Wavelet Analysis of Satellite Images for Coastal Watch

Antony K. Liu, Chich Y. Peng, and Steve Y.-S. Chang

Abstract—The two-dimensional wavelet transform is a very efficient bandpass filter, which can be used to separate various scales of processes and show their relative phase/location. In this paper, algorithms and techniques for automated detection and tracking of mesoscale features from satellite imagery employing wavelet analysis are developed. The wavelet transform has been applied to satellite images, such as those from synthetic aperture radar (SAR), advanced very-high-resolution radiometer (AVHRR), and coastal zone color scanner (CZCS) for feature extraction. The evolution of mesoscale features such as oil slicks, fronts, eddies, and ship wakes can be tracked by the wavelet analysis using satellite data from repeating paths. Several examples of the wavelet analysis applied to various satellite images demonstrate the feasibility of this technique for coastal monitoring.

Index Terms—Marine technology, marine vehicle detection and tracking, process monitoring, satellite applications, wavelet transforms.

I. INTRODUCTION

MESOSCALE oceanic processes, such as internal waves, ship wakes, fronts, ice-edge meanders, oil spills, surface slicks, upwelling, and eddies have been imaged by synthetic aperture radar (SAR), coast zone color scanner (CZCS), and advanced very-high-resolution radiometer (AVHRR), although the sea state conditions involved in this imaging have not been well calibrated due to lack of ground truth. The objectives of this paper are to develop algorithms and techniques for automated detection and tracking of mesoscale features in satellite imagery by wavelet analysis and to relate the evolution of these features to oceanic processes in coastal waters. Reliable imaging of such mesoscale features, combined with a definition of the conditions under which imaging is feasible, would lead to an important data product: satellite-derived maps for tracking mesoscale features in the coastal zone.

The combined use of sensors from several satellites, such as AVHRR, SeaWiFS (Sea-viewing Wide Field-of-view Sensor), OCTS (ocean color temperature sensor), and ERS-2 or RADARSAT SAR can provide frequent high-resolution coverage of the coastal zone. Coastal processes affecting sea surface temperature, pigment concentration, or surface roughness can be studied using IR (infrared), ocean color, or SAR data, respectively. Simultaneous satellite images, *in situ* measurements from moorings and ship operations, and wind records from buoys and meteorological stations can be used to detect and monitor the ocean environment. By using repeat satellite coverage, mesoscale features associated with coastal processes can be tracked from a sequence of satellite images through multitemporal satellite data analysis.

A new method for time-varying signal analysis, called the wavelet transform, has been developed for application at NASA/GSFC during the past three years and provides spectral decompositions via the scale concept. Basically, wavelet transforms are analogous to Fourier transforms, but are localized both in frequency and time, i.e., they enable the study of transient processes by localizing their properties in both time and frequency [1]. Recent investigations in physical oceanography [2] justify the efficiency and abilities of these transforms to analyze nonlinear dynamical ocean systems. Wavelet analysis of wind fluctuations over the wave groups and the long–short wave interaction have been reported [3], [4] using the one-dimensional (1-D) Morlet wavelet transform. The wavelet transform has proved to be a convenient tool for studying the details of transient air–sea interaction processes.

The two-dimensional (2-D) wavelet transform is a highly efficient bandpass filter, which can be used to separate various scale processes and show their relative phase/location information, e.g., in SAR imagery [5]. The 2-D Gaussian wavelet transform (often referred to as the “Mexican hat”) of a SAR image for the extraction of small-scale features can be used as an edge detector [6]. In a marginal ice zone study [7], the ice edge in each SAR image has been delineated by using a 2-D wavelet transform. The wavelet transforms of satellite images can be used for near real-time “quick look” screening of satellite data (feature detection), data reduction (binary image), and image enhancement (edge linking).

In this paper, the 2-D Gaussian wavelet transform will be briefly described in the next section. Wavelet analyses for feature tracking, such as oil spills, fronts, eddies, and ship wakes are then presented, along with some detailed discussion of algorithms and models. The application of satellite images to coastal monitoring and the results of wavelet analysis are discussed in the final section.

II. TWO-DIMENSIONAL GAUSSIAN WAVELET

The wavelet transform, \( W_s(a, b) \), of a function, \( s(x) \), where \( \mathbf{r} = (x, y) \), is expressed in terms of the complex valued...
wavelet function, \( w(x) \), as follows:

\[
W_w(a, b) = \frac{1}{\sqrt{a}} \int s(r) w^*(\frac{r - b}{a}) \, dr
\]

in which the wavelet function is dilated by a factor \( a \), and shifted by \( b \). The function \( w(x) \) is the basic wavelet which must satisfy the admissibility condition, but is otherwise subject to choice within certain limits [1]. Thus, the continuous wavelet transform ensures global energy conservation. The superscript (*) indicates complex conjugate. For data analysis, the mother wavelets frequently used are: a Gaussian-modulated sine and cosine wave packet (the Morlet wavelet); or the second derivative of a Gaussian function (the Mexican hat). In this study, the analyzing wavelet (a real value function) is defined as the second derivative of a Gaussian function as follows:

\[
w(x, y) = \frac{1}{a} \left( 2 - \frac{x^2 + y^2}{a^2} \right) \exp \left( -\frac{x^2 + y^2}{2a^2} \right)
\]

where \( a \) is the scale of the wavelet transform. Since convolution is commutative with respect to differentiation, the resulting wavelet transform is the Laplacian of a Gaussian smoothed function. Thus, its zeroes correspond to the inflection points of the original function [6]. The contours of zero crossing indicate the edges in the pattern of the input function. The wavelet transform is calculated as a convolution in the fast Fourier transform (FFT) domain and has computational efficiency. The Mexican hat wavelet has a close form, (2), so it can be used directly for operation without recursive scheme to generate the wavelet base function. The detailed procedure of wavelet analysis is discussed in the following section.

III. Wavelet Analysis for Feature Tracking

A flow chart of satellite image analysis using a 2-D wavelet transform technique of different scales and thresholds to detect various textures of mesoscale oceanic features is shown in Fig. 1 for reference. Satellite data will first be divided into subscenes, with coastal land and clouds masked. The histogram of satellite data from each subscene will also be examined for data screening. Promising subscenes will then be wavelet-transformed at various scales to separate various textures or features. The Laplacian of the Gaussian (the Mexican hat) wavelet will be used as a bandpass filter and its first derivative as a threshold for feature detection. The choice of the scale for wavelet transform depends on the physical scale of the oceanic processes to be extracted. The threshold value is chosen to ensure that the contours of oceanic features are well separated. Heuristic edge-linking methods will be used to enhance the images. Finally, a binary image can be produced in order to reduce the data volume. By overlaying ocean color, IR, and SAR binary images with some data fusion techniques, the evolution of mesoscale features (such as fronts, surface slicks, eddies) can be monitored by wavelet analysis using satellite data from subsequent passes.

A. Oil Slicks

The occurrence of oil spills due to accidents or dumping causes major environmental hazards. Early detection, monitoring, containment, and cleanup of spills are crucial for the protection of the coastal zone. Satellite remote sensing has become a useful tool to study marine pollution [8], [9]. The reason that oil slicks are detected on radar images is that oil films have a dampening effect on short surface waves. The dark appearance of surface oil on radar images is due to the smoothing of the ocean surface and is similar to the appearance of low wind areas. However, it is the distinctive shape of oil slicks which enables them to be identified with a high degree of confidence. For demonstration purposes, Fig. 2(a) shows a 25.6 km \( \times \) 25.6 km subscene (pixel size of 50 m) from the ERS-1 SAR of a surface film or oil slick dumped by a ship near the coast of Taiwan (the ship is the white dot near the left-bottom corner). Fig. 2(b) shows the film area extracted by the Mexican hat wavelet transform, with a median scale (\( a = 32 \) units of pixel spacing) to separate the surface film area from the open water.

Fig. 3(a) shows an ERS-1 SAR image of lower Shelikof Strait, Alaska, obtained on 23 October, 1991, with a size of 51.2 km \( \times \) 51.2 km. The pixel spacing is 100 m. An eddy is clearly identified in the image, with a series of boundaries characterized by concentric curvilinear lines as a spiral of surface slicks. The dark linear area of surface slick can be
delineated by the Mexican hat wavelet transform with a small scale ($a = 2$ units of pixel spacing), as shown in Fig. 3(b). Notice that the large dark areas disappear after applying this bandpass filter. Thus, both different textures and different feature sizes can be extracted by using the wavelet transform with different scales. The spiral line is then connected by the edge-linking method using the gradient information [10]. Short segments of line features have been removed. Only long lines are kept as black lines to superimpose on the SAR subscene to enhance the spiral. Based on potential flow of a source and a vortex:

$$\ln r - Q\theta = \text{constant}$$

(3)

where $(\gamma, \theta)$ is the polar coordinate and $Q$ is the ratio of divergence to vorticity. Based on the data points from the black lines, an estimate of $Q$ is found to be 0.172 by the least square fit of (3) to the black lines in the processed image. A model result from (3) is overlaid as a white curve in Fig. 3(b) for comparison. The spiral model result matches with the extracted data (black lines) in the SAR image reasonably well.

B. Eddies and Fronts

Eddies and fronts cause changes in temperature, turbulence, or transport influence and may be the primary determinant of recruitment to oceanic fisheries [11]. A frontal boundary is usually the separation line between high- and low-temperature areas in the IR image, and between rough and smooth areas in a SAR image. The Mexican hat wavelet transform can be used as an edge detector to separate dark areas from bright areas in SAR images. Fig. 4(a) shows an ERS-1 SAR image of an oceanic front from April 1, 1993 collected over the Strait of Taiwan. The SAR image of 100 km $\times$ 100 km in size has been look-averaged (average of 15 $\times$ 15 pixels) to 512 $\times$ 512 pixels (187.5-m pixel spacing from original 12.5-m pixel spacing). The frontal line is delineated by the wavelet transform with a median scale ($a = 8$ units of pixel spacing) as shown by the white line in Fig. 4(a). Fig. 4(b) shows the histogram of the intensity data from the SAR image. Notice that the two distinguishable peaks in the histogram indicate the
Fig. 4. (a) SAR image of an oceanic front from 1 April, 1993, collected over the Strait of Taiwan, with a frontal boundary delineated in white curves using the wavelet transform as an edge detector, and (b) the histogram of intensity of the SAR data with two peaks indicating the existence of a frontal feature.

The potential existence of a frontal boundary or feature. This type of information from the histogram can be used as a screening preprocess, as mentioned in Fig. 1.

Fig. 5(a) shows a CZCS ocean color image of 300 × 300 pixels (0.83-km pixel spacing) collected over the Gulf of Alaska on 12 April, 1979, with high pigment concentration along the coast. Fig. 5(b) shows the binary image resulting from the wavelet transform, with a small scale (α = 2 units of pixel spacing), a zero threshold for the high pigment concentration area (white area), and with a small scale (α = 2) for the eddy feature (white contours). The eddy feature extracted by wavelet transform has many coarse contours. These elongated contours were disconnected in the thinning process using the skeleton method [12] and reduce to the single-pixel-wide lines. In this thinning method, those pixels that can be removed without destroying connectivity are eliminated, while those that cannot are retained. These disconnected line segments were then connected by the edge-linking method based on the gradient information as discussed above. Finally, the connected lines were drawn with a constant thickness (the white contours) for better representation in Fig. 7(b). The wavelet analysis is found to be especially well suited for feature extraction in the ocean color images, since the high pigment concentration areas are relatively well defined in the coastal zone.

For tracking of temperature fronts, sequential AVHRR images can be used. Fig. 6(a) shows a 512 × 512 pixel AVHRR image of the Gulf of Oman (pixel spacing of 1 km) collected on 31 March, 1994, at 12:47 UT. Note that the land has a higher temperature during the daytime, and also note an oil spill with mild temperature located behind the sharp turn in the Strait of Hormuz. First, the cloud/land and ocean features are separated using different gray scales for different temperature ranges based on the histogram of the AVHRR data. Cloud and land are then delineated by the white lines, and the ocean-surface high-temperature features (yellow to green areas) are extracted by the dark lines using wavelet transforms with a small scale (α = 4 units of pixel spacing) and a threshold.
of one standard deviation. The method of edge linking based on the neighboring point was applied and the short segments were removed.

The same procedure is applied to an AVHRR image of the same area collected on April 1, 1994 at 1:21 UT [Fig. 6(b)]. Note that in this night image the land now has a lower temperature, and the oil spill is invisible. The oil spill may not have a significantly different temperature signature from the surrounding water at night, or it maybe sinking below the water surface. If two wavelet-transformed images are overlaid, a schematic diagram can be drawn to show the approximate flow pattern by following the motion of frontal features [Fig. 6(c)]. Note that three small eddies persist near the frontal boundary. This type of analysis can aid the numerical modeling of flow circulation in the Strait. By combined use of gray scale and wavelet transform, detection (with gray scale), tracking (with wavelet transform), and feature enhancement (with edge linking) can be performed with the satellite images.
Mesoscale eddies are key features associated with the ice margin and are usually attached to the ice edge. The surface effect models associated with grease ice, wave-current interaction, and atmospheric instability due to upwelling have been used to interpret the mesoscale features of eddies and fronts from ERS-1 SAR images [5], [11]. Typical scales of these eddies were 20–40 km. Rotation was mainly cyclonic, with a maximum speed of up to 40 cm/s. Eddies play important roles in the distribution of heat, mass, and momentum fluxes in polar regions and in the control of the ice edge and its locations.

SAR images are very useful for tracking the ice edge motion. A sequence of seven SAR images of the Chukchi Sea marginal ice zone (MIZ) obtained from 27 September–18 October, 1991, at three-day intervals have been investigated for ice edge advance/retreat [7]. Simultaneous current measurements from the northeast Chukchi Sea, as well as Barrow wind records, are used to interpret MIZ dynamics. The ice edge location in each SAR image has been delineated by using a 2-D wavelet transform with a large scale ($a = 16$ units of pixel spacing) and a 70% threshold. The ice edge motion is found to be highly dynamic, with hundreds of kilometers advance/retreat in three days. When the ice edges are relatively stationary, the formation of mesoscale eddies near the meandering ice edge is evident, especially on 15 October, 1991, as shown in Fig. 7.

C. Ship Wakes

Ships and their wakes are commonly observed in high-resolution SAR imagery from satellites. Image-processing techniques can enhance the detection of extremely weak ship wake patterns, so that even if the ship itself is invisible, the location of the ship is obtained. Detection of ship wakes by remote sensing can be useful to national defense intelligence, shipping traffic, and for the fisheries industry.

In SAR imagery, both stationary and moving ships appear typically as bright targets, with moving ships generating a trailing dark turbulence wake. In addition to the turbulent wake, one side of a ship’s Kelvin wake can sometimes be seen as a bright line in the SAR image. If the bright spot backscattered by the ship is absent in the SAR image, application of the wavelet and Hough transforms to the ship wake pattern can help to automatically locate the ship position and determine its heading, even in a noisy background.

Fig. 8 is an ERS-1 SAR image collected on 31 May, 1995, near the north of Taiwan. The image is centered at 25.62° N and 121.15° E, approximately 30 km offshore in the East China Sea. The SAR subscene in Fig. 13 is 25 km × 25 km, with 25-m resolution. The vertical is the ERS-1 flight direction and North is indicated by the arrow. A surface ship heading northeast, with the bright spot indicating the ship’s location, can be easily identified. Behind this ship, a long dark turbulence wake is clearly visible. The turbulent wake dampens any short waves, resulting in an area with low backscattering (as indicated by arrow A in Fig. 8). Near the ship, the dark wake is accompanied by a bright line, which may be caused by the vortex pair shed by the ship into its wake. The ship track follows the busy shipping lane between Hong Kong, Taiwan, and Japan. The ambient dark slicks are natural surface films induced by upwelling on the continental shelf; they indicate a low sea state with wind speed less than 5 m/s.

In the lower part of the image, another ship turbulent wake (long and dark linear feature oriented east–west) can be identified near location B in Fig. 8. A barely perceptible
Fig. 9. (a) ERS-1 SAR subscene (3.1 km × 3.1 km, 250 pixels) zoomed from box B in Fig. 1, focused on the V-shaped ship wake. The wavelet transform with a threshold is used to separate the dark turbulent wake (b) from the bright Kelvin wake (d). The Hough transform is applied to the wavelet-transformed images to detect (c) the dark turbulent wake and (e) the bright Kelvin wake as a function of angle (θ) and distance (r). (f) shows the ship wake detected by the Hough transform, indicated by arrows in (c) and (e), which is overlaid on the SAR subscene.

bright line connects to the end of this turbulent wake, forming a V-shaped wake in box B of Fig. 8. A 3.1 km × 3.1 km (250 pixels) subscene focused on this V-shaped wake (zoomed from box B in Fig. 1) is shown in Fig. 9(a). This subscene was first analyzed by using the wavelet transform with a small scale (α = 2 units of pixel spacing). A threshold was then set to the value, minus or plus one standard deviation from the histogram, allowing separation of the dark turbulent wake [Fig. 9(b)] from the bright Kelvin wake [Fig. 9(d)]. The wavelet transform is used here as an edge detector to enhance the wake pattern.

The classical Hough technique for curve detection is applicable for ship wake detection, since little is known about the location of a boundary, but its shape can be described as a parametric curve (e.g., two straight lines of V-shape for ship wakes) [10]. Its main advantages are that it is relatively unaffected by gaps in curves and by noise. The Hough transform is then applied to the wavelet-transformed images to detect the linear wake feature [12], [13]. The Hough transform maps the edge information into a function of angle (θ) and distance from the center of image (r), in which collinear elements are integrated into a single point, as shown in Fig. 9(c) and (e), for the dark turbulent wake and the bright Kelvin wake, respectively. One of the advantages of the Hough transform is that both the scale and orientation of the target pattern, in addition to its location, can be automatically determined. The maximum peaks of the Hough transform results can be easily identified, as indicated by the arrows in the figure. Fig. 9(f) shows the ship wake detected by the Hough transform overlaid on the SAR subscene. The location of the ship can be accurately estimated, and the wake angle is found to be 18°, which is quite consistent with the theoretical Kelvin wake angle of 19.5°.

The invisibility of the targeted ship may be caused by very low backscattering of the ship configuration, or the wake could have been formed by a submarine [13]. In the latter case, it must have been operating very close to the ocean surface, since the surface Kelvin wake is observable. The water depth in this location is approximately 100 m. The ship wake is pointing to the east; therefore, the “invisible” ship was moving from mainland China to the open ocean. Incidentally, the location of the ship is near the site of a Chinese missile test conducted a month later in July 1995. In this area, many rank-ordered internal wave packets are also easily observable from the SAR imagery, which indicates the existence of a shallow mixed layer.

The second case study of ship wake is from the same SAR image as the previous case. A SAR subscene of 3.2 km × 3.2 km (pixel spacing of 12.5 m) is shown in Fig. 10(a) with a surface ship (huge bright spot) and its dark turbulent wake. Note that a series of ship transverse waves is also visible. Fig. 10(b) shows the wavelet transform with a small scale (α = 2 units of pixel spacing) with a threshold of one standard deviation to extract the line segments in the ship wake. The Hough transform is then applied to match a transverse ship
Fig. 10. (a) ERS-1 SAR subscene of ship transverse waves, (b) the wavelet transform with a small scale, (c) the result of Hough transform to the wavelet-transformed image, and (d) ship transverse waves detected by the Hough transform, indicated by open circles for the peaks in (c), which is overlaid on the SAR subscene.

wake phase function [14]:

\[ X = A(1 - 0.5 \cos^2 \theta) \]  

(4)

where \( A \) is the axis behind the ship wake along the ship's direction of motion. When \( \theta = 0 \), \( A/2 \) is the wavelength of the transverse wave. The peaks of the Hough transform are shown in Fig. 10(c) as a function of \( A \) (pixels) along the ship's direction of motion. The sequential transverse wave can be easily identified by open circles in Fig. 10(c). The wavelength is estimated to be 106.3 m. Based on the dispersion relation, \( V \) is defined as

\[ V = \left( \frac{gA}{4\pi} \right)^{1/2}. \]  

(5)

The ship speed is approximately 12.86 m/s. According to the ship powering and steering survey, this is probably a fast cargo vessel or a huge passenger liner. Fig. 10(d) shows the detected transverse wave and ship wake overlaid on the SAR subscene, with an almost perfect match.

IV. COASTAL MONITORING AND DISCUSSION

The NOAA (National Oceanic and Atmospheric Administration) CoastWatch provides near real-time mapped satellite and in situ data and information for U.S. coastal waters suitable for hazard warning, ice and ocean monitoring, and environmental management [15]. A development project is underway to add SAR data and products to the CoastWatch product suite. One of the major areas of interest will be the coast of Alaska [11]. The use of wavelet transform techniques for the automated analysis of SAR, AVHRR, and SeaWiFS images to detect ocean features will be evaluated for CoastWatch applications.

The coastal zone is a highly productive and dynamic environment. Because of the fast growth of industry, pollution is one of the major issues for environmental protection [16]. Increasingly, coastal regions need reliable, high-quality resource and environmental information from remote sensing to better manage this vital area. Remote sensing with repeated coverage is the most efficient method to monitor and study marine productivity and pollution. The mapping of mesoscale ocean features in the coastal zone is a major potential application for satellite SAR data, especially for the ScanSAR on RADARSAT with 500-km swath. The use of SAR-derived observations to track eddies, surface temperature-related features, and river and estuarine plumes can aid in the management of fisheries. Especially in subtropical and tropical regions, uniform sea surface temperatures and cloud cover preclude AVHRR measurements of surface structure and obscure ocean color observations.

The wavelet transforms of satellite images can be used for near real-time “quick look” screening of satellite data (feature detection), data reduction (binary image), and image enhancement (edge linking). By combining ocean color (SeaWiFS or OCTS), SAR (ERS-2 or RADARSAT), and infrared (AVHRR) images (wavelet-transformed binary images) using some data fusion techniques, mesoscale features of various physical processes such as oil spills, surface slicks, fronts, upwelling, and eddies can be detected and tracked in the coastal zone. Wavelet analysis can provide a more cost-effective monitoring program that would keep track of changes in important elements of the coastal watch system.

In this paper, the wavelet transform has been applied to satellite SAR, AVHRR, and CZCS images, and the feasibility of this technique for feature extraction has been demonstrated. Several examples of wavelet analysis from various satellite images have been studied for the extraction of mesoscale features such as fronts, ice-edge meanders, oil slicks, ship wakes, and eddies. Algorithms and techniques for automated detection and tracking of mesoscale features from satellite imagery by wavelet analysis have been developed. While further development is needed to establish the automated system, the techniques developed here should remain valid for any image data. Reliable imaging of such mesoscale features by various sensors and definition of the conditions under which imaging is possible will provide a better understanding of oceanic processes influenced by sea surface temperature (IR), pigment concentration (ocean color), or surface roughness (SAR).

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