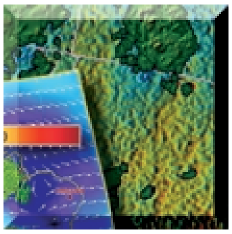

Coastal Observing Systems: The Role of Synthetic Aperture Radar

Johnny A. Johannessen

The availability of cloud- and light-independent synthetic aperture radar (SAR) data has for nearly a decade provided regular and global observation of ocean wave spectra. Furthermore, the radar's capability to detect and locate oil spills, bathymetric features in shallow water, and ships has also led to systematic use of SAR images in operational surveillance associated with marine coastal pollution control, bottom mapping, and fisheries. Recently, a new application has been developed for monitoring atmospheric boundary-layer processes and mesoscale coastal wind fields. With the capability to further advance the regular application of SAR data for upper ocean current and feature monitoring, it is evident that SAR will play a vital role in coastal ocean observing systems. (Keywords: Coastal zones, Observing systems, SAR application, Synergy.)

BACKGROUND

Marine coastal environments are considered to extend from the terrestrial coastal plains to the outer edges of the continental shelves. These zones contain some of the Earth's most diverse and productive resources and include extensive areas of complex and specialized ecosystems that are highly sensitive to human intervention as well as to climate variability and change. They are furthermore characterized by the interaction of complex and coupled physical and biochemical upper ocean and atmospheric boundary-layer processes at spatial and temporal scales ranging from meters to hundreds of kilometers and seconds to several days and longer. However, many of these processes and their interaction are still not well known, primarily as a result of lack of observations. Validations of physical or coupled biophysical numerical ocean models are consequently poor.

In a marine coastal ocean monitoring and prediction system, multisensor *in situ* and remote sensing observations of coastal currents, current fronts, eddies, upwelling patterns, algae patchiness, and high-resolution wind fields must be integrated and combined with fine-resolution numerical ocean models. Only via such an integrated system will a realistic representation of the initial state be properly used to provide reliable and accurate forecasts of, for instance, the location of eddies, upwelling patterns, and high concentrations of algae.

In addition, the possibility of simulating satellite observations, such as two-dimensional synthetic aperture radar (SAR) backscatter intensity images and sea surface temperature or surface chlorophyll A distributions, should be imbedded in such a monitoring and prediction system (schematically indicated in Fig. 1). This will facilitate the systematic comparison and minimization of the difference between observed and simulated images. In turn, this may advance the understanding of imaging mechanisms and ensure optimum analysis and interpretation of the satellite observations.

In this article the role of SAR in coastal observing systems is addressed and characterized in terms of current status and further research and development efforts that areas of coastal monitoring and application are undergoing. The use of synergetic remote sensing observations is also considered when it can lead to better interpretation of SAR images. In so doing, it is emphasized that increased awareness, interest, and systematic use of SAR data in coastal monitoring and management are needed.

STATE OF THE ART

Almost 10 years of continuous global SAR observations (since ERS-1, the European Remote Sensing satellite, in 1991) has advanced our knowledge and use of SAR for marine applications in regard to scientific research, operational usage, and environmental problems in coastal regions. Interactions of the cloud-independent active SAR microwaves with the ocean surface are strongly dependent on the roughness of the ocean surface at short gravity-capillary (Bragg scattering waves of the order of centimeters or decimeters), intermediate (1–10 m), and long (order of 100 m) wavelengths. By the use of retrieval algorithms it is possible to transfer the measured radar intensity and its spectral properties into estimates of near-surface wind, ocean wave spectra, and significant waveheight. The surface roughness is also modulated by surface current and the presence of surface damping materials such as oil or natural film, thus making it possible to obtain a picture of the current pattern.[1] However, quantitative interpretations of surface current features expressed in SAR images are still dominated by scientific research, as indicated later.

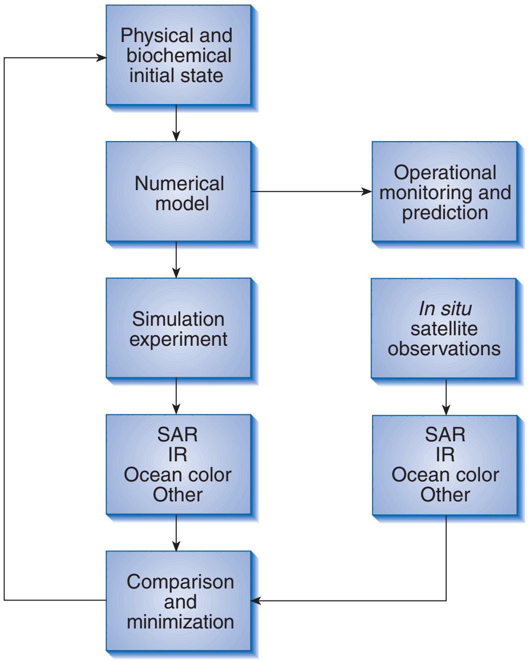

Figure 1. Schematic illustration of a marine coastal ocean monitoring and prediction system. (IR = infrared; SAR = synthetic aperture radar.)

In principle, two types of models or retrieval algorithms can be used in connection with SAR imaging of geophysical and biochemical quantities and processes in the marine coastal ocean environment.

1. Inverse models. Such models use SAR data and auxiliary data to retrieve geophysical parameters such as ocean wavelength and propagation direction, ocean wave spectra, wind speed (and direction), and shallow water bathymetry.
2. Forward models. For parameters like current shear and convergence/divergence, internal waves, and the characteristics of natural films and oil slicks, such models are available to simulate observed SAR images from the given parameter, background conditions, and radar system parameters.

The status of these models and algorithms is summarized in Table 1.

Ocean Waves

SAR imaging of waves has undergone substantial research in the past 10 years, and a range of modulation transfer functions (commonly named tilt and hydrodynamic modulation and velocity bunching) have been defined to retrieve ocean wave spectra under different environmental conditions and radar parameters. Wave modelers have thus been able to obtain global information on the two-dimensional wave fields in near–real time.[2] This has contributed to better global wave forecasts, particularly since the SAR data are allowing improved initialization of the swell field in the wave models.

However, for application in near-shore coastal regions, the SAR detection capability of the directional wave field usually breaks down owing to the shortening of the wavelength as the waves approach 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 parameterization of the

Table 1. Summary of SAR-based coastal ocean algorithm maturity.

Application	Algorithm description	Rank
Ocean waves	Use of inversion algorithm most common. Swell component is particularly well captured. Limiting factors are fetch, wavelength, and wave nonlinearity. Ambiguity removal is possible when single look complex (SLC) image data are used. Used operationally.	3–4
Near-surface wind fields	Use of CMOD4 algorithm and azimuth cutoff models is common. CMOD4 requires well-calibrated data. New methods also derive wind speed from azimuth smearing characteristics in the wave field. Limiting factors include validation data sources.	2
Air–sea interaction	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 stratification, height, and turbulence can also be derived, provided other data sources are available.	1–2
Surface currents, fronts, and eddies	Use of radar cross-sectional modulations across fronts to estimate current shear and strain. Models usually underpredict 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 nonlocal contributions to the small-scale roughness variations.	1–2
Internal waves and the mixed layer	Use of radar cross-sectional modulations associated with tidal current interaction with bathymetry to estimate internal wave amplitude, surface current patterns, and mixed-layer depth. Sensitive to wind conditions.	2–3
Natural films	Use of 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 spills, low winds, and land sheltering.	1–2
Oil slicks	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 films.	2–3
Shallow water bathymetry	Use of radar cross-sectional modulations associated with tidal current interaction with bottom features to locate and orient sandbanks. Sensitive to wind speed. Only applicable in waters less than about 30 m.	3

Maturity ranking: 4 = automated; 3 = not yet fully automated; 2 = supervised, still mostly a research tool; 1 = needs further development.

modulation transfer functions is uncertain, and further studies are needed to find the best approximation to these functions.

Near-Surface Wind Fields

Automatic retrievals of the wind field are very challenging. 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), is the use of algorithms such as CMOD4 (tuned to the ECMWF model) and CMOD-IFREMER (tuned to buoy data) or estimates of azimuth cutoff smearing. In ideal situations, when the SAR image expressions reveal wind direction such as that associated with wind streaks, shadowing by land, etc.,[3,4] it is also possible to derive a complete estimate of the vector wind field. It is necessary, however, to pay careful attention to the radiometric calibration of the images, including the effects of analog-to-digital converter saturation, when the backscatter intensities are used to estimate the wind speed. (Note that the saturation problem should be avoided in the 8-bit analog-to-digital converter to be used in the advanced synthetic aperture radar [ASAR] on Envisat.) Since the SAR image also provides an estimate of the wave spectra, it is furthermore possible to look for the wind direction if the wave propagation direction is resolved without ambiguity. This will, of course, break down in shallow water when the waves are interacting with the bathymetry.

When 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 Portabello,[5] who showed 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. Such high-resolution mesoscale wind fields can, for instance, allow for much more precise estimates of advection and transport, both in the atmospheric boundary layer and in the upper ocean.

Air–Sea Interaction

As the global coupled atmosphere–ocean circulation models gradually approach a 10-km spatial resolution, it becomes of fundamental importance to advance the flux parameterization at the sea surface. Atmospheric boundary-layer processes and air–sea interactions typically have horizontal scales ranging from tens of meters to tens of kilometers. Therefore, the detailed manifestation of the surface roughness and stress variations imaged by the radar offers an excellent opportunity to investigate such interactive processes. 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. 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 the investigation of how these types of expressions can be used to provide estimates of atmospheric boundary-layer conditions, notably the height, stratification, and turbulence characteristics of the boundary layer.[6] See also articles by Brown (this issue) and Young (this issue).

Surface Currents, Fronts, and Eddies

Existing advanced and simple models for the simulation of SAR backscatter signatures of current fronts provide similar overall results. They appear less intense than the observed signatures in satellite SAR images, especially at X band and C band. 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.[7] This requires better parameterization of the source terms, both the local term connected with the short gravity-capillary waves and the nonlocal term induced by the longer waves that modulate the shorter waves and sometimes cause wave breaking. Another effect 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.

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 Waves and the Mixed Layer

Internal wave expressions can 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. Simulation models give estimates of SAR backscatter signatures of internal wave patterns that are of the correct order of magnitude.[8] In many cases the internal wave source locations, wavelengths, and propagation speeds can be directly determined from available SAR imagery. However, if we actually wish to estimate the strengths of the currents associated with the waves, it may be possible to apply an inversion scheme based on forward models. Moreover, the expressions of internal wave features can also allow the subsurface hydrographic and velocity structure and mixed-layer depth to be assessed, in particular in combination with numerical models.

Oil Slicks and Natural Films

The basic question for most end-users is how to distinguish man-made oil spills from natural films and other “look-alike” features. A combination of theoretical studies and controlled experiments can be made to measure surface film properties and relate them to radar backscatter signatures at different frequencies and polarizations. However, 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.[9]

Shallow Water Bathymetry

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. Studies of bathymetry estimation in shallow water such as those conducted in the Plaatgat area (of The Netherlands) using inverse methods show that if the number of ship survey tracks is reduced by a factor of 3–5, the root-mean-square error of the assessed depth map is still less than 30 cm.[10] This is the accuracy currently required by the Dutch

Ministry of Transport and Public Works (Rijkswaterstaat). The conclusion is corroborated by the results of depth assessments in other areas. It demonstrates that the use of SAR remote sensing mapping techniques can lead to a substantial reduction of the costs of traditional sounding campaigns. The key limiting factors are the sensitivity to wind speed and the water depth.

THE FUTURE

SAR Advances

The future SAR systems may have several frequencies, polarizations, and operating modes (i.e., "imagette," image, wide swath, and global monitoring) which are characterized by various spatial resolutions and coverages. Their individual contributions to the many specific applications within coastal monitoring and prediction as discussed in this article will vary, as illustrated in Table 2[11,12] (see also the article by Attema et al., this issue).

Although the image mode has the largest range of application, it is usually constrained by limited global coverage and correspondingly long revisit times. In contrast, the wide swath and global monitoring modes offer much better spatial coverage at shorter revisit times. However, these two latter modes are not applicable to wave field detection, ship detection, or shallow water bathymetry monitoring, and it is also questionable whether the global monitoring mode can be used for internal wave detection. Because these different application areas have very specific requirements for temporal and spatial resolutions, the optimum solution is to operate several different SAR systems simultaneously in space. As indicated in Table 3, this opportunity is indeed possible with the launch of Envisat, foreseen toward the end of 2000, operating together with Radarsat.

To make optimum use of these new SAR sensor systems and improve the general application of SAR imaging data, a series of upgrades of retrieval algorithms are necessary. These can be summarized briefly as the need to

1. Advance and optimize existing SAR wave spectra retrieval

Table 2. Overview of application areas versus the various Envisat SAR operating modes, including swath widths and resolutions.

Application	Imagette (5 km @ 30 m)	Image (100 km @ 30 m)	Wide swath (500 km @ 150 m)	Global monitoring (500 km @ 1 km)
Wave fields	VV	VV	N/A	N/A
Wind fields	VV/HH	VV/HH	VV/HH	VV/HH
Air–sea interaction	VV/HH	VV/HH	VV/HH	VV/HH
Current features	N/A	VV/HH	VV/HH	VV/HH
Internal waves	N/A	VV/HH	VV/HH	N/A
Natural films	N/A	VV	VV	VV
Oil spills	N/A	VV	VV	VV
Bathymetry	N/A	VV/HH	N/A	N/A

Note: N/A = not applicable, further explained in the text; HH and VV = horizontal and vertical transmit/receive polarization, respectively.

Table 3. Overview of currently operating, approved, and planned spaceborne SAR systems.

Satellite	Agency	Sensor type	Launch	Status
ERS-1	ESA	C-band VV	1991	Operation terminated
JERS-1	NASDA	L-band HH	1992	Operation terminated
ERS-2	ESA	C-band VV	1995	Operating
Radarsat-1	CSA/NASA	C-band HH	1996	Operating
Envisat	ESA	C-band VV/HH	2000	Approved
Radarsat-2	CSA/NASA	C-band HH	2001+	Approved
ALOS	NASDA	L-band HH	2001+	Approved/planned
LightSAR	NASA	L-band VV/HH	2001+	Unclear

Note: The table does not account for the numerous airborne SAR systems. ESA = European Space Agency; NASDA = Japanese National Space Development Agency; CSA = Canadian Space Agency; NASA = U.S. National Aeronautics and Space Administration; JERS = Japanese Earth Remote Sensing satellite; ALOS = Japanese Advanced Land Observing Satellite.

algorithms developed for the ERS satellite data for use with Radarsat and Envisat data, taking into account the many new and different operating modes
2. Develop more physical-based models for wind field retrievals by advancing and optimizing existing SAR wind retrieval algorithms developed for ERS data for use with Radarsat and Envisat data, taking into account the many new and different operating modes
3. Advance the opportunity to characterize and estimate spatial backscatter variability in connection with dominant air–sea interaction processes
4. Advance the quantitative interpretation 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
5. Advance the classification of internal wave signatures into their physical generation mechanism, upper-layer hydrographic structure, mixed-layer dynamics, and associated imaging mechanism
6. Advance the discrimination among natural films, man-made oil spills, and natural oil seepage (from reservoirs)
7. Develop and optimize a physical-based backscatter model for shallow water bathymetry retrievals

It should also be emphasized that the specific status and corresponding need for development and improvements are strongly interlinked. For instance, a successful completion and improvement of the wave field retrieval will indeed ensure a better chance to optimize the wind field retrievals. In turn, one can expect much better analysis and interpretation of air–sea interaction processes and surface current features. This makes the overall challenge for advancing the analysis and interpretation of SAR backscatter intensities more fundamental.

Sensor Synergy

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 synergy benefits include data from identical sensors, similar resolution image data from different sensors, data from similar sensors with different sampling capabilities, and data from different types of sensors with different sampling capabilities.[13] 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.[14] 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 infrared observations of atmospheric boundary-layer processes and of ocean surface current features and frontal boundaries.[1,14,15] Regarding the latter, it is anticipated that synergy using SAR and ocean color sensors will contribute in a similar manner. But we also anticipate a correlation in the SAR detection of natural films and their distribution with chlorophyll A patchiness derived from ocean color observation.

Simultaneous use of sea surface data from SAR combined with optical and infrared data can increase the capability to identify and interpret surface features compared with a situation where only SAR data are available. The key sensors recommended in such a pool of sensor synergy for coastal ocean monitoring are identified in Table 4. They include SAR, radar altimeter, and visible/infrared 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

Table 4. Synergy between SAR and other active microwave and optical instruments.

SAR imaging	Complementary quantity	Sensor synergy
Air–sea interaction and wind field detection	Large-scale wind field Significant waveheight Low-level cloud pattern	Scatterometer Radar altimeter Visible/infrared
Surface currents, fronts, and eddies	Surface geostrophic current (10-km resolution) Sea surface temperature field Surface chlorophyll A distribution	Radar altimeter Infrared Ocean color
Internal waves	Surface chlorophyll A distribution	Ocean color
Natural films	Surface chlorophyll	Ocean color
Oil spills		Ocean color

Note: No obvious complementary quantity exists for oil spill detection.

database functions, data processing and presentation software, and data analysis and interpretation routines.[14] Particularly important considerations for facilitating synergetic applications are image data browsing facilities, image data access and selection routines, minimization of geolocation/gridding errors, and advances in analysis and interpretation.

New satellite data such as SAR from ERS, Radarsat, and Envisat; ocean color data from the 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 interesting feature with Envisat is the opportunity for coincident ASAR and MERIS coverage.

Coastal Zone Monitoring

Given the international interest and recognition of the importance of the coastal zone, the international Land Ocean Interaction in Coastal Zones (LOICZ) Program within the International Geosphere-Biosphere Program (IGBP) has been established. A module for monitoring the coastal zone environment and its changes is also an integral component of the Global Ocean Observing System (GOOS), which was established in 1993 by the Intergovernmental Oceanographic Commission (IOC), the World Meteorological Organization (WMO), the United Nations Environment Program (UNEP), and the International Council for Scientific Unions (ICSU).

In addition, the Global Ocean Data Assimilation Experiment (GODAE) is aimed at the practical demonstration of real-time ocean data assimilation to provide regular and complete depiction of ocean circulation at scales of a few days at tens of kilometers. One of its prime objectives is to provide oceanic boundary conditions to coastal prediction systems. GODAE plans to execute its operational phase from 2003 to 2005.

The objectives of these efforts are listed in Table 5. From the list it is clear that a pilot demonstration experiment to assimilate ocean parameters derived from SAR, optical, and infrared satellite data in operational coastal ocean prediction systems (as shown in Fig. 1) would be timely. Currently, altimeter data, SAR wave spectra, and scatterometer vector wind field data are, to various degrees, used in global and regional ocean and weather forecasting models. On the other hand, the use of satellite data in coastal ocean modeling and data assimilation is challenging and will demand further investigation and validation.

The timeliness in developing and implementing a SAR analysis and interpretation system for specific application to the coastal zones and for extensive testing and pilot demonstrations at the onset of the next millennium is also good in view of the currently operating and future (approved or planned) spaceborne SAR systems, as shown in Table 3. The development and implementation of a SAR analysis and interpretation system for specific application to the coastal zones would also ensure valuable economic and social benefits.

Table 5. Key objectives associated with GOOS, LOICZ, and GODAE.

EuroGOOS	LOICZ	GODAE
Provide climate monitoring, assessment, and prediction	Assess carbon fluxes and trace gas emissions	Demonstrate real-time global ocean data assimilation to provide regular and complete depiction of ocean circulation at scales of a few days at tens of kilometers
Monitor and assess living marine resources	**Study economic and social impacts of global change on coastal systems**	**Provide oceanic boundary conditions to coastal ocean prediction systems**
Monitor the coastal zone environment and its changes	**Monitor coastal biogeomorphology and sea-level rise**	**Provide complete description of ocean physics upon which biological models can be developed and tested**
Assess and predict the health of the ocean	Investigate effects of changes in the external forcing or boundary conditions	Provide initial conditions for climate predictions
Provide marine meteorology and oceanographic operational service		Provide a method for systematic collection, handling, quality control, and scientifically consistent interpretation and analyses of data sets

Note: Those that are most relevant in coastal monitoring and predictions are in **bold**.

The importance of the coastal zone as an area of intense human activity with consequent environmental impact is beginning to be recognized. An important prerequisite for the sustainable management of coastal resources is the ability to predict change in coastal areas over periods of one to several decades. This requires an upscaling of the level of coastal marine research and, in particular, the strengthening of the technology and infrastructure for large-scale and long-term observation of the coastal seas.

The development and implementation of an advanced coastal ocean monitoring and prediction system with its underlying improved knowledge of dominant coastal ocean processes will, moreover, significantly contribute to our understanding of the economic development and social impact of the coastal environment. Notably, this is expected for marine resource management, marine environmental management (including preservation management, pollution prevention, cleanup and remediation, shoreline protection, and coastal hazard mitigation), marine coastal transportation, recreation, and development of industrial activities.

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