Synthetic Aperture Radar Imagery of the Ocean Surface During the Coastal Mixing and Optics Experiment

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Award #: N00014-96-1-0835
http://fermi.jhuapl.edu/cmo/cmo_index.html

LONG TERM GOAL

The long-term scientific goal of this effort is to understand the advantages and limitations involved in extracting quantitative information of oceanographic importance from Synthetic Aperture Radar (SAR) imagery of the ocean surface.

OBJECTIVES

The principal scientific objectives of this investigation are to delineate the 2-dimensional spatial characteristics of oceanic processes associated with coastal mixing and optics and to validate and improve our understanding of the physics that governs the imaging of oceanographic features such as internal waves, surface waves, and water-mass boundaries by microwave SAR. Our effort is unique in that it is supported by a large variety of *in situ* measurements collected during the Coastal Mixing and Optics (CMO) experiment. These measurements, which include density and current profiles, surface wave spectra, and standard meteorological measurements, are precisely the ones needed to accomplish our objective.

APPROACH

Our approach is to collect and archive SAR and AVHRR images over the CMO experimental area during the active phases of the experiment in August and September 1996 and the mooring-recovery cruises in the summer of 1997. Parameters extracted from this imagery are correlated with the extensive *in situ* measurements during CMO as well as those collected routinely from buoys, tide gauges, and meteorological stations in the area. These correlations and comparisons, coupled with results from our imaging models, provide a unique opportunity to validate and improve our understanding of the imaging physics and ultimately the utility of spaceborne SAR as a practical tool for oceanographic research.

WORK COMPLETED

- A new robust method for inferring water-column parameters from SAR internal-wave observations has been developed. This method makes use of the internal-wave signatures in the SAR imagery along with a knowledge of local climatology and bathymetry to infer the density difference between the top and bottom layer and the depth of the thermocline.

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*
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1. REPORT DATE **1998**	2. REPORT TYPE	3. DATES COVERED **00-00-1998 to 00-00-1998**
4. TITLE AND SUBTITLE **Synthetic Aperture Radar Imagery of the Ocean Surface During the Coastal Mixing and Optics Experiment**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Johns Hopkins University,Applied Physics Laboratory,11100 Johns Hopkins Rd,Laurel,MD,20723**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM002252.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

- Directional surface gravity wave spectra from the SAR imagery have been generated during the passage of Hurricane *Edouard* near the CMO experimental site in late August and early September 1996 and compared with concurrent observations from the CMO moorings and NDBC buoys during this major mixing event.

- The SAR intensity modulations caused by tidal current flow over the Nantucket Shoals have been correlated with tidal phase observations at Nantucket Island. A quantitative study of the variability of the image time series over this area as a function of variations in the tidally-induced surface current is underway.

RESULTS

I. Estimation of Water-Column Parameters from SAR Imagery:

In a recent study [*Porter and Thompson*; 1998], we have shown how it may be possible to remotely estimate various properties of the water column on the continental shelf using SAR imagery in conjunction with knowledge of the local bathymetry, climatological density data, and simple models for internal-wave evolution. Theoretical studies of two-layer fluids indicate that dissipation of internal waves impinging on shoaling water occurs when the depth of the bottom layer, which is decreased by the shoaling, becomes equal to that of the upper layer [*Helfrich*, 1980]. Using this idea, we have determined this critical depth for a particular case study by noting the location in the SAR image where the internal-wave surface signatures disappear. The depth of each layer at this position is then half the total depth. By assuming that the internal waves are generated at the shelf break on each diurnal tidal cycle, we have also estimated their phase speed by measuring the distance between successive packets in the imagery. With this information and the 2-layer dispersion relation, we have been able to estimate the fractional density change between the two layers. Furthermore, an estimate of the surface density is possible by using the climatological bottom density. The extensive CMO data base provides an ideal test bed to validate, estimate error bounds, and extend this procedure.

II. Wave Parameters from SAR During the Passage of Hurricane *Edouard*

During the last few days of August and the first few days of September 1996, Hurricane *Edouard* traveled north parallel to the US east coast reaching the vicinity of the CMO experimental area on 2 September, and then veered to the northeast into the North Atlantic where it eventually dissipated. We have three SAR images, on 30 August and 2 and 3 September, 1996, during the passage of *Edouard* near the CMO site. The availability of three SAR overpasses separated by only a day or so during a high-wind event such as Hurricane *Edouard* with extensive concurrent ground-truth data represents an extremely rare opportunity for the testing and validation of various ideas concerning how SAR responds to high-wave conditions. Each of our three images shows evidence of a strong surface-gravity-wave system associated with the nearby hurricane. Examination of this wave system in each of the three images clearly shows the evolution from a well-defined long-wave swell system while the

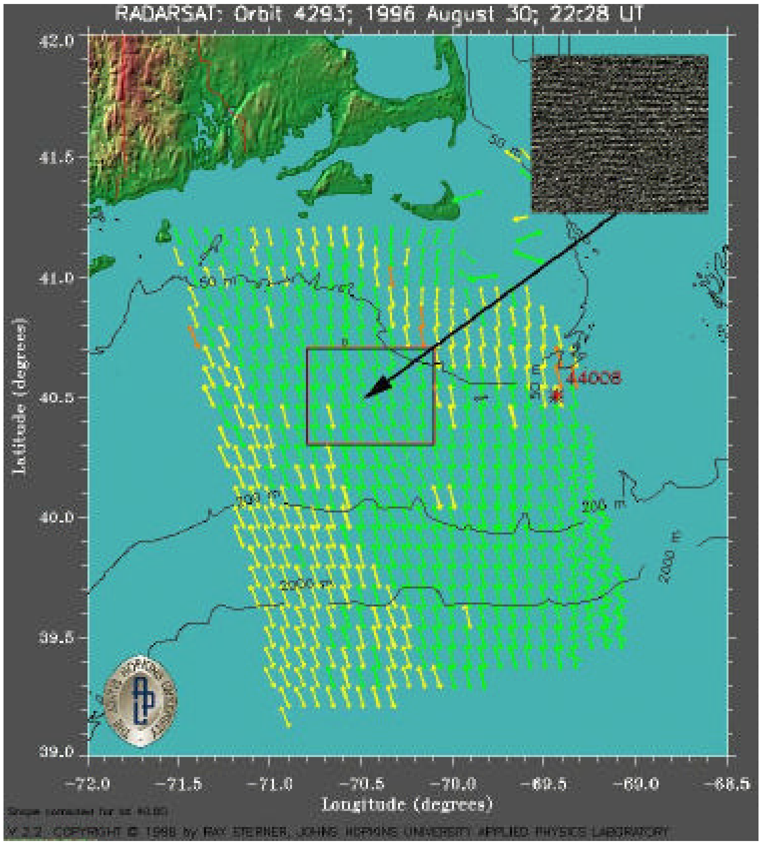

Figure 1: Estimated wave field from RADARSAT orbit 4293. The direction of the arrows at each grid point is the estimated wave direction (with a 180° ambiguity) and the length of the arrows is proportional to the wave period. The color scale denotes the relative energy in the spectral peak. The 50 m, 200 m, and 2000 m depth contours are also shown.

hurricane is still relatively distant from the observation area to a shorter-wavelength, broader, more energetic wave system when the hurricane is nearby. We have quantified the wave evolution by using the imagery to generate a field of wave spectra on a roughly 10 km grid over each of the three images. These wave fields are then used to examine the spatial variation of the dominant wavelength, wave direction, and significant wave height over the spatial extent of each image. The SAR images from which the wave fields were extracted may be viewed on our CMO web site at:

http://fermi.jhuapl.edu/cmo/radarsat_index.html

Figure 1 shows the spectral field of the dominant swell waves extracted from the RADARSAT image of 30 August when *Edouard* was still about 2000 km to the south of the CMO site off the Georgia coast. A high-resolution zoom (40 m pixels from the original image) of the region near the CMO mooring array (indicated by the red box) is shown in the inlay in the upper right corner of the figure where the long (~ 280 m) swell waves are clearly seen. The location of the National Buoy Data Center (NDBC) buoy 44008 is also shown to the east of CMO site. We have computed a sub-image spectrum (~ 10 x 10 km) at each grid point in Figure 1 and extracted the dominant wave period and direction. These quantities are indicated at each grid point by an arrow whose length is proportional to wave period and whose orientation indicates the propagation direction. (A 180° ambiguity in propagation

Table 1: Comparison of Buoy- and SAR-Derived Wave Parameters

Date 1996	Wave Direction (° T); (toward)				Dominant Wave Length (m)			
	CMO Mooring	SAR	NDBC 44008	SAR	CMO Mooring	SAR	NDBC 44008	SAR
30/8 22:28	360	336	NA	264	281	256	272	252
2/09 15:26	210	286	NA	292	141	179	108	126
3/09 10:58	270	251	NA	192 257	155	157	140	221

direction remains.) Note that for a few of the grid points in the southeastern portion of the image, two spectral peaks are indicated. This is because the spectra at these positions are so noisy that a clear single peak could not be identified. The strength of the spectral peak is indicated by the color of the vector at each grid point (weakest at green to strongest at yellow). One can see from Figure 1that these long swell waves are present over nearly the entire extent of the image. The dominant wavelength of the wave field ranges between 250 and 300 m. It is interesting to note that the wave system is quite apparent in the imagery even though it is aligned nearly along the azimuth direction of the satellite. The imaging of “azimuth-travelling waves” by SAR is generally not possible when their wavelength is shorter than the so-called azimuth cut-off. The minimum undistorted wavelength is approximately

$$l_{\min} = \frac{R}{V} H_S^{\frac{1}{2}}, \tag{1}$$

where R/V is the ratio of the satellite’s range to velocity and H_S is the significant-wave height [Monaldo and Beal, 1998]. The R/V ratio for RADARSAT is about 120 s, and the significant-wave height as measured by the *in situ* sensors at the overpass time was about 1.75 m. For the present example, $l_{\min}$ is about 210 m; well below the dominant wavelength so that the long azimuth-travelling swell seen in Figure 1 can be resolved quite readily. We have further substantiated the fidelity of this procedure by using the variation of the extracted wavenumbers as the waves propagate from deep water onto the shelf to estimate the bottom depth [Thompson, *et al.*, 1998].

In Table 1, we show comparisons of the SAR derived dominant wavelength and propagation direction for each of the three hurricane images with the corresponding *in situ* measurements at the CMO mooring and NDBC 44008. Note that since only dominant-wave period is measured by the NDBC buoy; we have used the dispersion relation (1) to compute the dominant wavelength. Generally, the comparison is quite good. The only major discrepancy is between the SAR-extracted parameters and the NDBC 44008 measurements on 3 September. An examination of the extracted wave field for this case shows that there are two solutions for the dominant wavelength for almost every grid point in the vicinity of buoy 44008. The reason for this is that the dominant wavelength of the waves in this region (as determined by the dominant period measured at the buoy) was only 140 m. Using the measured value of 7.3 m for the significant wave in (1), we see that l_{min} is about 325 m so that 140 m azimuth-traveling waves will not be properly imaged by the SAR. An interesting question is: Why are the waves near the CMO moorings nearly range-traveling while those near 44008 are traveling in the azimuth direction? Our present hypothesis is that wave refraction by the shallow bathymetry associated with the Nantucket Shoals may be responsible for the change in propagation direction near buoy 44008.

IMPACT/APPLICATIONS

Based on the preliminary findings discussed briefly above, our initial assessment of the utility of remote sensing observations as a practical tool for the investigation of processes in the littoral ocean is encouraging. There is, of course, much left to be done, and our ultimate conclusion will depend critically on further comparison with the *in situ* measurements and close collaboration with the other CMO investigators. this collaboration.

RELATED PROJECTS

This research described in this report has general relevance to various Navy and NOAA programs concerned with the remote-sensing of littoral processes. The investigation of the three hurricane images discussed above is directly relevant to our effort to determine quantitative estimates of wave “groupiness” and “long-crestedness” as part of the wave coherence working group in the ONR-sponsored Mobile Offshore Base program. This work also complements ongoing research to extract high resolution wind fields from SAR. Both of these efforts are funded by ONR Remote Sensing and Space and are currently underway in our group at JHU/APL.

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PUBLICATIONS

Porter, D. L. and D. R. Thompson, “Continental Shelf Parameters Inferred from SAR Internal Wave Observations”, *J. Atmospheric and Oceanic Tech*., (in press), 1998.