especially efficient under low wind conditions (relatively deterministic phase component redistribution).

The velocity bunching effect is controlled by the range-to-velocity ratio and the relative radial component of the scatterers velocity:

$$C_{vb} = \frac{R}{V} \frac{du_R}{dx_0}$$

where x_0 is the azimutal coordinate in the ocean plane, R is the range, V the carrier velocity and u_R the radial component of the target velocity. Linearity is observed for small values of $|C_{vb}|$ (Krogstad, 1992).

II.4. Azimutal smearing

The entire wave phase velocity field is also undoubtedly of fundamental importance in the SAR measurements. Besides a possible along-track scale distortion associated with the simultaneous motions of both the SAR instrument and the wave field (becoming significant for airborne SAR measurements having long integration time), the wave phase velocity field can also lead to a systematic deterministic misregistration between successive looks (defocusing effect). Such an effect lowers the apparent image contrast. But, in counterpart, it may give the opportunity to remove the directional ambiguity of imaged harmonic components, if one can sufficiently resolve the main wave pattern translation between the different looks as it occurs during the SAR integration time. To this end, a simple cross-spectral analysis between looks has proven to be a sufficient tool (even for the short 0.8 s integration time of ERS SAR satellite instrument) to provide the longer ocean wave propagation direction (Engen and Johnsen, 1995).

Such a crucial breakthrough concerning the potential use of cross-spectral analysis between SAR individual looks is now commonly well accepted to improve the analysis of SAR data. Thanks to NORUT efforts to suggest, develop and promote this idea, such a methodology is now routinely implemented and has been demonstrated to help directly determine the exact propagation direction of swell systems for 90 % of the measurements (as long as the signal to noise ratio is sufficiently high). Such a methodology has been validated and is currently used as a reference technique. This consensus has led the European Space Agency to change the Level 1 product from ERS to ENVISAT. For this latter satellite, single look complex (SLC) images will hence be routinely provided by ESA for the Wave Mode. From these SLC images, cross-spectral analysis will be used to provide the direction of propagation of the long waves without the 180° ambiguity which previously existed with ERS.

Furthermore, such a technique will also contribute to obtain speckle (intrinsic radar multiplicative noise) compensated image cross spectra. Based on a global dataset of complex SAR Wave Mode, different aspects of SAR processing have been tested (Lehner et al. 2000). In particular, it has been shown that not only azimuth cross-correlation but also range multilooking technique can be applied to deal with speckle bias. This improvement will first greatly help wave retrieval algorithms under low sea state conditions (low signal-to-noise conditions). But more significantly, such a cross-spectral methodology can be used to help to refine the measurement of the intrinsic induced sea surface motion degradation, the so-called azimuth cut-off parameter. Indeed, the use of noise-free cross-spectra can help to better identify and separate the non-linear contributions in the wavenumber domain. For all the existing wave spectrum retrieval algorithms, it is indeed essential to properly determine this spectral region, as well as to correctly estimate the associated cut-off parameter directly entering in the definition of an optimal quasi-linear approximation of the complete non-linear SAR mapping transform. As now introduced in a new cost function in the seminal inversion algorithm (Hasselmann et al., 1996), the azimuth cut-off estimate is the key parameter governing the strength of the exponential attenuation in the spectral azimuth domain.

The list below summarises the various effects and properties that contribute to the formation and/or the degradation of satellite SAR images:

- **Tilt modulation**: variation in reflectivity due to the local modification of the relative incidence angle by long wave slopes.
- **Hydrodynamic modulation**: variation in reflectivity due to the non uniform scatter distribution along a long wave profile.
- **Constructive azimuth velocity bunching**: deterministic misregistrations in the azimuth direction, associated with long wave orbital motions, leading to an apparent constructive redistribution of the backscatter intensity along the azimuth direction.
- **Destructive azimuth velocity bunching**: random misregistrations in the azimuth direction, associated with long wave orbital motions, leading to possible significant degradation in the azimuth resolution, leading to distortions of the resulting SAR ocean image spectra (non-linear reationship between SAR image spectra and ocean wave spectra).
- **Range elevation bunching**: misregistrations associated with long wave slope variations. The misregistrations are proportional to the surface elevation and depends on the nominal instrument incidence angle.
- **Acceleration smearing**: smearing in the SAR image associated with relative velocity changes during the SAR integration time.
- **Azimuth smearing**: reduced along-track resolution associated with both the unresolved random scatter motions and the limited scatter lifetime during the SAR integration time (finite scene coherence time).
- **Speckle**: multiplicative noise in the SAR images due to the coherent processing. Its statistical characteris-

tics will depend upon the chosen look summation technique. The inter-correlation (cross-spectral) technique will help to almost entirely remove the speckle distribution in the spectral domain.
- **System transfer function**: point target response characteristics which lead to a varying sensitivity over the SAR spectrum.

II.5. Transfer function relating wave fields to SAR images

Today, the SAR imaging mechanisms of the ocean surface waves, as well as the limitations, are fairly well understood. Analytical expressions describing the non-linear ocean-to-SAR spectral transform have been developed and published in the literature. After the integral formulation originally proposed by Hasselmann and Hasselmann, 1991, later reformulated and generalised by Krogstad, 1992, SAR investigators have readily access to a comprehensive tool to theoretically simulate a realistic ocean wave spectrum mapping onto the SAR domain.

The integral describing the non-linear rar to sar transform is given by:

$$\hat{I}^{SAR}(k) = \lim_{A\to\infty} \frac{1}{|A|} \int_A \exp\{-ik[\mathrm{v} + \xi(\mathrm{v})]\} I^{RAR}(v)dv$$

Where $\xi(\cdot)$ represents the displacements due to the radial velocity of the scatterers.

The PSD (Power Spectral Density) is given by :

$$P(k) = \lim_{A\to\infty} \frac{1}{|A|^2} \int_{A^2}\int \exp\{-ik[u - u_0)]\} G(u, u_0, k_a) du\, du_0$$

with :

$$G(u, u_0, k_a) = \mathrm{E}\left[I^{RAR}(u) \exp\{-ik_a[\xi(u) - \xi(u_0)]\}\right]$$

A quasi-linear expression is obtained for the first order part of this formulae.

As further demonstrated from numerous well documented investigations, the dominant modulation mechanism is clearly recognised to be due to the velocity bunching – constructive and destructive – phenomena, which are certainly very well described by the current theory.

This is clearly not the case for the hydrodynamic modulation definition which must help to linearly describe the small scale scatterers non uniform distribution over the longer wave profiles. Theoretically, such a modulation transfer function can be determined from the formulation of the energy balance equation of short waves. But practically, no comprehensive theory has been formulated to include the wind and wave age dependency in this function, and present formulation still rely on the chosen definitions of both the small scale spectral form and the relaxation parameter associated to the resonant Bragg waves. However, as noted above for spaceborne SAR instruments, velocity bunching dominates the other modulation mechanisms. Furthermore, for low incidence angle settings, the tilt modulation is also thought to dominate the hydrodynamic modulation, and recent results show a minor impact on the retrieval results when incorporating different improved hydrodynamic formulation.

Nevertheless, the prospect of the Advanced SAR (ASAR) to be deployed on board the ENVISAT satellite which can also operates at higher incidence angles and with both VV and HH polarisation settings will anew stimulate the hydrodynamic issue. In particular, it is recommended to concentrate the main efforts on a better representation of the hydrodynamic modulation transfer function for low and high wind speed conditions, large incidence angles (larger than for the ERS configuration), and/or HH polarisation where it is likely that the relative contribution and distribution of breaking events cannot be neglected. Indeed, large deviations between observation and standard two-scales model results have been observed in these conditions (Romeiser et al, 1994, Kudryavstev et al, 2001).

Concerning an improved definition of the tilt modulation transfer function, it is admitted that intermediate scale waves smaller than the SAR resolution cell (about 10 m) but larger than the resonant Bragg wavelength (about 8-10 cm) strongly contribute to the radar cross section at low incidence angle (less than 30°). The simplified two-scale composite model omitting such a contribution is thus not fully adequate to describe the radar cross section tilt modulation (Romeiser et al., 1997, Kudryavstev et al, 2001). Moreover, the most common tilt modulation definition relies on a particular shape of the elevation surface wave spectrum around the Bragg resonant wavenumber, stating that small-scale waves are saturated. Under such an assumption, the tilt modulation transfer function is thus wind vector independent for the whole range of wind speed. This is a quite unreasonable assumption, and in absence of a reliable physically-based scattering model, tilt model functions have been now developed using direct or empirical model estimates of the relative radar cross section decrease as a function of the incidence angle. Tilt modulation functions are then found to be wind speed dependent leading to much higher values than the standard ones under low to moderate wind speed conditions. Such a methodology has to be further tested but results obtained with CMOD inferred tilt functions indicate that better agreements are found when comparing measured and expected SAR pixel normalised variance parameters (Kerbaol et al. 1998). This estimation is routinely implemented in the ARGOOS two-step retrieval algorithms (Mastenbroek and De Valk, 2000). Comparisons between retrieval algorithms and the wave prediction model WAM seems to confirm a relative overestimation of the swell energy components using standard tilt modulation transfer function (Voorips and Mastenbroek, 2001).

III. WAVE AND WIND RETRIEVAL ALGORITHMS

Subsequent to the derivation of a comprehensive non-linear closed form analytical expression, different algorithms for inverting the specified spectral mapping relationship have been developed. A retrieval algorithm generally attempts to reconstruct the ocean wave spectrum by minimising the difference between its corresponding theoretical SAR spectrum (obtained with a forward transformation) and the satellite observation. The exact derivative of the non-linear transform being too cumbersome to carry out, most of the existing inversion schemes partially ignore the complete non linear mapping and mostly use the simplifying gradient of a so-called optimised SAR quasi-linear transform that best matches the full non linear transform. The first detailed evaluation of the ERS-1 SAR Wave Mode based on this inversion methodology was performed for a 3-day dataset in the Atlantic Ocean, by Brüning et al, 1994.

After the first inversion algorithm proposed by Hasselmann and Hasselmann in 1991 (the so-called MPI algorithm), improved versions of this algorithm have been developed (MPI, DLR). An explicit cut-off adjustment has been introduced, and a better «partitioning» scheme has been proposed to decompose the first guess a priori wave spectral information and to minimize the cost function (see the WASAR algorithm described by Hasselmann et al., 1996). More recently, DLR has still improved this algorithm by including the cross-spectral analysis, which is used to remove the 180° ambiguity in the propagation direction, and to get a better estimate of the speckle noise.

The alternative methods developed by ARGOOS, and more recently by NORUT and IFREMER (see below) is based on a simplified inversion method, which does not explicitly rely on the definition of an a priori guess spectrum. It consists of separating the retrieval scheme into two steps: one for the wind sea part of the spectrum, the other for the swell only contribution. In particular for the ARGOOS retrieval approach (Mastenbroek and De Valk, 2000), the first step uses the complete non-linear SAR forward transform starting from an a priori knowledge of the wind speed. Subsequently, the minimisation is done over the two main parameters governing the wind sea parameterisation : the sea state degree of development and the mean propagation direction. The necessary a priori wind sea spectrum can be provided from an a priori knowledge of the local wind vector as given by a concurrent measurement (ERS scatterometer) or from a numerical atmospheric model output. In the second step, the swell spectrum is directly estimated from the residual signal, i.e. the observed SAR spectrum minus the mapped wind sea contribution. To further simplify the inversion, this step can be done by assuming a linear mapping. To ensure the validity of the inversion, this two-step scheme is iterated. Concerning the 180° ambiguity in the swell propagation direction, an a priori guess spectrum model output and/or the result of a cross-spectral analysis when SAR single-look complex products are available can be used.

Further pushing the assumption that the imaged swell components do not significantly contribute to the total orbital velocity variance, and so to the apparent loss of azimuth resolution, simplified direct quasi-linear inversions have also been routinely implemented to retrieve the longer wave spectral information (once again giving an a priori knowledge of the propagation direction). Wave observations in the Southern Oceans from SIR-C/X-SAR have in particular been shown to be in satisfactory agreement with the US Navy's Wave Analysis Model (WAM) in most cases, and the remaining differences are likely due to forecast errors rather than to SAR errors (Monaldo and Beal, 1994). It must be noted however that in this shuttle-based SAR data set, the azimuth resolution degradation was significantly reduced, because of the small range-to velocity ratio of the platform. For such efficient methods, it is then essential and crucially recommended to properly determine the azimuth cut-off parameter. This parameter will indeed directly enter in the definition of an optimal quasi-linear approximation of the complete non-linear SAR forward transform. In particular, the azimuth cut-off estimate is the key parameter, which governs the strength of the exponential attenuation in the spectral azimuth domain.

For this particular problem, different techniques have also been developed to determine the observed spectral cut-off. They can be separated into two main schools: the SAR image spectral domain estimation, and the SAR spatial correlation domain estimation. When the SAR image itself is available (and especially the Single Look Complex (SLC) product), the spatial correlation technique offers the best results for most of the environmental conditions. Moreover, the inter-correlation technique from a SAR SLC product will be speckle free and will greatly help the azimuth cut-off parameter estimation. However, for the current operational applications requiring low bit rate data (ERS data), spectral domain estimations have to be applied so far (ARGOOS, ECMWF/MPI).

III.1. Summary of wave retrieval algorithms

- **Direct quasi-linear Inversion**: it is the most simple scheme. Once a cut-off parameter is estimated to model the azimuth resolution loss, a single operation is necessary to get an inverted wave spectrum (given the three principal modulation transfer function definitions, tilt, hydrodynamic, velocity bunching). Such a method provides reasonable results for weak cut-off parameter cases (airborne or shuttle SAR low Range/Velocity SAR measurements, low wind speed conditions, relatively low sea state conditions), and must only be applied to retrieve very long wave spectral information. Besides a required small cut-off, this technique will further suffer from lower wavenumber spectral features which are not simulated with quasi-linear transform but are associated with the genuinely non-linear SAR mapping of shorter wind waves. The inversion requires an a priori knowledge of the swell propagation direction.

- **Mixed Inversion**: this is also a rather simple method based on an optimised quasi-linear SAR spectral mapping. In such an approach, this quasi-linear transform is used both to compute the gradient of the cost function and to perform the forward mapping between the iterative steps. This algorithm has been first described by Krogstad and Vachon, 1994, and requires a first guess spectrum. The minimisation is carried out by updating the first guess wave spectrum within the regions defined by the union of the SAR and the first guess spectral domain. The cost function can include a term associated with the azimuth cut-off. This approach will also suffer from lower wavenumber features (cf. above). Also in case of opposite wave propagating systems as predicted by a first guess spectrum, one of them will be kept unchanged during the inversion. A partitioning technique is then necessary that will increase the computation burden.
- **Improved Mixed Inversion**: this approach combines the complete non-linear forward SAR transformation with the use of the gradient of an optimised quasi-linear one. This algorithm requires an a priori first guess spectrum. This approach had been first introduced by Hasselmann and Hasselmann in 1991, and has been revised and improved over the passed few years (cf above, Hasselmann et al., 1996). First, the overall level of the unmeasured high wavenumber part of the spectrum is somehow better controlled through the inclusion of an explicit cut-off penalty term in the cost function. Since the inversion method only modifies the detailed form of the spectrum in the spectral domain for which SAR spectral information is available, this technique would lead to unrealistic discontinuities in the transition interval separating the different spectral regions of influence. To overcome such a difficulty, a spectral partitioning is introduced into an additional iteration loop that updates the input spectrum. This inversion method is by far the most complicated scheme. However, since the scheme uses WAM as first guess and a spectral partitioning, the ambiguity is in most cases correctly solved for all modes. It can also be noted that the previous algorithm does use a specific method to estimate the azimuth cut-off parameter (adapted to ERS SAR Wave Mode products) which differs from most of azimuth cut-off estimation methods. Improvements of this inversion scheme have been achieved by extending the present algorithm with a cross-spectral analysis to improve removal ambiguity and to better handle low SNR spectra.
- **Two-step Inversion**: this is a relatively simpler algorithm using a first guess wind sea spectrum. This approach is based on the assumption that the wind sea part of the spectrum contributes the most to the non-linear imaging mechanism. The inversion is separated into two steps: first, a non-linear minimisation with respect to the wind mode, and then a linear minimisation with respect to the swell mode. The wind mode minimisation is done with respect to the wind sea peak direction and wave age. To this end, the full non-linear SAR forward transformation is used. The residual SAR spectrum, i.e. the observed SAR spectrum minus the estimated wind sea contribution, is then minimised with respect to any swell mode using a linear SAR approximation. At this stage, the contribution of the swell to the cut-off results is tested to further adjust the most likely wave age parameter: if necessary, a new iteration follows. This methodology strongly relies on an a priori good knowledge of the local wind sea condition. This algorithm has first been developed (ARGOOS, IFREMER) using co-located wind vector scatterometer estimates. Improving the direct SAR wind vector estimate would then further improve this method but analysis of a wave prediction model (WAM for example) can as well be used to initialise the wind sea modes for the first step. The cross-spectral analysis helps to remove the swell ambiguity propagation problem. The algorithm adopted at ESA to provide the so-called level 2 products belongs to this class of methods.

III.2. Wind estimate from sar

SAR images contain information not only on swell systems, but also on capillary-gravity waves, which respond quickly to the wind action on the ocean surface. Therefore the SAR may be viewed as an imaging scatterometer. SAR high-resolution products can then also provide local wind information at about 1 to 10 km resolution. Such detailed wind fields could obviously benefit both coastal meteorological and oceanographic applications. Furthermore, since surface waves and winds are closely related, the interest of deriving wind information from the SAR images is evident. More directly and as seen above, accurate SAR wind retrieval may be essential for the successful determination of the inverted SAR ocean wave spectrum

In addition, the next generation of spaceborne SARS (RADARSAT-I and II, ENVISAT) are not (or will not be) coupled with wind-scatterometer measurements as it has been the case for the ERS satellite missions. Therefore, efforts have to be carried on to improve the retrieval of wind information from SAR images. Furthermore, virtually all SAR ocean studies require the wind-related impact on the image because to first order, the ocean SAR backscatter is caused by wind-generated short scale waves. For example, interpretation of features such as current fronts, surface eddies, or internal waves must account for the possibility of the wind impacting the feature identification.

As a first methodology, the near surface wind speed may be estimated using scatterometer empirically derived radar cross section model function. Such an approach for high-resolution wind vector retrieval will work reasonably well for average conditions (in terms of fetch and swell). It is required (Horstmann et al., 2000) for the SAR data to be given in terms of absolute calibrated radar cross sections. For instance, due to saturation of the analog-to-digital converter in case of high backscatter (high wind speed), the ERS SAR images and imagettes need to be recalibrated, (Kerbaol et al., 1998, Lehner et al., 1998). As reported, errors found in the derived wind speed are mainly due to such ADC saturation problems but also from uncertainties of the wind input direction. It is also useful to keep in mind that numerous non-wind geophysical external effects can influence the radar backscatter.

Up to now, the method most widely used to estimate the wind from SAR images is based on one of the empirical models derived for the scatterometer observations (e.g. Stoeffelen and Anderson, 1993, CMOD model) to relate the radar cross-section to the wind vector. Conceptually, this is a limitation, because scatterometer data and SAR data do not contain the same variability, due to their different resolution (typically 50 km x 50 km for the scatterometer, a few ten to hundred of meters for the SAR). For instance, under low-wind conditions, the wind speed and direction may well be expected to significantly vary. The backscatter power is very sensitive for such a case with a high dynamic range. The resulting low-resolution measurement of a scatterometer will then be highly biased, dominated by areas of higher winds where the look direction of the instrument is more aligned with the local wind direction or/and the swell direction. A local SAR cross section measurement will not carry such an overall variability, and will thus have a greater dynamic range compared to the one associated with scatterometer model predictions. In particular, it must be expected that relative dependency with incidence angle will be more pronounced for SAR measurements than predicted by a CMOD type of model. Compared to wind estimates from scatterometer, SAR wind speed estimates obtained with the empirical models derived from scatterometer, will hence tend to be overestimated, in particular in low wind conditions.

This dependency of the radar cross-section with incidence angle can directly be inferred from relative radar cross section variations across the SAR image, but cannot be obtained locally from scatterometer measurements. This unique SAR capability can certainly help to improve our ability to retrieve the local wave vector, as well as to improve the definition of a local tilt modulation transfer function for wave retrieval algorithms. However, difficulties arise with the proper validation of such measurements with in situ ground truth. So far, empirical models of CMOD type (developed for scatterometer) are still used.

More crucial, the use of a SAR as a high-resolution scatterometer instrument is strongly hampered by its single antenna configuration. Contrary to a wind scatterometer instrument, the wind direction cannot be directly inferred since different azimuth signatures of the radar cross section are not measured. The wind direction must then be indirectly estimated either by identifying shadowing effects for near shore scenes or by analysing orientations of the smallest wavenumber spectral components. At this stage, it is not obvious to only attribute such a spectral signature to manifestations of roll vortices in the planetary boundary layer since the non linear character of the SAR mapping may produce low wavenumber features associated with the presence of very short wind waves (otherwise erased in the SAR spectrum). Whatsoever, current studies confirm that if detected, lower wavenumber variations can lead to robust wind direction estimates. In particular, Horstmann et al., 2000 reported that for ERS SAR images, 65 % of the investigated data exhibited wind-induced streaks to enable reliable wind direction estimates (up to the directional 180° ambiguity).

In parallel, it has also been demonstrated that another source of information can be exploited to complement SAR scatterometry-like analysis. Indeed, a SAR instrument not only provides spatial information in terms of mean and variance backscatter measurements, but also temporal information. These latter sources will characterise the temporal variability that occurs during the SAR integration time and can thus potentially help to estimate the local wind vector. In particular, this complementary source of information is directly related to the sea surface motions and the analysis of the observed spectral azimuth cut-off. According to theory, this latter parameter is proportional to the root-mean-square line of sight wave orbital velocity field. At near nadir incidence angles (ERS like configuration), this radial component is dominated by the vertical velocity variance, which is mainly supported by the shortest waves, in contrast with the height variance which is mainly supported by the longer waves (Jackson and Peng, 1985). For average environmental conditions, the portion of the spectrum supporting these waves can be associated with the wind sea part of the spectrum, and the measurable SAR azimuth degradation becomes a very valuable parameter to complement the backscatter analysis. Indeed, convincing comparisons between these cut-off parameters with simultaneous co-located scatterometer wind speed estimates first highlighted the preponderant role of the wind generated wave random motions in SAR azimuth resolution losses, and thus the ability to derive a simple wind speed algorithm (Kerbaol et al. 1998).

One must be cautious that SAR cut-off parameter estimates are also carrying long wave orbital motion information. The azimuth cut-off parameter is associated with the random wave motions, which are not supported only by purely wind-generated waves. In particular, in case of fetch-limited or relaxation conditions, as well as in the presence of large swell systems, this may affect the relation between cut-off wavelength and wind speed. Further analyses have to address possible dependencies of the relation between wind speed and azimuth cut-off on the spectral stage of development or wave age, in order to obtain a globally more valid and satisfying relationship.

Moreover, following the theoretical development that helps to define a two-step methodology for the wave spectrum retrieval algorithm, and exploiting the inter-look correlation technique, an improved method has been proposed (NORUT/IFREMER). The SAR ocean image spectrum is first expressed as a sum of a non spectrally resolved wind dependent contribution and a longer wave contribution. The idea is then to fully exploit the information contained in the wind dependent spectral domain. This is done by analyzing the cross-spectrum phase-plane tilt. Indeed, as theoretically predicted and also measured, the non-linear redistribution of energy in the SAR mapping is wind-direction dependent. If sufficiently sampled (depending upon the number of along-track points), this technique seems very reliable for high wind conditions. Furthermore, a differential azimuth cut-off estimator can also be defined by simply using the ratio of the azimuth cross- spectrum profiles obtained for two different look separation time. The idea is to make use of the extremely short life-time of the wind generated ripples that is impacting the overall smearing of the SAR scene. This extended analysis of the inter-look methodology is thus related to the measure of the SAR scene coherence time which is known to be also closely related to the local wind stress (breaking characteristics). These alternative approaches using spectral (kinetic) properties will complete our panoply to retrieve the local wind vector. However first tests performed on ERS re-reprocessed SLC data show that analysis on images larger than 10 km × 5 km are necessary to apply these methods.

The different parameters and methods to be used for extracting wind information from SAR measurements are listed below:

- **Radar cross section**: this imperatively requires radiometrically calibrated radar data. This radar backscatter measurement must then be related to the wind speed, given an a priori knowledge of the wind direction and a model function. In the case of ERS SAR measurements, investigations have been conducted using scatterometer empirically derived CMOD-like model functions. As known, the backscatter is not only dependent on the mean wind characteristics but also strongly dependent on the wind variability (e.g., if the radar cross section is proportional to the squared magnitude of the local wind, the mean radar cross section is proportional to the wind speed variance). Empirical models derived from global scatterometer observations will thus be somehow limited to retrieve local high-resolution wind estimates. Furthermore, empirical model function still needs to be defined for C-band HH polarisation measurements (RADARSAT, ENVISAT HH mode).
- **Incidence angle dependency**: this parameter will also imperatively necessitate properly radiometrically corrected radar measurements. The relative decrease within a SAR scene can indeed be related to wind speed, given an a priori knowledge of the wind direction and a model function. As stressed above, global empirical model functions integrate an overall mean wind variability and should not perfectly predict the dynamic range that can be locally observed. However, the use of both the radar cross section and its incidence angle dependency can certainly help to better constrain a wind retrieval algorithm scheme.
- **Pixel normalised variance variability**: As for the very high resolution measurements, the measured variability is mainly related to large scale wind fluctuations that can potentially be attributed to the presence of roll vortices in the planetary boundary layer. A standard procedure consists of analysing the spatial wind variation after inversion in terms of its spectral behaviour in the low wavenumber spectral domain. Using very large SAR scene, it is indeed expected to observe a spectral density increase with increasing spatial scales (Horstmann et al., 2000). Such a type of analysis must apply to large SAR scene. It is still under development but can be thought to be used to test the results from different inverted wind field solutions.
- **Low wavenumber spectral analysis**: this is now a standard procedure to assess the wind direction. It uses the results from a pattern (shape and orientation) analysis performed on low wavenumber spectral features. Commonly attributed to wind rows, the wind direction can be inferred assuming that these wind streaks are aligned at some angle with the mean wind direction. Atmospheric rolls are supposed to be more pronounced under unstable conditions. These method will obviously suffer from non-wind low wavenumber spectral signature such as in the presence of slicks and/or backscatter anomalies associated with mesoscale phenomena (currents, bottom topography, oceanic and atmospheric fronts, precipitations, ...).
- **Cut-off analysis**: this measurement is directly related to wave orbital variance parameter and thus implicitly carries a wind dependency. A simple relationship has first been developed based on direct comparisons between simultaneous ERS SAR Wave Mode measurements and ERS scatterometer winds (Kerbaol et al., 1998). The main weaknesses of this approach are the cut-off estima-

tion itself and biases potentially induced by non-local wave system contributions to the total orbital velocity variance as well as possible dependencies on the spectral stage of development. An improved cut-off analysis has been now proposed using speckle compensated SAR cross-spectra to better separate the highly wind aligned small-scale contribution from the large scale one. Cleaner spectral measurements can indeed help to better assess the SAR spectral level and rate of decay in the range of high wavenumber. Using a parabolic approximation of the characteristic function associated with pixel motions, it can be shown that in this spectral domain the cut-off is also highly sensitive to the wind direction. Further tests must be performed to properly assess the potential of such a new approach that can be easily combined to the scatterometry-type of method.

- **Cross-spectrum phase analysis**: As stated, the SAR ocean image spectrum can first be approximated as a sum of a wind dependency contribution and a so-called swell dependency. Although the wind sea spectrum is not linearly spectrally resolved, it appears that the cross-spectrum phase can still carry sufficient information (in the non-linear contribution wavenumber region) to deduce the wind direction. As found and expected, the higher the wind speed the more accurate is the retrieved wind direction. At lower wind speed, the technique indeed suffers from a commonly too low signal-to-noise ratio. In addition, this method seems better adapted for the analysis of large SAR scenes.
- **Time decorrelation**: SAR ocean scene coherence time may be evaluated by estimating smearing effects. To this end, the ratio between azimuth cross- spectrum profiles obtained for different look separation time is performed. The idea is to make use of the extremely short life time of the wind generated ripples that is impacting the overall smearing of the SAR scene. This technique do need a significant averaging process (large number of azimuth samples) and is not foreseen to be applicable to SAR Wave Mode data.

It must also be emphasised that a SAR instrument is a very unique instrument able to provide both spatial and temporal (Doppler) information. These measurements can undoubtedly help to extract wind vector characteristics with high accuracy. Spatial estimates can provide the mean and variance of backscatter measurements, as well as some wind-related features (wind rows, shadowing effects). Temporal variability that occur during the SAR integration time directly affects the surface wave imaging process and can contribute to better characterise the local wind vector (directional characteristics of the wave motions). We think that in the future, it is a proper combination of these two very valuable sources of information that will lead to the definition of particularly efficient SAR wind retrieval algorithms.

1.1. Examples of wave retrieval algorithms for ENVISAT

As already discussed above, the philosophy of the proposed ENVISAT ASAR wave retrieval scheme is to separate the algorithm into two steps: one for the identification of the purely non-linear contribution, the other for the swell only contribution. After identification and estimation of the non-linear contribution to the observed cross-spectrum (i.e. mostly the wind sea contribution), a residual SAR spectrum is computed from the subtraction between the observed spectrum and this non-linear contribution. The obtained remaining spectrum is then solely a quasi-linear contribution which can easily be solved with respect to the swell spectrum after proper estimation of the linear modulation transfer function (RAR MTF) and the azimuth cut-off parameter.

Figure 1 illustrates this theoretical partitioning between non-linear and quasi-linear mapping contributions. As clearly demonstrated, there is a significant part of the azimuth spectral region where the non-linear and the quasi-linear contribution do not overlap. In this particular region, the wind information can thus potentially be extracted.

The retrieval methodology starts by pre-processing the Single Look Complex (SLC) data to perform the look extraction and the cross spectral estimation. This pre-processing stage follows the steps listed below:

- Detrend the input SLC image using a Gaussian low pass filter operation where the width of the filter is set such as to remove the low frequencies not related to waves.
- Compute the co-spectrum and the two cross-spectra corresponding to three looks.
- Estimate the system transfer function, the bias of the co-spectra and remove it from the co-spectra.

This procedure gives one unbiased co-spectrum and two cross spectra generated with different look separation times. All of these spectral estimates are combined statistically and used in the wind and wave spectra retrieval.

For the wind retrieval part, both the spectral and the phase information of the cross spectra are combined with the radar cross-section (obtained after properly calibrating the image intensity). The wind retrieval methodology then follows:

- Estimate the azimuth cut-off factor by fitting cross-spectra to a pre-calculated look-up table. The look-up table is built using the direct SAR non-linear transform for conditions of fully-developed wind-waves. The empirical wind-wave spectrum fixed to build this look-up table follows a standard parameterization (Jonswap type).
- Fit the phase measurements of the cross-spectra to a pre-calculated look-up table with respect to wind direction. Again, the look-up table is based on simu-

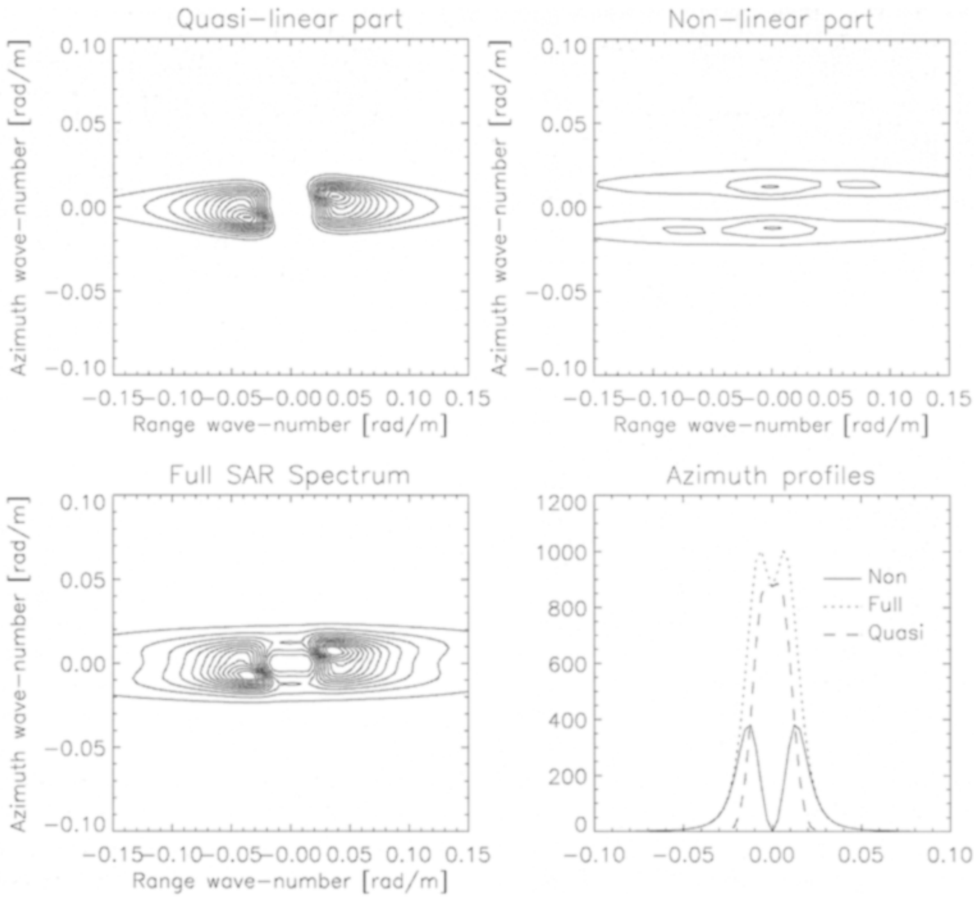

FIG. 1. — Simulated cross spectra (quasi, non-linear, and full transfer function) and azimuth spectral profile of the real part of ocean-to-SAR cross-spectral transform for windspeed = 10 m/s, wind-direction = 0 deg (counter clock wise from positive range axis), and look separation time = 0.1s.

Interspectres simulés (fonction de transfert quasilinéaire, non-linéaire et complète) et profil spectral en azimut de la partie réelle de la transformée interspectrale Océan-RSO pour une vitesse de vent de 10 m/s, une direction de vent de 0° (sens inverse des aiguilles d'une montre à partir de l'axe radial positif), et un temps de séparation entre vues de 0,1 s.

lated non-linear cross-spectral SAR mapping using prescribed wind-wave spectra.
- Use the wind direction, the measured radar cross section, and empirically derived backscatter model function (CMOD) to estimate the wind speed
- Alternatively or in addition, the azimuth spectral time decorrelation can be estimated from azimuth spectral ratios of spectra with different look separation times (0, t, and 2t). These decorrelation times can be combined with the look-up table to yield wind speed estimates.

For the wave spectrum retrieval part, the fundamental assumption is that the cross-spectral transform can be expressed as the sum of a non-linear part and a quasi-linear part. The different steps of the wave spectrum retrieval procedure are:

- Use the estimated wind field to extract the non-linear spectral part, the azimuth cut-off factor, and the MTF, from the pre-calculated look-up table. Again, the look-up table is built using the direct SAR non-linear transform for a large range of fully-developed wind waves conditions.
- Remove the non-linear contribution and solve for the real part (symmetric) and imaginary part (asymmetric) wave spectra for co and cross-spectra.
- Compute weighted average solutions for symmetric and asymmetric spectra using the clutter noise values.
- Compute the Signal-to-Noise Ratio (SNR) of the asymmetric spectra.
- If the SNR is above a given threshold, then smooth the asymmetric spectra (SNR dependent), and combine the symmetric and asymmetric wave spectra using their clutter noise levels to yield the ambiguity free wave spectrum.
- If the SNR is below a given threshold no ambiguity removal is performed and the symmetric spectrum is kept unchanged.

The swell inversion procedure will estimate the swell wave spectrum resolved by the SAR (the detected wavy pattern in the SAR scene). Note that, although the extrac-

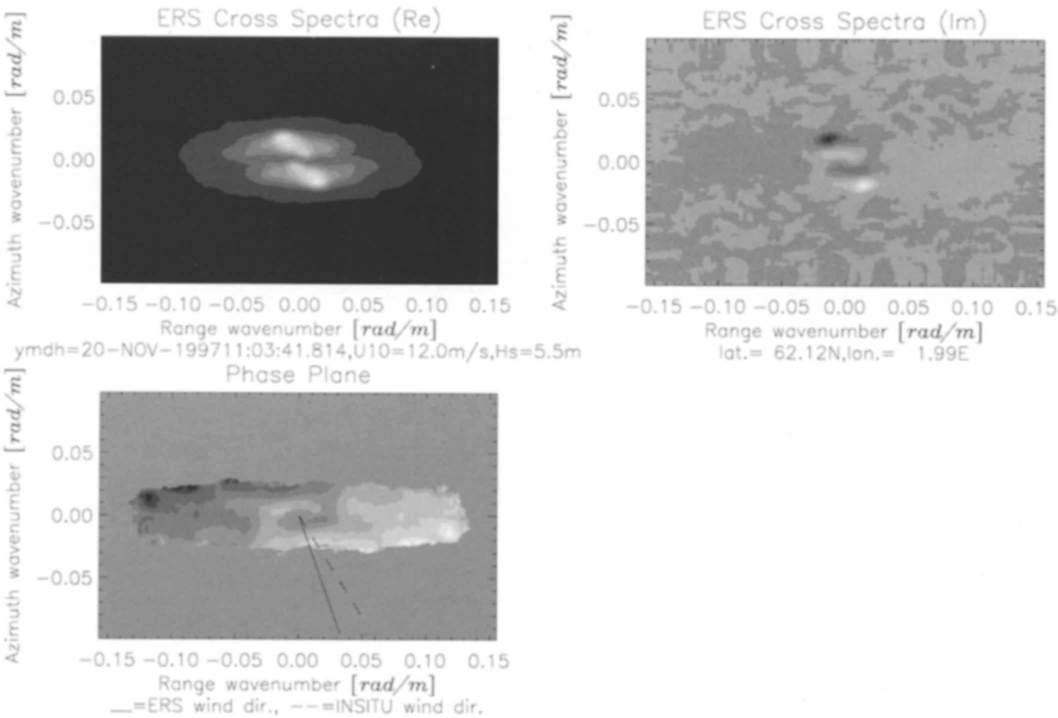

FIG. 2. — Cross spectrum (top left: real part, top right: imaginary part) with the corresponding cross spectral phase (bottom left) processed from ERS-2 SLC data. The SAR derived wind direction and the in-situ measured wind direction are indicated on the so-called phase spectrum.

Interspectre (en haut en gauche : partie réelle, en haut à droite : partie imaginaire) avec la phase interspectrale correspondante (en bas à gauche) traitée à partir de données ERS-2 SLC (Single Look Complex). La direction du vent déduite du RSO et la direction du vent mesurée in-situ sont indiquées sur le spectre de phase.

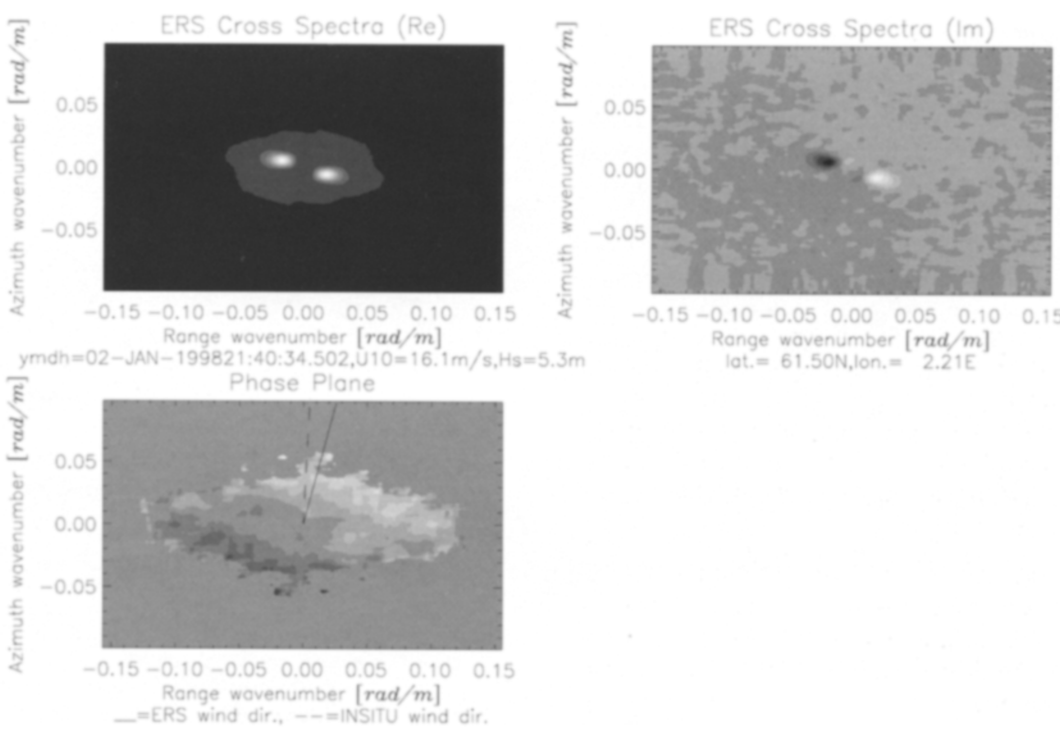

FIG. 3. — Same as Figure 2, for another case.

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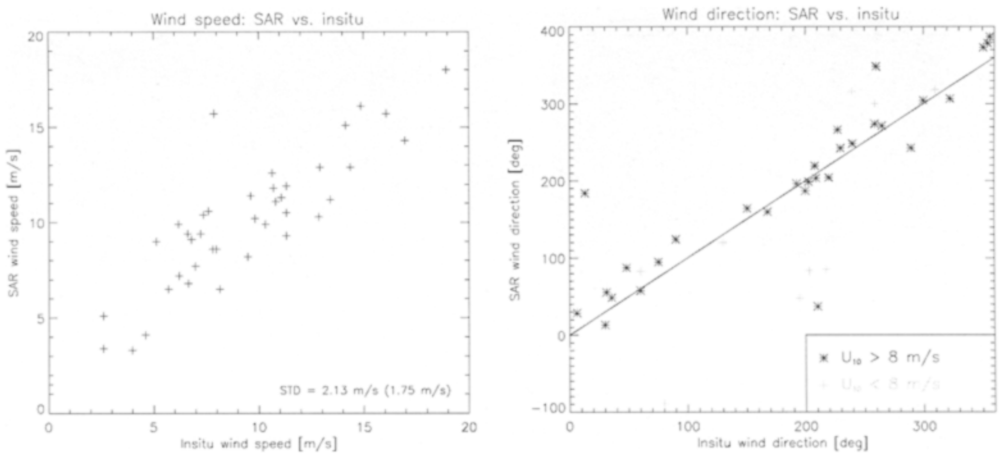

FIG. 4. — ERS SAR wind speed versus in-situ wind speed (left). SAR wind direction versus in-situ wind direction (modulo 360°) (right).

Vitesse du vent du RSO d'ERS en fonction de la vitesse du vent in-situ (gauche). Direction du vent du RSO d'ERS en fonction de la direction du vent in-situ (modulo 360°) (droite).

tion of the swell is based on the quasi-linear transform, the inversion use the full theoretical non-linear SAR mapping in the inversion process through the coupling with the non-linear part.

The SAR wind field retrieval methodology described above has been applied on ERS SLC data selected in the Norwegian Sea, collocated with in situ measurements from platforms and ships. Figures 2 and 3 present two illustrative examples of the wind direction information in SAR cross and phase spectra.

As shown in Figures 2 and 3, the cross-spectral phase exhibits a tilted orientation closely correlated to the local wind sea direction. As also clearly illustrated for both examples, the wind sea spectrum is not spectrally resolved. It must also be noted that the phase associated with the well-resolved swell components does not align with the phase plane of the cross spectra.

The results of this procedure on a larger set of ERS SLC image mode data are shown in Figure 4. As found the overall agreement is good, and clearly the best results are obtained for sufficiently high wind speed values. Indeed, for light wind speed conditions, the computed cross spectrum and consequently the phase spectrum are insufficiently well-resolved (low signal-to-noise ratio).

The wave retrieval procedure performances have been tested with ASAR Wave Mode Level 1 products (SLC image and cross-spectra) directly simulated using ERS Wave Mode raw data.

These results (see Fig. 5 to 8) show the effective promises to provide ambiguity free estimate of the SAR detected main wave pattern. This is solely done by using the cross-spectral analysis, and thus does not need external a priori source of information. Note that for these imagettes, an a priori fixed wind direction (45°) has been chosen in the wind-estimate algorithm

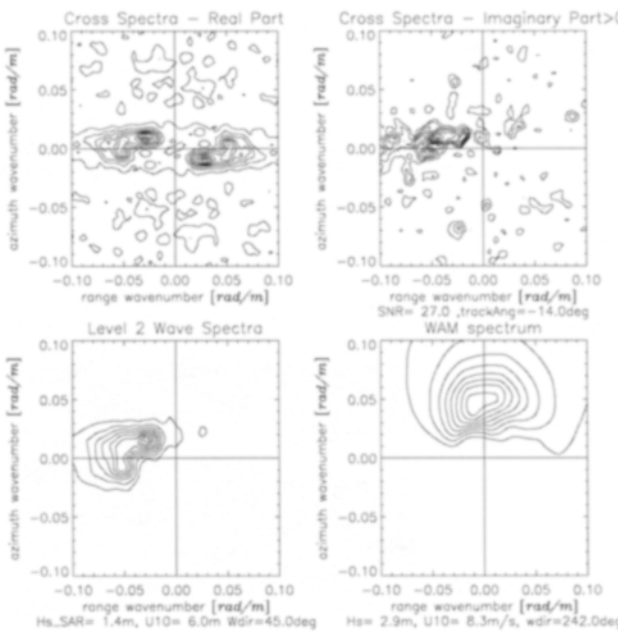

FIG. 5. — Inversion of SAR data (ERS data re-processed to simulate level 1 product of ENVISAT ASAR) within the SAR imaging domain using the algorithm developed for the level 2 product of ENVISAT ASAR wave mode. Top left (resp. right): real part (resp. imaginary part) of the SAR cross-spectrum. Bottom left: retrieved wave spectrum. Bottom right: wave model spectrum (wam), shown for comparison.

Inversion des données RSO (les données ERS sont retraitées afin de simuler le produit niveau 1 de l'ASAR d'ENVISAT) à l'intérieur du domaine d'imagerie du RSO en utilisant l'algorithme développé pour le produit niveau 2 du mode vague de l'ASAR d'ENVISAT. En haut à gauche (resp. droite) : partie réelle (resp. partie imaginaire) de l'interspectre RSO. En bas à gauche : spectre des vagues retrouvé. En bas à droite : spectre du modèle de vague (WAM), montré pour comparaison.

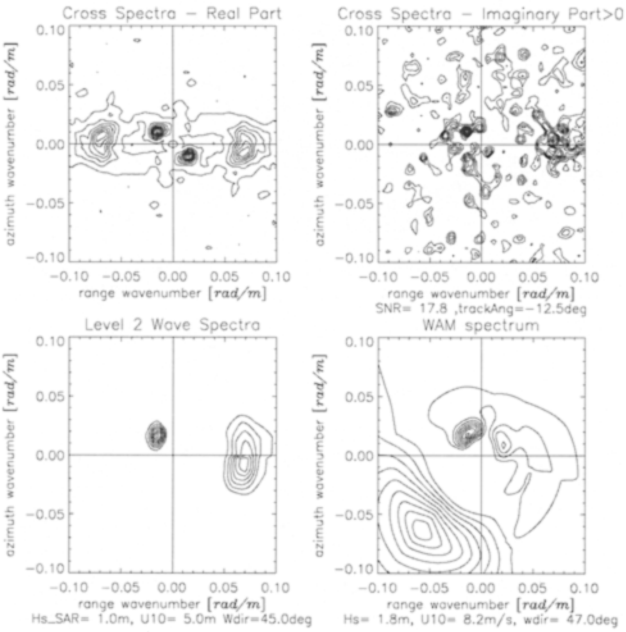

FIG. 6. — Same as figure 5, but for another case.

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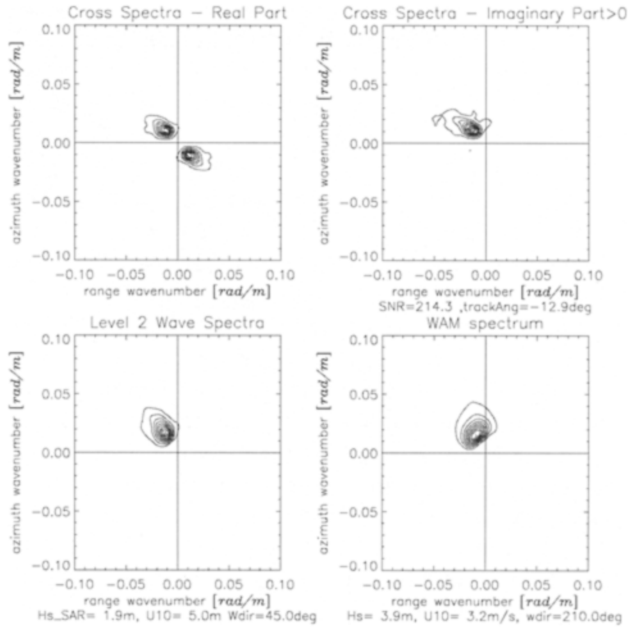

FIG. 8. — Same as figure 5, but for another case.

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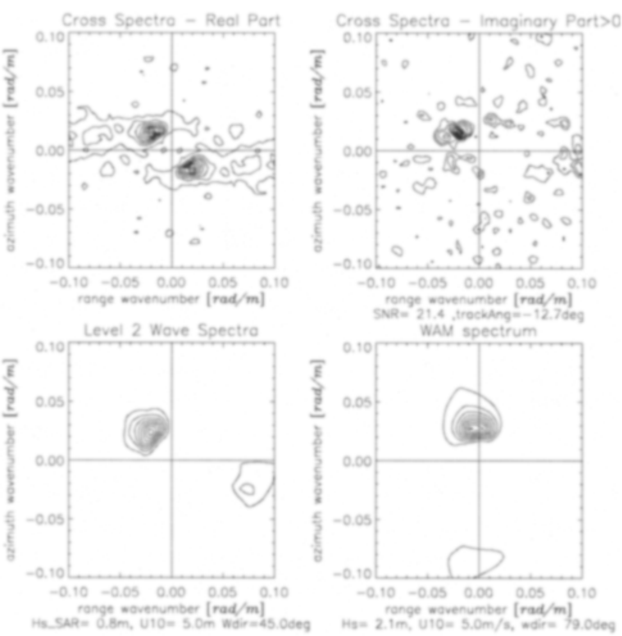

FIG. 7. — Same as figure 5, but for another case.

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(no estimate from the phase plane of the cross-spectrum). In spite of this crude approximation, the longer wave systems, well within the SAR imaging domain, are in an overall good agreement with the WAM predicted spectra.

III. 4. Discussion

To conclude this review on wave and wind retrieval algorithms, it must be emphasised and repeated that a spaceborne SAR measurement is strongly limited by the random motions that occur during the integration time. The wind sea systems will generally not be imaged (except near range propagating systems) and cannot be directly retrieved. Some spectral information in the lowest wavenumber spectral domain may well be associated with these short seas due to the non-linear ocean-to-SAR mapping (Le Caillec et al., 1996). As well, spectral information in the highest azimuth wavenumber spectral domain may be solely associated with the non-linear SAR mapping contribution.

The most salient and well-recognised capability of a spaceborne SAR consists of providing very valuable information on swell systems: such information being known to represent the most important source of errors in numerical model outputs. It is thus recommended that SAR wave retrieval algorithms be developed and improved to provide the best longer wave component spectral inversion. Although of fundamental influence to understand SAR imagery, the complete non-linear mapping may not be fully necessary for light to moderate wind speed conditions. In such cases, much more efforts must be devoted to the proper definition of the tilt and hydrodynamic modulation transfer functions, as well as to properly assess and properly handle the use of a cross-spectral analysis between looks to provide the main swell propagation directions.

Finally, significant improvements concerning the use of the cross-spectral methodology to remove the 180° swell directional ambiguity have already led to convince the European Space Agency to decide that the future ENVISAT ASAR Wave-Mode algorithms and products will be derived by processing single-look complex imagettes. Efforts and investigations mainly led by DLR using reprocessed ERS SAR raw data confirmed the importance of such a decision. As already stated, this will not only help to resolve the wave propagation ambiguity, but will contribute to obtain speckle compensated image cross-spectra. This latter improvement will greatly help wave retrieval algorithms under low sea state conditions. Furthermore, the azimuth cut-off estimates that are also crucial for quasi-linear inversion schemes are also expected to be more accurately determined from cross-spectral analysis between looks. Finally, this will help the identification of the purely non-linear contribution from the swell only contribution to be the base of simplified two-step inversion algorithms. After identification and estimation of the non-linear contribution in the observed co- and cross-spectra (i.e. mostly the wind sea contribution), a residual SAR spectrum can indeed readily be computed from the subtraction between the observed co-spectrum and this non-linear contribution. The obtained remaining spectrum is then solely a quasi-linear contribution which can easily be solved with respect to the swell spectrum after proper estimation of the linear modulation transfer function and the azimuth cut-off parameter.

It must be noted also that prior to wave retrieval from SAR spectral data, it is very useful to characterise the statistical information contained in the SAR image. Indeed, it can be used on one hand to check the homogeneity of the SAR scene (and eliminate non homogeneous cases), and on the other hand to constraint the inversion. Improved statistical information in terms of higher order statistics have been obtained from daily SAR imagette products of ERS-1 and ERS-2 satellites. In particular, the departure from standard Rayleigh statistics has been systematically observed. Such a phenomenon has been recognised to be mainly due to the high-resolution property of the SAR instrument, (Kerbaol et al. 1998, Lehner et al., 2001). Long wavelength gravity waves and swell systems, when present and imaged, effectively contribute to the distortion of the overall SAR image statistical distribution. Such a concept of large-scale inhomogeneities modulating a dense array of small-scale scatterers seems to adequately fit the description of the two-scale SAR composite ocean surface model. It can be introduced as a compound process, and the presence of observed image modulations will act to enhance the radar cross-section variance: this pixel variance increases linearly with the strength of the observed image modulation variance. Besides the mean radar cross section, a SAR pixel scene variance analysis can thus help to both test the SAR scene homogeneity , but also refine wave retrieval algorithms by adding a constraint to better specify an overall observed longer wave modulation variance estimation.

IV. CONCLUSIONS

Spaceborne SAR measurements, and more particularly, the SAR Wave Mode observations continuously collected by ERS satellites since 1991 constitute an invaluable source of information with a global coverage. These data are indeed both unique and important. Unique, because they are in many parts of the world the only source of spectral information. Important, because unlike measurements on integrated parameters like the overall surface wave height, they may carry enough directional information to improve the description of the local sea state. This dataset clearly enables us to gain a much clearer understanding of the specific SAR abilities to measure both wind and wave characteristics.

Concerning wave retrieval capability, a certain consensus exists today within the SAR scientific community to conclude that for the interpretation of spaceborne SAR data, the non linear character of the specific SAR mapping must not be ignored. Random temporal variations mainly associated with orbital motions during the SAR integration time are the main factor that contributes to azimuth resolution losses which totally inhibit the correct mapping of the shortest wave systems.

However, in mild wind conditions (below 4-5 m/s), wave retrieval schemes may be (and have been) developed with a certain success based on an optimised quasi-linear SAR transform. In particular, wave systems having their peak wavelengths longer than 200 meters may be somehow almost directly inverted under low to moderate wind speed conditions, i.e. in low latitude western basins dominated by swell systems.

On the other hand, the SAR high-resolution wind capabilities have also been demonstrated. Limited by the single antenna configuration, it is necessary to combine different extracted parameters, and different methods have been proposed. Today, studies are mainly devoted on the cross section analysis of SAR data. For the best cases, low wavenumber spectral signatures can also be used to infer the main wind direction. The other source of valuable information is associated with measurements of the temporal variability that occurs during the SAR integration time. In particular, the cut-off parameter has been shown to be a robust wind speed indicator, especially under strong wind directions. NORUT further extended this type of analysis to demonstrate the possible use of the cross-spectral methodology to infer the wind direction.

Main theoretical efforts and tests must be devoted in the future to the following points:

- **Tilt and Hydrodynamic modulation transfer function**: this is essential to improve the wave retrieval, in particular with the quasi-linear inversion, and for conditions which may be different from those of ERS (larger incidence angles, HH polarisation).

- **Improved cut-off analysis**: this is crucial for most of quasi-linear wave retrieval algorithms. This can serve to better characterise the SAR scene coherence time (life-time of the scatterers) as well as to provide a simple technique to monitor the instrument performance (mean global relationship between cut-off and backscatter measurements).
- **Improved wind direction analysis**: this is obviously the most crucial point to derive a consistent wind speed estimation. Low wavenumber spectral signatures as well as cross-spectral phase plane information and cross section incidence angle dependency must certainly be combined to improve current developments.
- **Physical-based backscatter model**: this is crucial for both modulation transfer definitions and any SAR wind retrieval algorithms. In particular, possible inclusion of breaking effects must be considered.

As recalled, a spaceborne SAR measurement is strongly limited by the randomness of the sea surface during the integration time: random motions and intermittent transients do strongly contribute to the blurring of the shortest wave components. Such phenomena are known. Consequently, the complete spectral information can only be indirectly retrieved. Spectral inversion results are thus not expected to be of the greatest accuracy for the wind sea part of the wave spectrum. On the contrary, it is clear that high-resolution SAR images carry valuable longer wave spectral information.

From our investigations, inversion schemes can lean on:

- **Cross-spectral analysis**: this simple tool is not time-consuming and can provide for most environmental conditions the necessary guess to remove the 180° ambiguity.
- **Improved cut-off estimates**: as stated above, this is crucial to define an optimised quasi-linear transform that can serve for a first step of the retrieval algorithm. Using cross-correlation techniques, cut-off parameters are more accurately determined with a better distinction between non-linear and quasi-linear SAR mapping contributions.
- **CMOD**: this model function has been demonstrated to be the base to both help to retrieve the local wind speed and the radar modulation transfer function. To date, there is no model function for HH-polarisation configuration.
- **Image statistics**: This has been proven to be of considerable use to identify a lack of homogeneity in a SAR image. It is also theoretically anticipated that the normalised pixel variance is proportional to the strength of the variance of the long wave modulation that is detected. It will thus help to better constrain the retrieved spectrum.

It thus seems imperative to concentrate on this particular problem to provide robust estimates for the longer waves. This will serve to improve the wave prediction models, not only in terms of a derived significant wave height parameter but also in terms of wavelength and directional properties. This improved spectral information will then obviously serve to improve our knowledge of the regional and global wave climatology.

As demonstrated with ENVISAT ASAR like products, the continuous efforts to retrieve wind and wave information led to considerable improvements. It is thus expected that in the next future SAR measurements would become a very valuable and necessary component of the Global Ocean Observing System (GOOS) for monitoring the coastal zone environment and its changes.

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