Marine SAR analysis and interpretation system – MARSAIS

J.A. JOHANNESSEN[1], R. GARELLO[2],
B. CHAPRON[3], R. ROMEISER[4],
P. PAVLAKIS[8], I. ROBINSON[6],
N. CONNOLLY[7], K. NITTIS[8],
T. HAMRE[1], S. UFERMANN[6],
W. ALPERS[4], H. ESPEDAL[1],
B. FUREVIK[1], V. CUMMINS[7], D. TARCHI[5]

Abstract

In a marine coastal ocean monitoring and prediction system, multisensor in-situ and remote sensing observations (of coastal currents, fronts, eddies, upwelling patterns, internal waves, phytoplankton distribution, algae patchiness, oil pollution and high-resolution wind fields) need integration and combination with fine resolution numerical ocean models. Only via such integrated systems will realistic representation of the initial state be derived and properly utilized to provide reliable and accurate forecasts of, for instance, location of eddies, upwelling patterns, and high-concentration of toxic algae. The role of SAR in such systems is addressed and characterized in terms of current status and further need for research and development. Use of synergetic remote sensing observations, in particular from optical remote sensing, is also considered in this context.

Key words: Remote sensing, Land observation satellite, Oceanographic survey, Synthetic aperture radar, Sea state, Surface state, Integrated system.

SYSTÈME D'INTERPRÉTATION ET D'ANALYSE DE DONNÉES RSO MARINES – MARSAIS

Résumé

Dans un système de prédiction et de surveillance en zone côtière, on a besoin d'intégrer les données obtenues par capteurs in-situ et par télédétection (courants côtiers, fronts, tourbillons, signatures de remontées d'eaux froides, ondes internes, distribution de phytoplancton, répartition des algues et champs de vent haute résolution) avec les résultats issus des modèles numériques à haute résolution. C'est uniquement par l'intermédiaire de tels systèmes intégrés que des représentations réalistes de l'état initial pourront être déduites et utilisées correctement afin de fournir des prévisions précise et fiable, par exemple, de la position des tourbillons, des remontées d'eaux froides ou des formations et des hautes concentrations en algues toxiques. Le rôle du RSO dans de tels systèmes est évoqué et caractérisé en fonction de l'état actuel des connaissances et des besoins complémentaires en recherche et développement. L'utilisation en synergie d'observations de télédétection, en particulier optique, est aussi abordée dans ce contexte.

Mots clés : Télédétection, Satellite observation Terre, Observation océanographique, Radar ouverture synthétique, État mer, État surface, Système intégré.

Contents

I. STATE OF THE ART

The interactions of cloud independent active synthetic aperture radar (SAR) microwaves with the ocean surface are strongly dependent on the roughness of the ocean surface at short gravity-capillary (Bragg scattering waves of order cm or dm), intermediate (1 to 10 m), and long wavelengths (order of 100 m). The availability of such spaceborne SAR data has for nearly a decade provided regular and global observation of ocean wave spectra [1]. Furthermore, its capabilities to detect and locate oil spills, bathymetric features in shallow water, and ships have also lead to systematic use of SAR images in operational surveillance associated with marine coastal pollu-

1. Nansen Environmental and Remote Sensing Center, Edv. Griegsvei 3 a, 5059 Bergen, Norway, email:johnny.johannessen@nrsc.no.
2. École Nationale Supérieure des Télécommunications de Bretagne, 29285 Brest, France,
3. Institut Francais de Recherche Pour L'Exploitation De La Mer, 29280 Plouzane, France,
4. Institute of Oceanography, University of Hamburg, 22529 Hamburg, Germany,
5. Joint Research Centre, 21020 Ispra, Italy,
6. Southampton Oceanographic Centre, University of Southampton, SO14 3ZH Southampton, UK
7. University College Cork, National University of Ireland, Cork, Irland
8. National Centre for Marine Research, Athens, Greece

TABLE I. — Summary of SAR based coastal ocean algorithm maturity for sea state retrievals. Maturity ranking: 4 = automated; 3 = not fully automated; 2 = supervised, still mostly a research tool; 1 = needs further development.

Sommaire de l'état de maturité des algorithmes basés sur des données RSO pour retrouver les états de mer en zones côtières. Niveau de maturité : 4 = automatique; 3 = non entièrement automatique; 2 = supervisé, reste principalement un instrument de recherche; 1 = nécessite plus de développement.

SAR MARINE COASTAL ALGORITHM MATURITY		
Application	**Algorithm rank and description**	
Ocean waves	**3-4.** Use of Inversion algorithm most common. Swell component is particularly well captured. Limiting factors are fetch, wave-length, and wave non linearity. Ambiguity removal is possible when Single Look Complex (SLC) image data are used. Used operationally.	S E A
Near surface wind field	**2-3.** Use of CMOD4 and azimuth cut-off models are common. CMOD4 requires well-calibrated data. New methods also derives wind speed from azimuth smearing characteristics in the wave field. Limiting factors include validation data sources.	S T A T E
Air-Sea interaction	**2.** Use of similarity theory in which the turbulent wind is derived. By use of other data sources the buoyancy flux can also be estimated. Other characteristics of the boundary layer such as boundary layer stratification, height, and turbulence can also be derived, provided other data sources are available.	

tion control, bottom mapping, and fisheries [2, 3]. Recently, a new emerging application has been developed for the monitoring of atmospheric boundary layer processes and mesoscale coastal wind fields [4, 5, 6]. With the expected capability to further advance the regular application of the SAR data for upper ocean current feature monitoring, it is evident that the SAR will play a vital role in marine coastal ocean monitoring and prediction systems [7, 8].

In this paper we provide an overview of the current state-of-the-art SAR ocean imaging capabilities according to three classes: – near surface wind field and sea state; – surface current and frontal features; and – surface slicks. This is also the starting point for the recently approved CEC funded MARSAIS project that aims to design and implement a generic Marine SAR Analysis and Interpretation System for specific application to the coastal zones. Further details about the goal and scientific challenges of this project according to those three classes mentioned are given in the subsequent back-to-back papers by [9,10,11,12]. Additional information is provided at the project homepage http://marsais.ucc.ie

Wind field and Sea state: SAR can provide detailed quantitative local wind information at about 1 to 10 km resolution (Table I). Currently the most reliable way of using SAR to determine wind speed, particularly its spatial variations at kilometer scales (much smaller than those achievable by scatterometry and radiometry), is the use of algorithms such as CMOD4 (tuned to the ECMWF model), and CMOD-Ifremer (tuned to buoy data) or estimates of azimuth cut-off smearing [4, 5]. In ideal situations when the SAR image expressions reveal wind direction such as associated with wind streaks and shadowing by land, it is also possible to derive a complete estimate of the vector wind field [5]. In cases where no estimates of the wind direction can be obtained from the image, the approach will have to take into account auxiliary information. One such approach was recently examined by [13] showing that the combination of a high-resolution atmospheric model (HIRLAM) and SAR images can provide optimum retrievals of the mesoscale (1-km resolution) wind field in coastal regions. SAR based wind retrievals in the Marginal Ice Zone and along the coastal plain of an Arctic Island with relatively high mountains has also been validated against a mesoscale atmospheric model as reported by [14].

Recently, a new SAR wind field retrieval method [15] has been proposed which is based on the consideration of the decorrelation time and phase spectra computed from inter-look processing of single-look-complex (SLC) SAR data. This method has been adapted by ESA and will be used to provide the ENVISAT ASAR Level 2 wind field product.

High resolution wind fields will obviously benefit both coastal meteorological and oceanographic applications where spaceborne scatterometers and radiometers lack the required spatial resolution. For instance, it will allow for much more precise estimates of advection and transport both in the atmospheric boundary layer and in the upper ocean. Regarding the latter, such improvements are for instance needed in the context of monitoring and prediction of oil spill and toxic algae drift-trajectories.

The detailed manifestation of the surface roughness and stress variations imaged by the radar moreover offer an excellent opportunity to investigate atmospheric boundary layer processes and air-sea interactions. Commonly detected in SAR images are expressions of boundary layer convection in the form of two-dimensional rolls and three-dimensional cells. The former features are often used to derive quantitative estimates of the wind direction. Atmospheric gravity waves, originating from shear instabilities or topographic influences, can also lead to low-wavenumber signals expressed in SAR images [16,17]. However, in such cases, the wind direction is perpendicular to the feature rather than parallel as it is for rolls. An emerging new research field is to investigate how these types of expressions can be used to provide estimates of atmospheric boundary layer conditions, notably its height, stratification, and turbulence characteristics [18].

TABLE II. — Summary of SAR based coastal ocean algorithm maturity for current retrievals. Maturity ranking: 4 = automated; 3 = not fully automated; 2 = supervised, still mostly a research tool; 1 = needs further development.

Sommaire de l'état de maturité des algorithmes basés sur des données RSO pour retrouver les courants en zones côtières. Niveau de maturité : 4 = automatique; 3 = non entièrement automatique; 2 = supervisé, reste principalement un instrument de recherche; 1 = nécessite plus de développement.

SAR MARINE COASTAL ALGORITHM MATURITY		
Application	**Algorithm rank and description**	
Surface Current Fronts and Eddies	**1-2.** Use radar cross-sectional modulations across fronts to estimate current shear and strain. Models usually underpredict the modulations at X- and C-band. Very sensitive to wind conditions. The main challenge is to improve the parameterization of the source term, including partitioning in local and non-local contributions to the small-scale roughness variations.	**CURRENT**
Internal Waves & Mixed layer	**2-3.** Use of radar cross section modulations associated with tidal current interaction with bathymetry to estimate internal wave amplitude, surface current patterns and mixed layer depth. Sensitive to wind conditions.	
Shallow Water Bathymetry	**2-3.** Use of radar cross-sectional modulations associated with tidal current interaction with bottom features to locate and orient sand banks. Sensitive to wind speed. Only applicable in waters less than about 30 m.	

Accurate SAR wind estimates may also be essential for the successful determination of the inverted SAR ocean wave spectrum. SAR imaging of waves has undergone a substantial amount of research in the past ten years, and a range of modulation transfer functions have been defined to retrieve ocean wave spectra under different environmental conditions and radar parameters. However, for application in coastal regions the spaceborne SAR detection capability of the directional wave field usually breaks down due to the shortening of the wavelength as the waves are approaching shallower water. In such cases a shallow water wave model must be used to advect the wave field from the open ocean boundaries (transition zone from deep water to shallow water) toward the shorelines. Moreover, in the vicinity of the transition zone, the parameterisation of the modulation transfer functions is uncertain, and further studies are needed to find the best approximation to these functions. More details on this subject is reported in [9].

Currents and Frontal Features: Existing models for the simulations of SAR backscatter signatures of current fronts usually provide similar overall results in which the simulated frontal strength is less than the observed (Table II). To make further progress at a fundamental level, it may be necessary to use more sophisticated wave spectral, wave-current interaction (including the effect of wave breaking), and radar backscattering models [8]. This requires better parameterization of the source terms, both the local term connected with the short gravity-capillary waves and the non-local term induced by the presence of the longer waves which modulates the shorter waves and sometimes lead to wave breaking. Another process that needs better understanding (complementary with the previous objective) is the wind stress feedback in which enhanced surface roughness can also further increase the stress. Although such parameterization exist they are yet to be systematically integrated [8].

In addition to the SAR imaging of short wave-current modulations which lead to elongated bright and dark radar cross-sectional anomalies, the longer wind waves and swell also interact with spatially varying currents, leading to wave refraction. Hence, under good wave imaging conditions, it is possible to quantify wave refraction and, in combination with traditional wave-ray tracing models, obtain an estimate of the spatial variation of the surface current.

Internal wave (IW) expressions can also be considered as a special type of imaging of surface current features. Their expressions are in general formed either via hydrodynamic modulation or via film-induced damping [19]. Simulation models give estimates of SAR backscatter signatures of IW patterns, which are of the correct order of magnitude [20]. In many cases the IW source locations, wavelength and propagation speeds can be directly determined from available SAR imagery. The expressions of IW features can also allow assessment of the subsurface hydrographic and velocity structure and mixed layer depth, in particular in combination with numerical models.

Moreover, underwater bathymetry is visible on SAR images through the radar signature of ocean surface current changes and corresponding modulations of the shorter gravity-capillary waves [3]. The key limiting factors are the sensitivity to wind speed and the water depth. Nevertheless, this SAR mapping capability can lead to a substantial reduction of the costs for traditional sounding campaigns.

In this special edition [10] provides more details on the SAR imaging capabilities of near surface current features.

Slicks: According to many statistical estimates oil discharges contribute three times more amount of oil releases into the sea, than that due to accidents. It is now commonly agreed that SAR is a principal observing method in monitoring these frequent oil-spilling due to

TABLE III. — Summary of SAR based coastal ocean algorithm maturity for slick retrievals. Maturity ranking: 4 = automated; 3 = not fully automated; 2 = supervised, still mostly a research tool; 1 = needs further development.

Sommaire de l'état de maturité des algorithmes basés sur des données RSO pour retrouver les nappes en zones côtières. Niveau de maturité : 4 = automatique; 3 = non entièrement automatique; 2 = supervisé, reste principalement un instrument de recherche; 1 = nécessite plus de développement.

SAR COASTAL OCEAN ALGORITHM MATURITY		
Application	**Algorithm ranking and description**	
Natural Film	**1-2.** Use radar cross-sectional damping to specify the extent and orientation of film area. Signature is not unique and can be associated with heavy rain cells, oil spill, low winds and land sheltering. This is a supervised algorithm.	**SLICKS**
Oil Slicks	**2-3.** Use of radar cross-sectional damping to characterize extent of spill. Used operationally in combination with airborne surveys. Signature may be masked by factors listed above for natural film. This is a supervised algorithm.	

ship operations (e.g. tank washings and/or de-ballast operations). However their extended operationalization is sometimes limited due to insufficient SAR image acquisition and coverage and difficulties in unsupervised discrimination of oil spills from other features e.g. natural films, and natural oil seepage (Table III).

Currently, for the practical determination of slick type and its origin (whether natural or man-made), single-frequency and polarization SAR image data, combined with empirical and conceptual algorithms, supported with wind history and drift models, appear to be most promising [2].

[11] provides a more complete discussion on surface slick detection by SAR.

II. SENSOR SYNERGY

The potential benefits of combining data from several sensors and satellites can make an important contribution to coastal ocean monitoring, both in regard to operational applications and scientific research. The synergetic benefits include data from identical sensors; similar resolution image data from different sensors; data from similar sensors with different sampling capabilities; and different types of sensors with different sampling capabilities [21]. In addition to increasing the spatial and temporal coverage this synergy also offers opportunities to advance the analysis and interpretation of the remote sensing data [22]. In turn, the interaction of geophysical quantities can be better understood and formulated in process models. Limited studies have revealed promising capabilities using SAR and IR observations of: atmospheric boundary layer processes; and ocean surface current features and frontal boundaries [6, 7, 22, 23].

Regarding the latter, it is anticipated that synergetic use of SAR and ocean color sensors will contribute in a similar manner. But we also anticipate correlation in SAR detection of natural films and the distribution of chlorophyll-A patchiness derived from ocean color observations. Some evidence of this was recently documented by [24] for near coincident observations of ERS-2 SAR and SeaWiFS of an algae bloom along the southern coast of Norway.

The key sensors recommended in such a pool of sensor synergy for coastal ocean monitoring include: SAR, radar altimeter, and visible/IR radiometers. Synergetic use of such multisensor, multispectral, multiresolution, and multitemporal data will necessitate some adaptations to the usual monitoring system components such as user interface, data transfer protocol, data archive and database functions, data processing and presentation software, and data analysis and interpretation routines [21]. Particularly important considerations for facilitating synergetic applications are: image data browse facilities, image data access and selection routines, minimizing geolocation/gridding errors, and advances in analysis and interpretation.

New satellite data such as SAR from ERS, RADARSAT and Envisat, ocean color data from Sea-Viewing Wide-Field-of-View Sensor (SeaWiFS), Modular Optoelectronic Scanner (MOS), Ocean Color Monitoring (OCM launched on Indian Oceansat 1), Moderate Resolution Imaging Spectroradiometer (MODIS) and Medium Resolution Imaging Spectrometer (MERIS), and optical / infrared data from Advanced Very High-Resolution Radiometer (AVHRR), Along Track Scanning Radiometer (ATSR) and Advanced Along Track Scanning Radiometer (AATSR) will significantly improve this capability for sensor synergy. In particular, a new and very interesting feature with Envisat is the opportunity for coincident ASAR and MERIS coverage.

In [12] further details on capabilities to use synergetic approach to optimize interpretation of satellite data are addressed.

III. USER ASPECTS

Improvements in availability, sensor range and resolution of remotely sensed data (both airborne and satellite) provide a practical and valuable tool for integrated coastal zone management (ICZM) [21, 25]. Management strategies for coastal and marine resources need to adopt a relatively wide spatial and temporal perspective. A vision for enhanced coastal zone management involves the use of Earth observation (EO) based technologies in integrated management systems, where EO products will be more and more integrated into intelligent systems capable of assimilating different types of data to produce what is requested by resource managers. However, decisions on the development and nature of resource management strategies are seldom directly founded on scientific results derived from advances in EO technology. Scientists are often frustrated that their knowledge is not put to use and the public perceives the scientific process as detached from their immediate influence. The EU Demonstration Programme on ICZM highlighted the lack of awareness amongst ICZM practitioners of many technologies, data and information available to them [26]. However, the level of use of EO data in ICZM is increasing, which indicates that there is a greater awareness of EO data in the so-called user community. Users include government departments and agencies, small and medium enterprices (SMEs) and research institutions that make use of the products generated by operational remote sensing applications. Different applications require different products. As a result, the identification of specific data and product requirements by different end user sectors is an important task that has to be augmented by a user requirement analysis procedure.

Coastal zone managers are seen as key users of SAR products and services, therefore their requirements need to be addressed within the implementation of MARSAIS. Potential end users of SAR are those involved in industries and activities such as: offshore oil and gas; wind and wave energy sitings; coastal fisheries; aquaculture; mineral extraction; defence; pollution management; climate prediction; port operations; marine engineering; dredging; coastal protection; ship-routeing; tourism and public health; environment protection and preservation. By identifying potential end users of SAR, the MARSAIS consortium aim to:

- identify and understand the data and information needs of coastal zone managers;
- develop a dialogue between MARSAIS toolkit developers and potential customers;
- ensure that user driven MARSAIS products are developed and effectively exploited;
- ensure that the final product can deliver critical parameters at appropriate resolutions for usage; and
- ensure that the final product is presented with an appropriate user-friendly interface.

In order to achieve these aims a fundamental activity of the MARSAIS project is to consult potential end users via questionnaires, through user consultation workshops and through the establishment of a MARSAIS Advisory Group (MAG) and a MARSAIS User Group (MUG). The use of workshops will assist in educating potential end users to make better use of EO data and information. In this way, the applications of EO will be promoted, making them more widely understood in accordance with the RTD priorities of the Fifth Framework Programme.

IV. SUMMARY

The importance of the coastal zone as an area of intense human activity with consequent environmental impact is beginning to be recognized. Hence it is of fundamental importance to design and implement a system of coastal observations and predictions to fulfill the need for sustainable management of coastal resources in the context of economic, social, environmental, and scientific objectives. Such a system has a high priority for many coastal regions because of the importance of coastal area development and the intimate effects of coastal changes on economic development and human habitation.

Almost 10 years of continuous global spaceborne SAR coverage (since ERS-1 launch in 1991) has advanced our knowledge and use of SAR for marine application, both in regards to scientific, operational and commercial usage. With the coming flight operations of calibrated, spaceborne SARS (Envisat, Radarsat-2, Japanese ALOS, and possibly the joint UK/German TerraSAR), employing wide swath and spot SAR technology in addition to the standard narrow swath (100 km) and fine wave mode (~10 km), global SAR application will be on the threshold of a new era, presenting new and unique opportunities for the international marine coastal user community.

A series of upgrades of retrieval algorithms are necessary in order to take full account of these new spaceborne SAR systems with their many different operating modes. These can be summarized briefly as the need to:

– advance and optimize existing SAR wave spectra retrieval algorithms developed for ERS data.

– develop more physical based models for wind field retrievals by advancing and optimizing existing SAR wind retrieval algorithms developed for ERS data.

– advance the opportunity to characterize and estimate spatial backscatter variability in connection with dominant air-sea interaction processes.

– advance the quantitative interpretation and characterization of SAR imaging of ocean features such as horizontal current shear and convergence, as well as, frontal dynamics including upwelling and eddies for different wind and wave conditions.

– advance the classification of IW signatures into their physical generation mechanism, upper layer hydrographic structure, mixed layer dynamics, and associated imaging mechanism.

– advance the discrimination between natural films, man-made oil spills, and natural oil seepage (from reservoirs).

– develop and optimize a physical based backscatter model for shallow water bathymetry retrievals.

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REFERENCES

[1] HEIMBACH (P.), HASSELMANN (S.), HASSELMANN (K.), Statistical analysis and interpretation of WAM model data with global ERS-1 SAR wave mode spectral retrievals over 3 years, Advances in Oceanography and Sea Ice Research using ERS Observations, *Journal of Geophysical Research-Ocean*, **103**, n° C4, pp. 7931-7979, April 15, 1998.

[2] ESPEDAL (H.A.), JOHANNESSEN (O.M.), JOHANNESSEN (J.A.), DANO (E.), LYZENGA (D.), KNULST (J.C.), COASTWATCH'95, A tandem ERS-1/2 SAR detection experiment of natural film on the ocean surface, *J. Geophys. Res.*, **103**, n° C11, pp.24969-24982, October 15, 1998.

[3] HESSELMANS (G.), CALKOEN (C.), WENSINK (H.), Mapping of Seabed topography to and from SAR, In *Proceedings Third ERS Symposium, Space at the service of our Environment*, ESA Publication Division, ESA SP-414, pp. 1055-1058, May 1997.

[4] CHAPRON (B.), FOUHAILY (T.E.), KERBAOL (V.) Calibration and validation of ERS wave mode products, I Document DRO/OS/95-02, March 1995.

[5] KORSBAKKEN (E.), JOHANNESSEN(J.A.), JOHANNESSEN (O.M.). Coastal wind field retrievals from ERS synthetic aperture radar images. *J. Geophys. Res.*,**103**, n° C4, pp. 7857-7875, April 15, 1998.

[6] Coastal and Marine Applications of Wide Swath SAR, *Johns Hopkins APL Technical Digest*, (editors R.C. Beal and W.G. Pichel) **21**, n° 1, January-March 2000.

[7] JOHANNESSEN (J.A.), SHUCHMAN (R.A.), DIGRANES (G.), LYZENGA (D.R.), WACKERMAN (C.), JOHANNESSEN (O.M.), VACHON (P.W.), Coastal ocean fronts and eddies imaged with ERS-1 SAR, *Journ. of Geophys. Res.*, **101**, n° C3, pp. 6651-6667, March 15, 1996.

[8] LYZENGA (D.R.), Effects of intermediate-scale waves on radar signatures of ocean fronts and internal waves. *J. Geophys. Res.*, **103**, 18,759-18,768, 1998.

[9] CHAPRON (B.) *et al.*, SAR remote sensing of wind and wave field, *Annals of Telecommunications*, **56**, n° 11-12, 2001.

[10] ROMEISER (R.), ALPERS (W.) *et al.*, SAR remote sensing of near surface current features, *Annals of Telecommunications*, **56**, n° 11-12, 2001.

[11] PAVLAKIS (P.) *et al.*, SAR remote sensing of slicks, *Annals of Telecommunications*, **56**, n° 11-12, 2001.

[12] ROBINSON (I.), UFERMANN (S.) *et al.*, Synergy between SAR and other sensors for remote sensing of the coastal ocean, *Annals of Telecommunications*, **56**, n° 11-12.

[13] PORTABELLO (M.), STOFFELEN (A.), JOHANNESSEN (J.A.), Towards an optimal inversion method for SAR wind retrieval, *J. Geophys. Res.* (Ocean), November 2001.

[14] FUREVIK (B.), SANDVIK (A.D.), JOHANNESSEN (O.M.), SAR retrieved wind speed in the Marginal Ice Zone and in the Arctic coastal regions-comparison with in situ data and output from an atmopsheric model, accepted in IEEE, November 2001.

[15] JOHNSEN (H.), ENGEN (G.), HOGDA (K.), CHAPRON (B.), DESNOS (Y-L), Validation of Envisat ASAR wave mode level 1b and 2 b products using ERS SAR data, *Proc. Of CEOS SAR Workshop*, ESA SP-450, Toulouse, pp. 59-64, 1999.

[16] VACHON (P.W.), JOHANNESSEN (O.M.), JOHANNESSEN (J.A.), An ERS-1 SAR image of atmospheric lee waves, *J. Geophys. Res.*, **99**, n° C11, pp. 22483-22490, 1994.

[17] VACHON (P.W.), JOHANNESSEN (J.A.), BROWNE (D.P.), ERS-1 SAR images of atmospheric gravity waves, *IEEE Transactions on Geoscience and remote sensing*, **33**, n° 4, July 1995.

[18] YOUNG (G.S.), SIKORA (T.), Distinguishing boundary layer signatures from mesoscale and ocean clutter in SAR imagery, In *Proceedings IGARSS'98*, IEEE, 1998.

[19] DA SILVA (J.C.B.), ERMAKOV (S.A.), ROBINSON (I.S.), Role of surface films in ERS SAR signatures of internal waves on the shelf 3. Mode transitions, *J. Geophys. Res.*, **105**, n° C10, October 2000.

[20] BRANDT (P.), ROMEISER (R.), RUBINO (A.), On the determination of Characteristics of the Interior Ocean Dynamics from Radar Signatures of Internal Solitary Waves, Journal of Geophysical Research (in press), 1999.

[21] MILES (M.), JOHANNESSEN (O.M.), SAMUEL (P.), HAMRE (T.), JENSEN (V.), SANDVEN (S.), ROBINSON (I.), SCOON(A.), Synergetic use of infrared, optical and microwave remote sensing observations, ESA/ESTEC Contract No. 11968/96/NL/CN, Noordwijk, The Netherlands, April 1998.

[22] ROBINSON (I.), JOHANNESSEN (J.A.), Opportunities for combined SAR and ATSR ocean observations during the ERS Tandem mission, *Proceedings 3rd ERS Symposium, Space at the service of our environment*, ESA Publ. Div., ESA SP-414, pp. 1337-1342, May, 1997.

[23] JOHANNESSEN (J.A.), VACHON (P.W.), JOHANNESSEN (O.M.), ERS-1 SAR imaging of marine boundary layer processes, *Journal of the Russian Academy of Science* (Study of the Earth System from Space), n° 3, pp. 79-88, May-June, 1996.

[24] PETTERSSON (L.H.), DURAND (D.), personal communication.

[25] DURAND (D.), POZDNYAKOV (D.), SANDVEN (S.), CAUNEAU (F.), WALD (L.), JACOB (A.), KLOSTER (K.), MILES (M.), Characterisation of inland and coastal waters with space sensors. European Commission. A study for the Centre for Earth Observation (CEO). Study contract reference number 1409-1998-06F1ED ISP NO, 1999

[26] DOODY (J. P.), PAMPLIN (C. F.), GILBERT (C.), BRIDGE (L.), Thematic Study F: Information required for integrated coastal zone management. European Union Demonstration Programme on Integrated Management in Coastal Zones. Study contract reference number 3050/STU/9700186. 1998.