STATUS REPORT ON THE REMOTE SENSING OF CURRENT FEATURES
BY SPACEBORNE SYNTHETIC APERTURE RADAR

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ABSTRACT

Spatial variations in ocean surface currents can become visible in synthetic aperture radar (SAR) images via hydrodynamic modulation of the surface roughness. The interpretation of such SAR signatures is a challenging problem, since the imaging mechanism is quite complex and nonlinear and cannot be inverted easily. Furthermore, the distinction between SAR signatures of current features and other phenomena can be difficult. However, SAR is the only existing technique for the observation of current variations on spatial scales of tens of meters from satellites. There is a vital demand for such information, particularly in coastal regions. A variety of algorithms have been developed for the retrieval of information on current features from SAR images for different purposes. We give an overview of the state of the art, existing and potential applications, and future perspectives and requirements.

1. INTRODUCTION

Compared to the retrieval of wind vectors or wave spectra from synthetic aperture radar (SAR) images of the ocean, the interpretation of SAR signatures of current features is a more complex and diverse problem: Depending on the nature, the dimensions, and the strength of a current feature as well as on the wind speed vector and the imaging geometry, the modulation of the SAR image intensity can be dominated by different highly nonlinear mechanisms, and SAR signatures of similar features can look quite different under different conditions. Furthermore, completely different phenomena such as current features, variations in the wind field, rain, surfactants, or sea ice, can give rise to very similar signatures, which are often superimposed upon each other. This can lead to a complete misinterpretation. Finally, one must be aware of the fact that only current gradients, not absolute current values, can be retrieved directly from SAR intensity images.

Due to the complexity of the problem, it is practically impossible to develop a universal tool for an automatic interpretation of SAR signatures of current features: The highly nonlinear, multi-stage SAR imaging mechanism cannot be inverted easily; simplifications by linearization or the use of empirical model components are not adequate for wide parameter ranges. Furthermore, one cannot expect to obtain a unique and exact solution for a retrieved current field without additional information or a priori assumptions about its nature.

Despite these difficulties and limitations, SAR images of current features are being used successfully by a number of users for several specific applications. In this paper we give an overview of the state of the art and of future perspectives in this field. In the following section we discuss the SAR imaging mechanism of current features, basic strategies for the retrieval of information on current features from their SAR signatures, typical users of SAR images of current features and their specific applications and requirements, and existing alternatives to the observation of current features by SAR. In section 3 we present examples of existing algorithms for various purposes and typical results. Section 4 gives an outlook to expected and desirable improvements in the near future, including a direct retrieval of absolute currents from Doppler centroid processing of conventional SAR data and high resolution current measurements by along-track interferometry. We discuss requirements and recommendations for a better monitoring of current features by future spaceborne SARs. Finally, our main conclusions are discussed in section 5.

2. BACKGROUND

The fact that current gradients in the ocean can become visible in microwave radar images has been known since the 1970s. First spaceborne SAR images of the ocean with impressive signatures of oceanic features were acquired during the SEASAT mission in 1978 [1]. First theoretical models of the radar imaging mechanism were developed in the 1980s. With the launch of the scientific satellites ERS-1 and ERS-2 in 1991 and 1995, respectively [2], and of the commercial RADARSAT-1 in 1995 [3], the systematic use of spaceborne SAR for the remote sensing of current features began.

Today, recent and upcoming wide swath SARs such as ENVISAT ASAR [4] and RADARSAT-2 SAR [5] pro-
vide continuity and improved coverage at C band, and future systems at different frequencies, such as the German TerraSAR-X (X band) [6][7], will extend the variety of available data. The following subsections give a brief overview of basic principles, users and user requirements, and alternatives to spaceborne SAR.

2.1. SAR Imaging Theory of Current Features

A first quantitative, analytical theory of the SAR imaging of the spatially varying currents over underwater sandwaves was presented in 1984 [8]. Another group of authors published results of numerical simulations on the basis of the same fundamental ideas and equations in 1985 [9].

According to these theories, variations in the radar image intensity result from the straining of the short Bragg waves at the water surface, which are in resonance with the microwaves, by the spatially varying currents. After some simplifying assumptions in [8], the modulation of the image intensity was found to be proportional to the surface current convergence in radar look direction and to the reciprocal value of the so-called relaxation rate of the Bragg waves. The relaxation rate is a measure of the tendency of surface wave intensities to return to an equilibrium value after a distortion. It increases with the wind speed and with the wavenumber. Accordingly, the expression derived in [8] predicts that the strongest signatures of surface current gradients should be observed at low radar frequencies and that the maximum of the modulation should occur at the location of the strongest current convergence in look direction.

This first model was valuable for a basic understanding of the imaging mechanism, and it could be inverted easily, but it was found to underestimate most observed radar signatures, to overestimate the frequency dependence of the image intensity modulation, and to miss some other observed effects such as phase shifts between current gradients and radar signatures. Better results are obtained with so-called composite surface models which account for contributions of the entire two-dimensional ocean wave spectrum to radar signatures, such as the models described in [10] and in [11], [12]. The latest versions of these models account for effects of SAR imaging artifacts and of additional modulation mechanisms such as wave breaking. Nevertheless, the quantitative explanation of some observed signatures, such as very bright narrow lines at oceanic convergent fronts, is still a challenging problem for which no universal, generally accepted solution exists. Due to the complexity of the models and a lack of suitable reference data from experiments, the inclusion, tuning, and – in particular – the validation of new model components is usually difficult and time consuming or – in some cases – not possible at all.

2.2. Current Retrieval Strategy

Since SAR image intensities are sensitive to current gradients and not to the currents themselves, only variations in the surface current field, but not absolute currents, can be retrieved from observed SAR signatures if no additional information is available. As described in [13], the inversion of the imaging mechanism can theoretically be performed in an iterative approach, where a first-guess current field is modified until best agreement between simulated and observed SAR signatures is obtained. However, the resulting best estimate of the current field is not necessarily independent of the choice of the first-guess current field and the optimization strategy, thus these elements of the model inversion scheme must be selected with great care. Further problems can arise from the facts that the existing SAR imaging models are not perfect, that some model parameters are usually not well known, and that SAR signatures of wind variations can be very similar to the ones of current variations and occur at the same locations. Due to these limitations and difficulties, the full model inversion from a SAR image to a two-dimensional surface current field is not a very promising approach. For most existing applications, very specific algorithms have been developed, which exploit characteristic properties of the current feature of interest for major simplifications.

2.3. Users and Applications

Despite the limitations of the method and the difficulties in the data interpretation, spaceborne SAR is a valuable tool for a number of applications, since it is the only available instrument which can provide information on current features in areas of many square kilometers with a spatial resolution on the order of meters on a regular basis. Such information is particularly important in coastal areas, making the potential output attractive to a wide user community. International collaborations such as the Global Ocean Observing System (GOOS) and its European branch EuroGOOS were specifically set up to increase the operational exploitation of marine data and identify the requirements of existing and potential end users [14]. In a more SAR-specific context, a similar analysis of end-user requirements has been carried out within the European project MARSAIS (Marine SAR Analysis and Interpretation System) [15].

Results of these studies suggest that typical users come from a variety of research-oriented and industry backgrounds, all of which are strongly related to or dependent on coastal dynamics. These include environmental protection and preservation agencies, coastal authorities, fisheries, oil and offshore industries, oceanographic research institutions, and users from a military background. Since quantitative information on ocean currents is difficult to retrieve with currently available al-
2.4. Alternatives to SAR

SAR is the only existing technique for the observation of surface current variations on spatial scales of tens of meters from spaceborne platforms. To understand its potential for particular applications, one should be aware of alternative methods and instruments for current measurements and their characteristic advantages and disadvantages. These are listed in the following.

Airborne SAR: SAR images very similar to the ones from satellites can be acquired from airborne platforms as well. The imaging mechanism and the data processing and interpretation techniques are the same. Advantages: Radar parameters, imaging geometry, and flight times can be optimized for the particular application. Disadvantages: The coverage in space and time is quite limited compared to a spaceborne SAR, and logistical efforts and operation costs may be more expensive than the use of standard data products from a satellite.

Multi-temporal image analysis / feature tracking: Instead of looking for signatures of current gradients in a single SAR image, one can try to identify features floating on the sea surface, such as oil films, in two images separated by some minutes to hours and compute the surface currents from the displacement of these features. This method is being used successfully for monitoring sea ice motions. Advantages: Absolute two-dimensional velocity vectors are obtained (mean velocities for the time period between the two images). Disadvantages: There are no suitable features in most SAR images of the open ocean; the time lag between spaceborne SAR images of the same area from the same sensor is usually too long; the spatial resolution of this current retrieval method is quite limited; the observed velocities of features are not necessarily surface current velocities. The method may be useful, however, for studies of the dynamics of larger current features, such as mesoscale eddies and meandering fronts (Gulf Stream). Also data from other spaceborne imaging sensors, such as ocean color or sea surface temperature images, are suitable for this kind of analysis.

Microwave Doppler radar: Like a police radar, a Doppler radar measures Doppler shifts of the frequency of the backscattered radar signal, which are proportional to line-of-sight (radial) target velocities. Conventional SAR images do not contain Doppler information, since the Doppler history of the backscattered signal is used for obtaining a high resolution in azimuth direction (flight direction) by creating a long synthetic aperture. However, some Doppler information can be preserved and used for current retrieval at lower resolutions, as described in section 4.3. Advantages: Absolute currents can be detected; the imaging mechanism is much more direct than the SAR intensity imaging mechanism of current features. Disadvantage: Limited spatial resolution. Doppler measurements at full SAR resolution can be obtained from an along-track InSAR with two antennas; see section 4.4. There are also ground-based microwave Doppler radars for current measurements. They can be used, for example, for current measurements in rivers or tidal channels, but the spatial resolution and coverage is quite limited. Two-dimensional current measurements can be obtained by looking at a test area from two different directions.
**HF radar:** The HF radar (high frequency radar) is a Doppler radar using wavelengths in the meter range. HF radar systems can be used for current measurements from the shore or from ships. State-of-the-art HF radar systems, such as WERA [17], have a maximum range on the order of 60 km and a spatial resolution of 300 m or worse. Two-dimensional current measurements are obtained by looking at a test area from two different directions. Advantages: Continuous current measurements with a temporal resolution of a few minutes can be obtained over long periods, which is important, for example, for the monitoring of shipping routes with strong tidal currents. Disadvantages: Limited spatial coverage and resolution; access to test areas and logistic requirements may be a problem; HF radar is not well suited for open ocean applications.

**Optical imaging:** Roughness variations at the sea surface, which result from wave-current interaction and which modulate the image intensity of SAR images, can also become visible in optical imagery of areas where specularly reflected sunlight is available. The imaging theory is discussed, for example, in [18]. In principle, this may be an alternative to SAR, but the imaging geometry is quite complex, and only areas which reflect direct sunlight towards the sensor can be probed. The method will not work at night or if clouds are present over an area of interest. Furthermore, some spaceborne optical sensors, such as SeaWiFS [19], have specific tilting mechanisms to avoid sunglint in the images, thus they cannot be used at all for this application.

**Radar altimetry:** Radar altimetry is a well established technique for the observation of geostrophic currents in the open ocean by measuring sea surface heights from satellites [20]. Latest instrument designs or mission concepts promise height measurements with a fine along-track resolution on the order of a few 100 meters [21] as well as measurements of cross-track surface slopes [22][23], permitting to retrieve two-dimensional current variations on scales of a few kilometers. Advantages: Depth-integrated currents are detected; the data satisfy the requirements of many open-ocean applications. Disadvantages: Only phenomena which affect the sea surface elevation are detected; the resolution is low compared to the resolution of a SAR; the measuring principle is not suited for coastal applications. Radar altimeters and SARs complement each other rather than competing with each other.

**In-situ measurements from moorings, buoys, or ships:** Of course one can measure currents in situ, which is usually done by mechanical instruments or by acoustical instruments, such as acoustic Doppler current profilers (ADCPs). Advantages: The techniques are well established and respected and can be used without major efforts; measurements can be performed at the depths of interest; continuous measurements over a long period are possible. Disadvantages: Only point measurements are obtained; near-real-time data access from moorings and buoys is difficult; ice in the water, animals, ships, etc. can destroy the instruments.

**Drifters / tracers:** Instead of measuring currents at fixed locations (Eulerian approach), one can monitor the locations of drifters or chemical tracers which are floating freely within the moving water masses (Lagrangian approach). Advantage: One obtains information on actual paths of individual elements of the water body, integrated over relatively long times. Disadvantages: The coverage in space and time and the spatial and temporal resolution are very limited. This method is mainly used for observations of large scale circulation phenomena over long periods.

Hence, direct surface current measurements at spatial resolutions comparable with SAR images are extremely difficult. This limits the availability of validation data.

### 3. EXISTING ALGORITHMS

A variety of algorithms for the retrieval of information on current features from SAR imagery has been developed for a variety of purposes. We cannot discuss all existing algorithms and their specific qualities and potential applications in the context of this paper. However, we give an overview of some important classes of algorithms and particular examples which are representative of the state of the art in this field. For each algorithm class we describe the problem it is trying to solve, typical users and applications and their requirements, the technical concept of the algorithms, and the present status of the algorithm development and utilization.

#### 3.1. Feature Detection

A correct detection and / or classification of SAR signatures of current features is a fundamental requirement for any further interpretation. While the detection of ships or oil spills has been performed in operational environments for a while, most existing algorithms for signatures of current features are less mature for various reasons: Signatures of current features are more complex than signatures of ships or oil spills; they can be similar to signatures of atmospheric or other features; and requirements of different users and applications are much more diverse than the well-focused requirements in the fields of ship and oil detection.

**The problem:** While SAR signatures of ships are always brighter and signatures of oil spills are always darker than the ambient image intensity and both kinds of features have clear other characteristic properties such as
typical shapes and sizes, surface current features can give rise to bright and dark signatures with wide ranges of modulation depths, sizes, and shapes. Furthermore, there can be very similar signatures of other features such as variations in the wind field. While specialists may be able to identify signatures of features of their interest and select appropriate algorithms for their further interpretation, this can be difficult for inexperienced users or just not reasonable in operational environments which require an automatic, ideally unsupervised, analysis of many SAR images. In addition to the general detection problem, SAR signatures of current features are often superimposed by signatures of atmospheric features which can be very similar. In such cases, a reliable classification algorithm is required to identify and separate signatures of oceanic and atmospheric origin and to avoid misinterpretation. An example of an ERS SAR image with signatures of oceanic internal waves as well as signatures of surface films and various atmospheric phenomena is shown in Fig. 1.

Applications and users: Feature detection and classification algorithms are useful for almost all applications dealing with SAR imagery of ocean scenes. They facilitate the interpretation of images with many different signatures, such as the one shown in Fig. 1. They are a basic requirement for an automatic analysis of large numbers of SAR images. Very likely, the availability of reliable feature detection algorithms would attract many new users of SAR imagery, who are interested in information on particular features that can be retrieved from SAR signatures, but who lack the knowledge or capacity to perform the feature detection or specific algorithm developments on their own. A reliable classification of SAR signatures of oceanic and atmospheric origin would improve the exploitation of both kinds of signatures, since information on wind variations on spatial scales on the order of some hundreds of meters within areas of many square kilometers can be quite valuable for meteorologists and can hardly be obtained from other spaceborne sensors.

Algorithm concept: An algorithm for the detection of signatures of (oceanic) internal waves was presented in [24]. It is based on a wavelet transform. It can analyze SAR images for the presence of internal waves signatures and show the location of such signatures. A more general wavelet-based algorithm, which can detect and classify signatures of features like fronts, internal waves, and eddies as well as ice edges and oil spills, was presented in [25]. A flow chart of this algorithm, which nicely visualizes the different steps of feature detection and classification, is shown in Fig. 2. For the detection of line features, a Radon transform [26] may be more appropriate than a wavelet transform.

If dual-polarization images, such as ASAR Alternating Polarization Mode data from ENVISAT [4], are available, one can exploit characteristic differences in the dependence of signatures of current and wind variations on the polarization. Very drastic differences of this kind were found in airborne real aperture radar data from the JUSREX experiment off the U.S. east coast in 1992: Pairs of images of the same scene at HH and VV polarization, acquired at a frequency of 13.3 GHz (Ku band) and a near-grazing incidence angle of 80°, exhibit pronounced signatures of oceanic internal waves at HH and of atmospheric convection cells at VV polarization – the two images look completely different [27].

A first theoretical explanation for the observed effect was given in [28]: Wave-current interaction usually has the strongest effect on wave intensities in the wavelength range of decimeters to meters, while wind variations on relatively short spatial scales will mainly modulate the shorter ripple waves which are directly generated by the wind. Since the relative contribution of waves which are long compared to the Bragg waves to
the backscattered power is larger at HH than at VV polarization, signatures of oceanic phenomena are stronger at HH. However, the model discussed in [28] cannot explain why radar signatures of wind variations should be stronger at VV than at HH polarization, since the relative contributions of short waves to the backscatter at both polarization should be the same.

Present status: To our knowledge, none of the described feature detection / classification algorithms has been implemented in such a way that it is being used operationally, although successful tests and performance analyses have been performed. The lack of mature feature detection and classification tools may be one of the main reasons for the relatively poor utilization and exploitation of SAR images of current features at present.

Fig. 2. Flow chart of the feature detection and classification scheme described in [25] (provided by A. Liu).

Characteristic polarization dependencies of SAR signatures of oceanic and atmospheric features have also been found in SAR data acquired from spaceborne platforms and at steeper incidence angles: Fig. 3 shows a pair of C band SAR images of a scene in the Atlantic Ocean which were acquired from the Space Shuttle Endeavour during the SIR-C / X-SAR mission in April 1994. The incidence angle is 31°. Both images exhibit strong signatures of two different features: A large signature consisting of multiple lines, extending from the lower left to the upper right, and a smaller signature consisting of a single bright line in the lower left, oriented almost perpendicular to the large signature. While the modulation depth of the large signature is almost the same in both images, the small signature is clearly stronger at HH than at VV polarization. Very likely, the feature causing the large signature is an atmospheric internal wave, while the small feature must be an oceanic feature. This is a matter of ongoing research. Unfortunately, high-resolution in-situ data from the test area are not available.

3.2. Feature Tracking

Feature tracking has already been listed in section 2.4 as an alternative to the retrieval of current gradients from SAR image intensity variations. We would like to mention it once more under "existing algorithms", since it is a method for the retrieval of absolute currents from multitemporal SAR images which can be quite useful where such images are available and where the knowledge of absolute currents is important. It can also com-
ple the analysis of signatures of surface current gradients, since information on mean currents can be valuable for the generation of a first-guess current field for further iterative optimization.

The problem: Conventional SAR intensity images do not contain information on absolute currents. If two or more SAR images of the same scene are available with a time lag that is short compared to the decorrelation time of visible surface feature patterns, one can try to identify features which are moving with the surface current and determine current vectors from the locations of these features in the different images.

Applications and users: Absolute current measurements are useful for a variety of applications. Since the spatial resolution and coverage of the currents that can be determined from multi-temporal images is quite limited (depending on the visible features and on the resolution and temporal separation of the SAR images, resolutions on the order of hundreds of meters to kilometers are realistic), one cannot use this technique to obtain information on current gradients at oceanic fronts (see section 3.3) or spatial variations of the currents over oceanic internal waves (section 3.4) or underwater bathymetry in coastal waters (section 3.5). However, low-resolution information on absolute surface current vectors can be valuable for oceanographic studies on largerscale features such as the Gulf Stream or eddies. Furthermore, low-resolution currents from multi-temporal image analysis can provide valuable information on mean currents for a further retrieval of current variations at a higher resolution from SAR intensity signatures of features like oceanic fronts or underwater bathymetry.

Algorithm concept: Feature tracking requires the availability of two or more SAR images of the same scene with some time lag. Distinct features must be visible in both images (or pairs of adjacent images), which can be identified unambiguously. For example, patterns in surface films can be used. The feature tracking algorithm itself can be an extended feature detection algorithm or an algorithm analyzing the cross correlation function of the two images for individual sub-areas. For a correct calibration of the results, the rectification and collocation of the SAR images must be carried out with care.

An example of a feature tracking exercise with airborne SAR data was presented in [29]: In this case, two images of surface film patterns near the Gulf Stream edge with a temporal separation of 20 minutes were analyzed. Reasonable agreement of the SAR-derived currents with ADCP data was found; remaining differences are at least partly due to wind drift effects. The two SAR images and retrieved current vectors as well as a diagram showing a comparison of SAR-derived and ADCP-derived currents are shown in Fig. 4.

To some extent, even slick patterns in single SAR images can be used as indicators of surface flow patterns [30][31][32][33]. However, as shown in [29] (cf. Fig. 4b), the slicks do not necessarily line up with the currents: The slick orientations are governed by the current gradients rather than the mean currents.

Present status: Feature tracking algorithms have been developed and used successfully for many technical applications, using images of a variety of objects from a variety of sources. The main problem in their applica-
tion to spaceborne SAR imagery of the ocean is the fact that suitable data are hardly available: To track surface features like surface films with spatial scales of tens to hundreds of meters, which can move at velocities on the order of decimeters to meters per second and change their shapes on time scales of minutes to hours, one needs images with a temporal separation on the order of minutes. Such data are not available from a single spaceborne SAR. However, tandem missions with two satellites on the same orbit, following each other within several minutes, can provide suitable data. Such missions are under consideration for topographic mapping purposes. In the framework of a tandem mission with a considerable duration of several months, the implementation and use of feature tracking algorithms for oceanographic studies may be useful.

3.3. Current Gradient Retrieval at Ocean Fronts

SAR signatures of oceanic current fronts, which can be very narrow bright lines, have attracted the interest of oceanographers as well as remote sensing scientists for quite a while, since they provide valuable information on circulation and mixing processes on the one hand, and they can cause enormous difficulties for modelers of SAR signatures of current features on the other hand, since most imaging models underestimate the observed strong signatures significantly. Thus SAR images with signatures of current fronts are popular test cases for SAR imaging models and interpretation algorithms. An example of an ERS SAR image of oceanic fronts off the south coast of Mexico is shown in Fig. 5.

The problem: The detection of signatures of fronts in SAR images is relatively easy, since fronts will usually become visible as distinct lines which are clearly brighter or darker than the ambient regions or which separate regions of different mean image intensities. However, the further interpretation of the signatures is difficult since the convergent currents at ocean fronts can give rise to a variety of effects which have an impact on the backscattered radar signal, such as hydrodynamic wave-current interaction, wave breaking, or wave damping by accumulated surface films. Furthermore, different temperatures of the water masses at both sides of an oceanic front can affect the atmospheric stratification and thus give rise to wind stress variations. The parameterization and / or modeling of these phenomena is quite difficult. Furthermore, high-resolution reference data from in-situ measurements for a calibration and validation of imaging models and current retrieval algorithms for ocean fronts are very rare.

Applications and users: Information on ocean fronts is useful to fishing industries and resource planners as well as oceanographers interested in circulation and mixing phenomena, transport of pollutants, nutrients, etc.

Fig. 5. ERS-2 SAR image of coastal waters off the Pacific coast of Mexico (3 April 1996, 16:50 UTC), showing signatures of several current fronts (from http://www.ifm.uni-hamburg.de/ers-sar, © ESA).

Algorithm concept: Until now, research in this field has mainly focused on dedicated experiments and case studies for a better understanding of fundamental hydrodynamic processes at current fronts. The analysis of radar signatures of current fronts has usually been complemented by in-situ measurements and analytical or numerical model calculations, such as in [34], [35], [36], [37], [38], [39], [40], [41]. The temporal evolution of current fronts is analyzed in [42]. Radar imaging models of ocean fronts have been discussed, for example, in [43], [44], [45]. A radar imaging model performance analysis was presented in [46]. The relative effect of current shear vs. convergence on SAR signatures of ocean fronts has been assessed in [35], [37]. The exploitation of information from multi-frequency / multi-polarization SAR images for an independent iterative optimization of current and wind variations at the Gulf
Stream front is demonstrated in [47]. A prototype of an interactive tool for an automatic analysis and interpretation of SAR signatures of current fronts on the basis of numerical simulations has been developed and demonstrated within MARS AIS [15]. Nevertheless, all existing models and algorithms for SAR signatures of ocean fronts are still pre-operational. For more information on latest developments in this field see [48] in this issue.

**Present status:** The existing models and algorithms for the analysis of SAR signatures of ocean fronts are in a pre-operational stage and cannot be given to inexperienced users. For the development and validation of robust models and algorithms, further dedicated experiments and theoretical studies need to be performed.

### 3.4. Analysis of Internal Waves Signatures

In a stratified ocean the interaction of the tidal flow with topographic features can generate internal solitary waves (ISWs), for instance at sills [49][50] and at continental shelf breaks and slopes [51][52][53]. The ISWs are gravity waves and usually develop as a single soliton which disintegrates into a train of ISWs. The associated currents induce regions of convergent and divergent surface currents, which can become visible as bright and dark bands, respectively, in SAR images. A first theory of the radar imaging mechanism of ISWs was presented in 1985 [54]. Since then, numerous investigations of ISW SAR signatures have been carried out, showing that ISWs are ubiquitous in the ocean [55].

**The problem:** It is difficult to derive oceanic parameters from SAR signatures of ISWs because the relationship between environmental parameters (stratification, bottom topography, ambient current, wind speed and direction) and ISW parameters (characteristic half width, amplitude, propagation speed) is quite complex. However, assuming a two-layer stratified ocean, the mixed-layer depth [51][56] and the temporal and spatial evolution of an ISW [49] can be estimated to some extent from the SAR signatures. The development and demonstration of an inversion scheme for the retrieval of oceanic parameters from SAR signatures of ISWs has been one of the objectives of MARS AIS [15].

**Applications and users:** In continental shelf regions, shoaling and breaking of ISWs enhances nutrient concentration and mixing [57][58]. This is of interest primarily for studies concerning the nutrient budget and biological activity on continental shelves. Deep water ISWs, such as the ones observed in the Sulu Sea [59], can have peak-to-trough amplitudes of more than 100 m, and propagation speeds exceeding 2 m/s. Current changes caused by the passage of such an ISW may create shear currents that are dangerous for any sort of underwater activity. Moreover, there is evidence that ocean tides alone are insufficient to account for the loss of rotational energy of the Earth-Moon system [55], and that the energy of ISW dissipation may make a small but significant contribution [60]. Accordingly, parameters of interest for scientists and other users are the presence and frequency of ISWs, their amplitudes, characteristic half widths, propagation speeds, pycnocline / interface depths, and the current variations during the passage of ISWs.

**Algorithm concept:** Many models have been developed to describe ISWs [55]. Under the assumption of a two-layer stratified ocean, an ISW can be described by a one-dimensional form of the Korteweg-deVries (KdV) equation for shallow water waves [61][62]. The algorithm developed within MARS AIS uses a combination of an analysis of the SAR signatures of ISWs (location, wavelength, modulation depth of the image intensity), analytical calculations, and simulations with the forward SAR imaging model M4S [11][12]. Profiles are extracted from the ISW signatures in a SAR image as shown in Fig. 6. A look-up table relates densities and depths of the two water layers, total water depth, propagation speed, and surface currents according to the KdV equation. Possible realizations of the horizontal surface current profile associated with each individual ISW of the wave train are obtained from the look-up table, depending on the ISW's propagation speed (determined from its distance from the point of generation and the tidal phase), the total water depth, and first-guess values of the densities and depths of the two water layers, using climatalogical values.

For each current field corresponding to a possible parameter combination, the numerical SAR imaging model M4S is used to compute a theoretical SAR image intensity profile. The model results are then compared with the measured intensity profile. The density and water layer depth values that correspond to the best-fit simulated SAR signature are considered as best estimate of the actual oceanic conditions in the test case. Fig. 7 shows a SAR image intensity profile derived from Fig. 6 together with the corresponding best-fit model result.

**Present status:** The algorithm developed within MARS AIS is available only to project partners so far. It has been applied to data acquired in the Straits of Gibraltar and Messina, comparing well with in-situ validation data collected at the latter location. However, further work is needed before the algorithm can be applied to a wider range of geographic locations or to extend the algorithm to areas with ISWs for which the shallow-water approximations do not hold [55][63]. Accurate knowledge of wind speed and direction are required as input parameters for the algorithm since they can have a significant effect on the resulting SAR signatures [64], as can natural or anthropogenic surface films [65].
Fig. 6. ERS-2 SAR image of the area south of the Strait of Messina, Mediterranean Sea (27 October, 1995). The map inset shows the location of the frame together with the bathymetry. The inset on the bottom left shows a blowup of the area marked by the white square (31 km x 31 km). Three black rectangles mark user-defined transects. The small black square in the main image marks the region over which image intensities were averaged for wind speed retrieval (from S. Kern).

Fig. 7. Profiles of the measured (blue) and modeled (red) relative SAR image intensity for one of the transects shown in Fig. 6; correlation and regression coefficients are 0.797 and 0.983, respectively (from S. Kern).

3.5. Bathymetry Assessment

One of the most mature applications based on SAR imagery of current features is the monitoring of bathymetric changes in coastal waters. In close collaboration with coastal authorities (Rijkswaterstaat), the small company Argoss in the Netherlands has made quite some progress in this field during the last years. A detailed overview of their "Bathymetry Assessment System" (BAS) with example results is given in [16]. For more literature on the radar imaging of underwater bottom topography see, for example, [8], [9], [18], [66], [12], [67].

The problem: It has been known since the 1970s that underwater bottom topography in coastal waters can become visible in radar images [68][69]. First theoretical models were presented in 1984 and 1985 in [8], [9]. It was realized that the radar signatures, which sometimes appear to show the actual underwater bathymetry (an example is shown in Fig. 8) result from a modulation of tidal currents by the spatially varying water depths. The inversion of SAR images into topographic maps would be quite attractive for various applications, thus several research and development projects in this field have been carried out since the 1980s.

Applications and users: Bathymetric surveys are important for applications such as the monitoring of shipping routes, morphodynamics, coastal protection, and high-resolution circulation modeling. Typical users are coastal authorities, environmental protection agencies, oil and offshore industries, and research institutions. Bathymetric surveys have traditionally been performed by echosoundings from ships, which are time-consuming and expensive, particularly if they have to be carried out frequently in highly dynamic areas. The integration of SAR data in a bathymetric monitoring system makes sense if it helps to reduce costs or to improve the spatial and temporal coverage and sampling.

Fig. 8. ERS-1 SAR image of the east coast of China (8 July 1995, 2:34 UTC), showing clear signatures of underwater bottom topography (from http://www.ifm.unihamburg.de/ers-sar, © ESA).
Algorithm concept: The BAS uses a combination of echosoundings on a relatively coarse grid and SAR imagery. A model suite consisting of a flow model, a wave-current interaction model, and a radar scattering model, is applied to an initial bottom topography obtained from the echosoundings, and model parameters as well as water depths between the existing data points are optimized iteratively until best agreement between simulated and observed SAR signatures is obtained.

Present status: The BAS has been applied successfully to a variety of test areas and scenarios (mainly off the Dutch coast), including dedicated validation studies as well as quasi-operational applications. It has been shown that the amount of echosoundings can be reduced significantly (compared to a purely traditional approach) without losing accuracy and spatial resolution (see [16]). Argoss is offering bathymetry retrieval as an operational service. As far as we know, the Dutch coastal administration Rijkswaterstaat (RWS) decided in fall 2003 to integrate the Bathymetry Assessment System into its operational coastal monitoring activities.

4. THE FUTURE

As can be seen from the algorithm descriptions in section 3, the exploitation of SAR signatures of many kinds of current features is still in an experimental stage. Reasons for this are manifold: Existing algorithms or numerical imaging models are not available to potential users, have not reached mature levels of development, or are not sufficient to satisfy the requirements of some applications. Also the spatial and temporal coverage of the areas of interest of some potential users and a continuous data availability over longer periods can be serious problems. In the following we discuss these problems and possible solutions as well as the potential of two emerging new techniques for current measurements by SAR, that is, the Doppler centroid analysis and along-track interferometry.

4.1. Improved Exploitation of Available Data

The current feature algorithms that are available today and the corresponding SAR images are not being used by many potential users, even if the results would satisfy their requirements perfectly. Many people, laboratories, or agencies are not aware of the availability of SAR imagery and algorithms and of their potential. Another problem is the fact that many algorithms have not reached a stage of development where they can be used by inexperienced users without major problems or where they have been tested and validated so convincingly that potential users are willing to use them for routine applications. Projects like MARSAIS [15], in which interpretation algorithms for SAR signatures are implemented with user-friendly interfaces and presented to potential users together with educational material and example results, are hopefully helping to overcome these shortcomings and to improve the awareness and the acceptance of the potential of SAR imagery.

Other users may be reluctant to use SAR images in operational contexts since the continuity of the data supply is not guaranteed: Satellites like ERS-1, ERS-2, and ENVISAT must be considered as research satellites with a limited lifetime, which have been designed to achieve certain mission goals and to test and demonstrate some new technologies and data products, but there has been no guarantee for a continuous availability of the data products over periods longer than the lifetimes of the satellites. This is a significant difference between existing spaceborne SARs (except, perhaps, the RADARSAT program) and other remote sensing instruments or satellites such as the AVHRR program of NOAA or the METEOSAT program of ESA [70].

Further impediments to the use of SAR data and algorithms may arise from the difficulties and costs associated with the ordering and the analysis of SAR images: Inexperienced users may be not willing or not able to figure out what kinds of data products they can order, how this must be done, and how the data must be processed to obtain the desired information. Also the availability of user-friendly algorithms is a problem in this context. Since the current features and the specific applications of different users are quite diverse, space agencies cannot deliver higher-order data products to end users (as it can be done, for example, with SAR-derived wind fields and ocean wave spectra), but they must give the SAR images themselves to the users and hope that the users know how to interpret the data. A free distribution of feature detection algorithms and other useful tools and educational materials to customers of SAR images would probably help to make the handling and interpretation of SAR imagery easier and to attract some of the less ambitious users this way.

4.2. Model and Algorithm Improvements

Not only the availability and ease of use of existing algorithms, but also the quality of the underlying theoretical models for the SAR imaging mechanism of current features is a considerable problem which has been completely neglected in some recent projects with a strong emphasis on the demonstration of the capabilities of SAR to inexperienced potential users. In fact, there are many open questions in the modeling of SAR signatures of oceanic phenomena, and the basic research in this field needs to be continued if the development of more accurate, more reliable, and more general algorithms for the retrieval of information on current features is a serious objective.
A hot topic in this field is the modeling of wave breaking effects. The breaking of ocean waves can reduce the energy in some parts of the wave spectrum and enhance the energy in other parts. Furthermore, steep waves can become highly nonlinear and form higher-order harmonics. The evolution of the waves in spatially varying current fields and their radar backscattering properties under such conditions can be quite different from predictions of small perturbation theories. Several studies on wave breaking processes and their effect on radar signatures have been carried out during the last 10 years or so [71][72][44][45][73], but a completely satisfactory model has not been developed yet, and some more dedicated laboratory and field experiments will probably be required in order to understand all relevant physical processes of wave breaking and to validate various model components (see also [48]). Also other modulation mechanisms, such as the feedback effects between the spatially varying surface roughness and the wind stress [74][75], need to be investigated in more detail.

In this context one should be aware of the fact that there are some mature numerical SAR imaging model suites which are available to interested users and scientists for test calculations and scientific investigations, such as the ERIM Ocean Model (EOM) based on the theory described in [10], the M4S model [11][12][81], and the WHIT model [66][67]. These programs offer various options for model terms and parameters and can be quite valuable for sensitivity analyses of SAR signatures, the development of inversion algorithms, and similar activities. To obtain the model suites (source code or executables), one should contact the authors. Also the model used at the U.S. Naval Research Laboratory [44][45] and the one described in [48] may be available on request.

4.3. Current Retrieval from Doppler Centroids

In the conventional processing of SAR raw data, the Doppler history of the backscattered signal is exploited for the creation of a long synthetic aperture in order to obtain a high resolution in azimuth direction. As an artifact of this processing, the extra Doppler shift associated with the line-of-sight velocity of a moving target is translated into an azimuthal displacement of this target in the image (train-off-the-track effect). Except for this effect, the fully processed SAR image does not contain explicit information on target velocities anymore.

One can, however, preserve some information on mean Doppler shifts (Doppler centroids) by processing the data at a reduced resolution or retrieve Doppler shifts from the phase statistics of complex data. This idea was first proposed in 1979 in [76], but it could not be demonstrated very well with L band SAR data from SEASAT. A successful demonstration with C band data from ERS SAR was presented in the late 1990s [77]. A crucial element of the technique is the computation of theoretical Doppler centroids of non-moving terrain, which result from the relative motion between satellite and rotating earth, and which need to be subtracted from the measured Doppler centroids to obtain the Doppler shifts associated with sea surface motions. The spatial resolution obtained from the Doppler centroid analysis is on the order of 1 to 2 km, thus comparable to the real aperture radar resolution of a spaceborne SAR.

The Doppler centroid analysis has also been demonstrated with ENVISAT ASAR wave mode data. The qualitative agreement between SAR-derived surface velocities and the known general circulation has been found to be good, but the correction of absolute retrieved radial surface velocities for contributions associated with the local wind vector and ocean wave spectrum is crucial and a matter of ongoing studies [78]. If these problems can be solved, surface current measurements with SAR at spatial resolutions on the order of kilometers can be quite attractive for some applications. Furthermore, a systematic application of the method to historical ERS-1 and ERS-2 SAR raw data (particularly wave mode data covering the global oceans) could result in a quite valuable data base of worldwide surface currents since 1991. Details of the Doppler centroid analysis technique, example results, and potential applications are discussed in another paper in this issue [78].

4.4. Along-Track InSAR

The along-track InSAR (along-track interferometric SAR) technique combines the high resolution of a SAR with Doppler shift measurements. Thus an along-track InSAR can directly detect radial surface currents and current variations on spatial scales of a few meters. The concept was first proposed in 1987 in [79]: Two complex SAR images of a scene (containing amplitude and phase information of the backscattered signal for each pixel) which are acquired with a short time lag on the order of milliseconds exhibit phase differences proportional to the time lag and to the Doppler shift of the signal. To obtain two images with a short time lag, two SAR antennas must be separated by some distance in flight (along-track) direction.

Experiments with airborne along-track InSARs have been performed since 1989 [80]. The data interpretation has turned out to be more complicated than originally expected, since the InSAR-derived velocities have to be corrected for contributions of wave motions. However, the InSAR imaging mechanism of currents is much more linear than the SAR intensity imaging mechanism of current gradients, and the correction of the data is relatively easy and does not require specific assumptions regarding the nature of a current feature of interest.
like the interpretation of SAR intensity imagery. Detailed theoretical descriptions of the along-track InSAR imaging mechanism and the inversion problem can be found in [80], [81], [82].

Along-track interferometry from a spaceborne platform was recently demonstrated with data from the Shuttle Radar Topography Mission (SRTM) in early 2000 [83][84]. The interferometric X band SAR on the Space Shuttle Endeavour was mainly designed for the generation of digital elevation maps of land surfaces by cross-track interferometry. The cross-track antenna separation was 60 m. For technical reasons, there was also an along-track separation of 7 m, which could be used for current measurements. Unfortunately, the along-track separation of 7 m and the corresponding time lag of 0.5 ms between the two SAR images are quite short compared to the ideal time lag at X band, which would be on the order of 3 to 5 ms [81], [82]. This results in a relatively low sensitivity for small current variations and relatively high phase noise. However, phase noise can be reduced by averaging over many pixels.

Fig. 9 shows an example of a current field derived from an SRTM phase image of the "Waddenzee" area off the Dutch coast. This current field looks still somewhat noisy, but it exhibits clear signatures of tidal current patterns. A comparison with a simulated current field from the Dutch circulation model KUSTWAD [85] for the same tidal phase revealed an overall correlation of 0.558, which is reasonable in view of the remaining noise in the SRTM result and obvious systematic differences between the SRTM- and KUSTWAD-derived currents in some parts of the test area. Very likely, these differences can be attributed mainly to actual differences between the current field at the time of the SRTM overpass and the simulated current field, not to shortcomings of the SRTM result.

As discussed in [84], results of a more detailed statistical analysis indicate that the agreement of spatial variations in the SRTM- and KUSTWAD-derived current fields on different length scales is constantly good down to scales on the order of 1 km. Autocovariance functions of both current fields show consistently that most of the variations occur at longer length scales. Accordingly, one can conclude that practically all variations in the current field which are relevant to the circulation model are resolved by SRTM. In view of the fact that the parameters of SRTM are quite unfavorable for current measurements, this is an encouraging result.

A simulation with the numerical SAR / InSAR imaging model M4S, using the current field from KUSTWAD as input and all relevant parameters of the SRTM overpass scenario, confirmed that M4S is well suited for the simulation of InSAR data products. Not only the dominant current patterns, but also the noise characteristics of the original SRTM data are reproduced realistically in the simulation. M4S can thus be used well for performance analyses of future InSARs or InSAR concepts.

As a first satellite with along-track InSAR capabilities, the German TerraSAR-X will be launched in late 2005 [6][7]. The phased-array X band SAR antenna of TerraSAR-X with a total length of 4.8 m can be switched to a split antenna mode, in which two halves act as separate receiving antennas with an along-track separation of 2.4 m between the phase centers. The split antenna mode will be implemented mainly for polarimetric measurements over land and ice, but it can be used as well for interferometric current measurements with an effective time lag of 0.17 ms.

At an incidence angle of 40° this translates into a horizontal velocity / phase ratio of about 140 m/s per 2π. That is, the sensitivity is even worse than the one of SRTM in the "Waddenzee" test case by a factor of about 3.6; a current change by 1 m/s corresponds to a phase difference change of only 2.6°. However, the single-look spatial resolution of TerraSAR-X (3 m in the stripmap mode with a swath width of 30 km) is much higher than the one of SRTM (12.5 m); more than 1100 independent samples of the phase difference can be averaged within 100 m × 100 m. Model predictions indicate that this will finally result in current measuring capabilities very similar to the capabilities of SRTM in the "Waddenzee" test case. That is, one can expect current measurements at reasonable quality at a resolution of a few 100 meters from TerraSAR-X.

Fig. 9. Line-of-sight current field derived from an SRTM phase image of the Dutch coast; test area size = 70 km × 70 km (from R. Romeiser).
With a longer antenna separation, much higher resolutions could be obtained, and the InSAR could be used, for example, for measurements of orbital wave motions (see also [86]). Also the limitation to one-dimensional measurements of the line-of-sight current component could be overcome with a dual-beam along-track InSAR, as proposed in [87]. If a successful TerraSAR-X mission triggers a considerable demand for along-track InSAR data, such advanced along-track InSAR systems can be implemented on satellites within about 10 years. In view of the facts that along-track InSAR is clearly superior to conventional SAR for all applications dealing with surface current features and that there is a high demand for current measurements and for information on current features, this is a likely development.

4.5. Future SAR Mission Requirements

As already mentioned, some continuity in the availability of certain types of SAR imagery (say, C band VV data) appears to be desirable, since users will have to analyze signatures of current features on their own and will not want to invest considerable amounts of money in the development and implementation of algorithms and data handling structures which can be used for very limited periods only. For many applications an improved temporal sampling of test areas would be more important than, for example, improvements in the spatial resolution or changes in the available radar frequencies. To some extent, a better temporal sampling can be achieved by using wide swath SARs such as the ones on RADARSAT-1 [3], ENVISAT [4], or RADARSAT-2 [5]. Even better are concepts with multiple satellites, such as the French-Italian COSMO-SkyMed program for an advanced monitoring of the Mediterranean Sea (http://www.alespazio.it/program/tlr/cosmo/cosmo.htm).

The frequency requirements for different applications are somewhat diverse, although this is not a critical problem: C band is fine, but because of a more linear relationship between surface current gradients and modulated Bragg wave and SAR image intensities at lower frequencies, L band would be desirable for the retrieval of surface currents or bathymetric maps from SAR imagery. In contrast, the along-track InSAR imaging mechanism is more linear at higher frequencies [81], the two InSAR antennas can be so closely together at X band that they can be installed on a single platform, which is practically impossible at L band (the ideal antenna separation scales with the radar wavelength). Thus X band is preferred for along-track InSARs. An along-track InSAR is quite desirable, since it permits direct current measurements at full SAR resolution.

Regarding the radar polarization, dual-polarization (HH and VV) systems have advantages for the identification of signatures of oceanic and atmospheric phenomena (see section 3.1). Incidence angle requirements are diverse: The incidence angle should not be too high to avoid signal-to-noise problems (particularly at HH polarization) and complicated scattering effects such as shadowing or multiple scattering, and it should not be too low to avoid strong specular reflection. For current measurements by along-track InSAR or Doppler centroid analysis, incidence angles should be as high as possible to maximize the relative contribution of horizontal velocities to the Doppler shift of the signal by the moving water surface. Altogether, incidence angles of about 30° to 60° appear to be the best compromise.

Finally, we would like to point out that a dual-beam SAR or InSAR system looking forward and backward at, say, 45° from the broadside direction would have several advantages for oceanographic applications: In addition to the possibility to measure two current components at once, a system of this type would permit an analysis of feature contrast variations with look direction, and it would certainly benefit wind measurement applications.

5. DISCUSSION

Since the first Workshop on Coastal and Marine Applications of Wide Swath SAR in 1999 [88], considerable progress has been made in the field of the observation of ocean current features by SAR: Commercial services such as the "Bathymetry Assessment System" have been established, various pre-operational image interpretation algorithms for oceanic internal waves, fronts, and other features have been implemented and demonstrated, and initiatives like EuroGOOS and MARSAIS have investigated user requirements quite comprehensively and tried to disseminate the potential of spaceborne SAR to many potential users. Furthermore, some progress has been made in the forward modeling of processes such as wave breaking or the feedback between the hydrodynamically modulated surface roughness and the wind stress, new data analysis techniques such as the Doppler centroid analysis have been developed, along-track interferometry from space has been demonstrated, and attractive new sensors and sensor modes, such as the Alternating Polarization Mode of ENVISAT ASAR or the split antenna mode of TerraSAR-X have been implemented or will be implemented in the near future.

The implementation of the Doppler centroid analysis, high-resolution current measuring capabilities of upcoming InSARs, and a better temporal sampling by multi-satellite systems will make the use of SAR data products attractive for some applications for which satisfactory data products cannot be derived from the intensity images which are available today, such as a near-real-time monitoring and the assimilation of SAR-derived current fields into circulation models for re-
search, public safety, search and rescue, pollution monitoring and prediction, fisheries, or recreational applications. Based on existing data which would be available immediately, one could generate maps of coastal current features such as fronts, eddies, or internal waves, derive an internal wave climatology, and analyze the data for an improved general understanding of physical and biochemical processes in the oceans. A better dissemination of the potential of SAR for such applications is desirable.

A great potential for a better exploitation of SAR imagery lies also in synergies between data from SAR and other sensors [89], as well as in synergies with numerical models and between different SAR data products: For example, temperature data from radiometers and SAR-derived mean wind speeds can be valuable for the interpretation of a SAR signature of an oceanic front.

Some of the emerging applications are just around the corner, some will need more time. However, we are quite optimistic that the use and exploitation of spaceborne SAR for applications related to current features will keep growing and that the introduction of the new technologies and improved algorithms will be a success. Finally, the retrieval of useful and reliable information on current features from SAR data is a more challenging problem than the retrieval of ocean wave spectra or wind fields, and the development and implementation of mature algorithms has consumed more time, money, and manpower, but in view of the variety of potential applications and the promising results of recent projects, this investment appears to be justified.

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