# Breaking Waves Affecting Microwave Backscatter 1. Detection and Verification

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This paper is the first of a two-part series concerning detection and characterization of wave breaking when using microwave techniques. The importance of wave breaking in both microwave remote sensing and air-sea interaction has led to this investigation utilizing a  $K_u$  band continuous wave Doppler scatterometer. Simultaneous microwave, video, and environmental measurements were made during the SAXON-CLT experiment off Chesapeake Bay in the fall of 1988. The scatterometer was pointed upwind at an incidence angle of  $45^{\circ}$ and had an illuminated area that was small compared with the wavelength of the dominant surface waves. This first paper presents the schemes developed to detect individual breaking waves and verification of the method using video recordings. The most successful scheme is based on thresholds in both the radar cross section and the Doppler bandwidth. Microwave events consisting of a sea spike in the radar cross section accompanied by a large bandwidth were found to be associated with the steep forward face of waves in the process of breaking. The location of the illuminated area with respect to the phase of the breaking wave and the stage of breaking were found to influence the detectability of individual breaking waves. Approximately 70% of the sea spikes associated with waves that produced whitecaps were identified by the most successful detection scheme. The second paper examines how the degree of wave breaking, as measured by the microwave technique developed in this paper, depends on wind and wave conditions.

## 1. INTRODUCTION

Deepwater wave breaking plays an important role in air-sea interaction, in surface wave dissipation, and in the generation of currents. Statistics on the frequency of breaking waves and their dependence on wind and wave conditions are needed to quantify the role of wave breaking in the upper ocean. Most attempts at field measurements of breaking waves have been subjective and qualitative because of the difficulty of unambiguously detecting and quantifying individual events. Microwave measurements in both the field and laboratory have indicated that sharp-crested and breaking waves can significantly enhance active microwave scattering. Identification of individual breaking waves based on quantitative microwave measurements may offer a significant improvement over detection techniques relying on visual observations.

This paper is the first part of a two-part investigation, based on work by Jessup [1990], which presents quantitative measurements of distinctive events in microwave backscatter from the ocean surface that are caused by breaking waves. The major objectives of Part 1 are to investigate the characteristics and the source of the microwave return from breaking waves and to determine whether microwave measurements can be used to identify individual breaking waves reliably. Part 2 [Jessup et al., this issue] presents the dependence on wind and wave conditions of events detected using the most successful scheme from Part 1. Results using microwave measurements are compared with previ-

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Paper number 91JC01993. 0148-0227/91/91JC-01993\$05.00 ous measurements of wave breaking and with analytical modeling by other authors.

Previous research concerning the characteristics of microwave backscatter from breaking waves was recently summarized by Jessup et al. [1990]. The term "sea spike" generally refers to abrupt, large-amplitude excursions in the backscattered radar cross section. The association of sea spikes with steep and breaking waves was first observed in measurements at grazing incidence angles [Katzin, 1957; Long, 1974, 1983; Kalmykov and Pustovoytenko, 1976], some of which included the use of video recordings [Lewis and Olin, 1980] and range tracking [Ewell et al., 1984].

The correlation between sea spikes and breaking waves has also been noted in measurements at moderate incidence angles. Scattering mechanisms postulated for this measurement regime [Alpers et al., 1981] have been used to improve predictions of the mean radar cross section based on the composite surface model, especially for horizontal polarization [Lyzenga et al., 1983; Donelan and Pierson, 1987]. In the laboratory, polarizationindependent returns from breaking waves were measured by Duncan et al. [1974]; Kwoh and Lake [1984] found specular scattering from the turbulent wake region and the generation of capillary waves, as well as a nonspecular contribution attributed to wedge diffraction. Field measurements by Kwoh et al. [1988] also showed evidence of specular returns from breaking waves. Bragg resonant scattering from the turbulent region just ahead of a breaking crest was cited by Banner and Fooks [1985] as the primary scattering mechanism for stationary breaking waves generated in a flume. In recent laboratory measurements, Melville et al. [1988] found that microwave scattering by breaking waves correlated with the mechanical wave energy dissipated.

Keller et al. [1986] found large scatterer velocities and increased Doppler bandwidths associated with the passage of breaking waves in the field. In a preliminary experiment in the

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North Sea [Jessup et al., 1990], we found that large sea spikes in moderate-incidence-angle backscatter were consistently associated with visual evidence of wave breaking. However, the video recordings used in that study were of poor quality and limited duration. *Phillips* [1988] has considered the friction velocity dependence of sea spikes produced by breaking waves (see Part 2).

This brief review indicates that the detection of individual breaking events might be possible by considering a combination of the microwave parameters that are indicators of their extreme geometry and turbulent nature. The general characteristics of moderate incidence angle microwave backscatter associated with breaking waves that have been indicated in the literature include (1) sea spikes in the radar cross section, (2) polarizationindependent backscatter, (3) large mean Doppler frequency, and (4) increased Doppler bandwidth. In this study we have used these qualitative observations as a guide to exploring quantitative criteria for detecting individual breaking waves.

## 2. EXPERIMENTAL PROCEDURE

Our preliminary work in the North Sea [Jessup et al., 1990] was done during an experiment which was not designed to investigate the microwave signature of breaking waves. The encouraging results of that effort led us to perform a more extensive experiment devoted specifically to the detection and characterization of breaking waves using microwave techniques. We made simultaneous microwave, video, and environmental measurements during the SAXON-CLT experiment (Synthetic Aperture Radar and X-Band Ocean Nonlinearities experiment which took place at the Chesapeake Light Tower in the fall of 1988). Figure 1 shows the location of the CLT, which is situated in 12 m of water approximately 25 km off the mouth of Chesapeake Bay near Norfolk, Virginia, U.S.A.

Figure 2 is a diagram of the tower viewed from the north showing elevation levels and the location of the instrumentation. Surface wave reflections from the permanent boat landing (vertical black bars) on the northwest corner and the temporary bumpers made of horizontal wooden beams attached to the north side were observed by eye at various times during the experiment. Except during extreme sea conditions, the effect of these reflections at the scatterometer illuminated area 26 m away from the tower was minimal.

## 2.1. Instrumentation

The microwave backscatter measurements were made using a  $K_{u}$  band (14 GHz) continuous wave Doppler scatterometer identical in design and performance to that used in the North Sea [Jessup et al., 1990; Keller and Plant, 1990]. The instrument incorporates linear dual-polarized antennas which provide simultaneous vertical (VV) and horizontal (HH) like-polarization measurements. The scatterometer and video camera assembly was mounted at an incidence angle of 45° on the upper rail at the helicopter deck 26 m above mean low water. In this geometry, the elliptical 3-dB illuminated area on the sea surface was approximately 1.1 m  $\times$  1.5 m. To keep the scatterometer pointed into the wind as much as possible, its location was changed as the wind direction varied.

Independent measurements of surface displacement were made using a capacitance-type wire wave gauge mounted on a 7-mlong boom attached to the catwalk on the east side of the tower (see Figure 2). Although the scatterometer data acquisition system was run continuously, only selected portions of unprocessed surface displacement data could be recorded. Because the microwave data covered a significantly longer time than the wave gauge measurements, we used the surface displacement spectrum derived from the microwave measurements to provide an adequate amount of wave data. The method used to compute the spectrum, developed by *Plant et al.* [1983], is based on linear wave theory and assumes that the wave direction is aligned with the wind direction and that the Doppler velocity is dominated by the orbital velocity of the surface waves. The Doppler-derived spectra and those computed from the wire wave gauge measurements were in good agreement for frequencies up to roughly 0.5 Hz, above which the Doppler-derived spectra begin to fall off owing to the finite dimensions of the illuminated area. In some cases, the magnitude of the Doppler-derived spectra was lower than that of the wire wave gauge measurements, which may have been due to the assumption of a unidirectional wave field.

Measurements of wind speed and direction, air and sea temperature, and relative humidity were processed in real time to produce average values at 10-min intervals. The anemometer, air temperature sensor, and relative humidity probe were mounted at the top of the light tower approximately 42 m above the sea surface (see Figure 2). The sea temperature sensor was tethered from a float and remained approximately 1 m below the sea surface.

The logarithmic wind profile U at height z is given by

$$U_z = \frac{u_*}{\kappa} \left[ \ln(z/z_0) - \Phi(z/L) \right] \tag{1}$$

where  $\kappa = 0.40$  is von Kármán's constant,  $z_0$  is the roughness height of the surface, and L is the Monin-Obukhov stability length. Values of friction velocity  $u_*$  and wind speed referenced to a height of 10 m,  $U_{10}$ , were iteratively computed from (1) using the 10-min averages of wind speed, air-sea temperature difference, and relative humidity [Large and Pond, 1981; Smith, 1988]. The computed results were further averaged to produce values of  $u_*$  and  $U_{10}$  corresponding to the 1-hour measurement periods used below.

Direct measurements of friction velocity were made during the SAXON-CLT experiment with a sonic anemometer mounted on the end of the instrument boom (see Figure 2). Since some of the sonic anemometer measurements were found to be susceptible to tower interference (G. Geernaert, personal communication, 1989), they were used only for comparison with the friction velocity values computed using the bulk formulation outlined above. In general, the agreement between the bulk method values and the unaffected sonic anemometer data was consistent with the expected performance of the bulk formulation [*Blanc*, 1985].

Simultaneous video recordings of the area illuminated by the scatterometer were made with a video camera mounted on the antenna assembly and aligned with the geometric axis of the antennas. This alignment was calibrated in the field with the scatterometer aimed vertically downward and a corner reflector hanging along the axis of the antennas. We estimated that the alignment was accurate to within 0.5 m.

## 2.2. Data Processing

To provide continuous data acquisition and rapid access to experimental results, we used a personal computer to acquire and process the microwave data in the field. Selected periods of the scatterometer and wave gauge data were also recorded on an analog tape recorder to have an archive of unprocessed data. A second personal computer was used to produce the 10-min averages of environmental measurements.



Fig. 1. Location of U.S. Coast Guard Chesapeake Light Tower (CLT), 25 km off Cape Henry, Virginia Beach, Virginia, U.S.A., in 12 m of water. Latitude 36°55 N, longitude 75°43 W. Depth contours in meters.



Fig. 2. Diagram of CLT as viewed from the north side showing elevation levels and instrument locations. The oblique incidence scatterometer used in this experiment was mounted at the 26 m level at several locations around the tower.

Characterization of the backscattered signal was provided by estimating the moments of its power spectrum. The zeroth moment of the spectrum is the return power and is a measure of target strength. The first moment of the spectrum normalized by the zeroth moment corresponds to the mean Doppler frequency shift, which is proportional to the power-weighted line-of-sight velocity of the scatterers within the illuminated area. The square root of the second moment of the power-normalized spectrum provides a measure of the Doppler spectral bandwidth, indicating the range of scatterer velocities responsible for the return signal. The reciprocal of the bandwidth can be interpreted as a measure of coherence time.

The microwave signal was digitally sampled at 2 kHz and reduced to time series of the received power, mean Doppler frequency, and Doppler bandwidth with a time step, or integration time, of 0.25 s. The mean Doppler frequency and bandwidth were computed using the covariance moment-estimation technique commonly used in weather radar [*Doviak and Zrnic*, 1984]. The mean Doppler frequency estimator showed excellent agreement with periodogram estimates, whereas the bandwidth estimator tended to underestimate spectrally computed values. The bandwidth estimator was in better agreement with the periodogram estimates at higher bandwidths than at lower bandwidths. Since our main interest was in characterizing breaking events (which tend to have large bandwidths), we judged the performance of the second-moment estimator to be adequate for our purposes.

## 2.3. Data Editing

To account for the wide variety of environmental conditions encountered during the SAXON-CLT experiment, we used our previous experience [Jessup et al., 1990] to set constraints on the wind direction relative to the antenna look direction and on the variability of wind speed over the duration of the chosen record length of 1 hour. The angle  $\phi$  between the wind and look direction was restricted to the range  $0^{\circ} \leq \phi \leq 25^{\circ}$  for all data processed. The frequency of breaking events [Phillips, 1988; Jessup et al., 1990; Part 2] was expected to have a cubic friction velocity dependence; thus a constraint on the variability of  $u_{\bullet}$  and the wind speed was used to reduce scatter due to fluctuations in the wind stress. The standard deviation of  $u_{\bullet}$  and  $U_{10}$  for each 1-hour record was limited such that the range of  $u_{\bullet}$  values during any 1-hour period was less than 2.5 cm s<sup>-1</sup> and the range for  $U_{10}$  was less than 0.5 m s<sup>-1</sup>. For  $u_* \leq 25$  cm s<sup>-1</sup>, the number of large sea spikes was too small to permit meaningful statistics over the 1-hour measurement period, and thus data with  $u_*$  below this value were not included.

The editing process left a data set of thirty-eight 1-hour records for analysis, composed of seven subsets of several hours each. The data are summarized in Table 1, which lists the number of 1-hour records used in each run and the range of parameters characterizing the wind and wave conditions. The frequencies  $F_{LO}$  and  $F_{HI}$  correspond to the peak frequencies of the surface displacement spectra, which are generally associated with swell and wind waves, respectively. Equilibrium of wave conditions did not exist. Runs designated 4, 5, and 9 showed mixed sea conditions, as indicated by two distinct peaks in the surface-displacement spectra. For runs 1 and 6, the spectra had single, low-frequency peaks characteristic of long-wavelength swell. Runs 11 and 12 also showed unimodal surfacedisplacement spectra, but with peak frequencies in the range of locally generated wind waves. Fetch lengths for runs 1 and 4 were essentially unlimited, whereas the remainder of the runs had fetch lengths between 28 and 32 km.

# 3. MICROWAVE SIGNATURE OF BREAKING WAVES

As was outlined in section 1, previous measurements suggest that microwave backscatter at moderate incidence angles from steep and breaking waves can produce distinctive signatures in the return power and Doppler frequency spectrum. Figure 3 shows spectral maps, or time series plots, of the Doppler spectra for VV (top) and HH (bottom) returns during the passage of a breaking wave. Each individual spectrum represents 0.25 s, with time increasing up the page for a total duration of 15 s. Positive frequencies on the right correspond to a line-of-sight velocity toward the antennas. Evident in both the VV and HH spectral maps is a large event with a mean Doppler shift of nearly 250 Hz (line-of-sight velocity of 2.7 m s<sup>-1</sup>) and a large bandwidth. The magnitude of the backscattered power is comparable for VV and HH polarization, indicating a polarization ratio,  $\sigma_{VV}^0/\sigma_{HH}^0$ , near unity. The polarization ratio is clearly greater than unity at times away from the breaking event. (Also apparent in Figure 3 is the spectral image of the extreme event reflected about zero frequency. The image is primarily due to phase imbalance between

TABLE 1. Data Run Characteristics

| Run<br>ID | Hours | F <sub>LO</sub> ,<br>Hz | F <sub>HI</sub> ,<br>Hz | SWH,<br>m | <i>u</i> *,<br>cm s <sup>-1</sup> | $U_{10}$<br>m s <sup>-1</sup> | Fetch,<br>km |
|-----------|-------|-------------------------|-------------------------|-----------|-----------------------------------|-------------------------------|--------------|
| 1         | 6     | 0.13-0.16               | N/A                     | 1.4-1.8   | 23–32                             | 6.3–9.6                       | unlimited    |
| 4         | 4     | 0.11                    | 0.27-0.35               | 0.7-1.0   | 26-30                             | 7.1-8.5                       | unlimited    |
| 5         | 5     | 0.11                    | 0.25                    | 1.0-1.1   | 26-31                             | 6.3-7.9                       | 32           |
| 6         | 3     | 0.09-0.11               | N/A                     | 1.5-1.8   | 38-43                             | 9.6-10.5                      | 32           |
| 9         | 5     | 0.10                    | 0.24-0.27               | 1.1-1.3   | 42–46                             | 10.4-11.5                     | 28           |
| 11        | 3     | N/A                     | 0.220.24                | 0.7–1.0   | 25-33                             | 6.2-8.3                       | 32           |
| 12        | 12    | N/A                     | 0.20-0.25               | 1.0-1.2   | 38-48                             | 8.4-11.7                      | 32           |
|           |       |                         |                         |           |                                   |                               |              |

Run ID is identification number, hours is number of hours in the run;  $F_{LO}$  is peak frequency of the surfacedisplacement spectrum in the range associated with long-wavelength, low-frequency swell;  $F_{HI}$  is peak frequency of surface-displacement spectrum in the range of short-wavelength, high-frequency wind waves; SWH is significant wave height, defined as  $4[var \eta(t)]^{4}$ , where  $\eta(t)$  is the surface displacement measured in meters;  $u_*$  is friction velocity (see equation (1));  $U_{10}$  is wind speed referenced to an elevation of 10 m above the sea surface (see equation (1)); fetch is distance from measurement site to nearest land in upwind direction. N/A, not applicable.



Fig. 3. Doppler spectral map showing time series of relative power distribution (linear scale) for VV polarization (top) and HH polarization (bottom) illustrating the microwave signature of a breaking wave. Time increases up the page, and the total elapsed time is 15 s. The large amplitude event due to a breaking wave exhibits a large Doppler shift, increased bandwidth, and comparable power for VV and HH polarization [from Jessup, 1988].

the in-phase (I) and quadrature (Q) demodulates of the receiver output.)

The time domain signature of breaking waves independently identified from simultaneous video recordings is illustrated in the time series of the mean values of radar cross section, Doppler frequency, and bandwidth shown in Figure 4. The top two traces show several sea spikes in  $\sigma^0$  (linear scale) for VV and HH polarization. The mean Doppler frequency, *F*, is shown in the third trace, and the fourth trace is the Doppler bandwidth, *B*. The times in minutes and decimal seconds mark several large sea spikes in  $\sigma^0_{VV}$  and  $\sigma^0_{HH}$  and large excursions in bandwidth exceeding the indicated thresholds. The times of whitecaps observed within the 3-dB illuminated area are noted on the axis of the mean-Doppler-frequency time series. These data from high wind conditions ( $u_* = 55 \text{ cm s}^{-1}$ ) show numerous consecutive breaking events illustrating several important characteristics of the microwave return from breaking waves.

The five large sea spikes identified in the  $\sigma_{HH}^0$  time series in Figure 4 have been labeled A through E. The maximum amplitudes of events A, B, and D are comparable for VV and HH polarization, suggesting scattering that is polarization indepen-

dent. For events C and E, however, the HH return is noticeably greater than the VV return. These examples are typical of a significant number of breaking events for which the polarization ratio  $\sigma_{VV}^0/\sigma_{HH}^0$  was less than unity, with minimum values near 0.70. While the dominance of the HH over the VV return is not consistent with analytical models for which Bragg scattering dominates, the phenomenon may indicate wedge diffraction [Lyzenga et al., 1983]. However, random fluctuations in the independent measurements of backscattered power for VV and HH polarization could produce short-duration events in which  $\sigma_{HH}^0$  exceeds  $\sigma_{VV}^0$ . The effect of the averaging, or integration, on the characteristics of the VV and HH sea spikes also may be a factor in the occurrence of these events. (An integration time of 0.125 s was used to process the data in Figure 4; see appendix.)

Figure 4 also shows some important timing relationships between the sea spikes in  $\sigma^0$  and maxima in the Doppler frequency and bandwidth. The  $\sigma^0$  maxima tend to occur simultaneously with local maxima in the mean Doppler frequency. On the other hand, the bandwidth maxima tend to occur after the local maxima in cross section. The delay between the  $\sigma^0$  and bandwidth maxima is typically about 0.25–0.50 s. The appearance of a whitecap in the 3-dB spot also generally occurs later than the coincident local maxima in cross section and Doppler frequency. Bandwidth maxima and the appearance of a whitecap in the 3-dB spot are nearly simultaneous.

Finally, the time series in Figure 4 show that whitecaps in the 3-dB illuminated area may not always be accompanied by a large sea spike in  $\sigma^0$  and, vice versa, that a large sea spike may occur unaccompanied by a whitecap in the 3-dB spot. For example, the third whitecap noted in Figure 4 is not associated with a distinctive peak in either the cross section or the bandwidth, whereas the sea spike labeled C is comparable in magnitude to the other events, yet no whitecap was observed in the 3-dB spot.

The general observations illustrated by the example in Figure 4 are that (1) sea spike maxima tend to occur close in time to local maxima in the mean Doppler frequency, (2) bandwidth maxima associated with sea spikes tend to be delayed from the cross section maxima by 0.25-0.50 s, (3) a large sea spike may be unaccompanied by the appearance of a whitecap in the 3-dB spot and vice versa, and (4) when a sea spike is accompanied by a whitecap in the 3-dB spot, its appearance occurs close in time to the bandwidth maxima.

A detailed study of the scattering mechanisms responsible for these characteristics of the distinctive microwave signature of breaking waves would require information on the sea surface geometry, which was not available in this investigation. However, the qualitative information provided by visual correlation between the microwave measurements and video recordings may provide a guide to research addressing specific scattering mechanisms. In general, our observations indicate that both tilt and hydrodynamic modulation of the radar cross section [e.g., *Alpers et al.*, 1981] may contribute to the microwave signature of breaking waves.

The scattering geometry of a particular breaking wave is determined by the location of the illuminated area with respect to the phase of the wave's rapidly changing surface profile. As the forward face of a wave crest approaches the illuminated area, the local incidence angle decreases to a minimum. The local incidence angle increases as the back side of the crest passes through the spot. By comparing the simultaneous microwave and video measurements, we found that most large jumps in  $\sigma^0$  associated with breaking occurred on the steep forward face of waves that ultimately formed a whitecap. If the wave slope is such that the local incidence angle is reduced to 25° or less, then the



Fig. 4. Time series of  $\sigma_{VV}^0$ ,  $\sigma_{PH1}^0$ , Doppler frequency F, and bandwidth B ( $u_* = 55 \text{ cm s}^{-1}$ ). Events exceeding  $\sigma_{pol}^0 = -5.2 \text{ dB}$  (0.30) and/or a bandwidth of 55 Hz and whitecaps observed in the 3-dB spot are identified by the time (minutes and seconds) that they occurred. Note (1) sea spikes in  $\sigma^0$  coincide with Doppler frequency maxima, (2) sea spikes typically occur before bandwidth maxima, (3) sea spikes may or may not accompany a whitecap in the 3-dB spot, and (4) bandwidth maxima coincide with whitecaps associated with a sea spike.

scattering begins to enter the specular regime and a large jump in  $\sigma^0$  would be expected. Our observations suggest that large sca spikes associated with breaking waves are primarily due to the change in local incidence angle.

Rapp and Melville [1990] found that the local slope of the forward face of breaking waves generated in the laboratory ranged from 0.3 to 0.7 for spilling and plunging breaking events, respectively. For the SAXON-CLT measurements made at an incidence angle of 45°, these slopes would result in a local incidence angle between 10° and 30°. Loewen and Melville [1991] have shown that the maximum in the radar cross section at moderate incidence angles occurs on the steep face of laboratory-generated waves just prior to breaking. If the geometry of breaking waves generated in the laboratory is similar to those found in the field, then the SAXON-CLT measurements support the notion that sea spikes associated with the forward face of breaking waves are due to large changes in the local incidence angle.

While most of the sea spikes we observed were associated with the forward face of breaking waves, some occurred almost simultaneously with passage of a crest through the center of the illuminated area. These events tended to come from the neighborhood of the crests of low-frequency swell exhibiting large modulations of short waves distributed over the crest region. The sea spikes associated with short-wave modulation near such long wave crests may be due to increased Bragg resonant scattering at a reduced incidence angle.

#### 4. DETECTION AND VERIFICATION

After the steep forward face of a breaking wave produces a sea spike, the breaking process continues as the crest approaches the illuminated area. Consequently, a whitecap may not appear until after its crest has passed the center of the illuminated area. In other words, the whitecap associated with a given sea spike may occur "downwave" of the center of the radar spot. From this observation, we concluded that the appearance of a whitecap within a specific distance downwave of the illuminated area is a more appropriate criterion for classifying sea spikes than its appearance within the 3-dB spot. Therefore we took our classification criterion to be the appearance of a whitecap within a distance of approximately 5 m downwave of the radar spot. A distance of 5 m is 10% to 20% of the wavelength of the dominant surface wave corresponding to the peak frequency of the surface displacement spectrum. Based on the size of the 3-dB illuminated area and the estimated uncertainty in the video alignment, a minimum whitecap size of 0.5 m was used.

We selected six different periods of video recordings from the SAXON-CLT experiment for detailed viewing. These recordings consisted of two 20-min periods from high wind conditions during run 6 (43 cm s<sup>-1</sup> <  $u_{\bullet}$  < 48 cm s<sup>-1</sup>) and four 1-hour periods from more moderate wind conditions during runs 11 and 12 (30 cm s<sup>-1</sup> <  $u_{\bullet}$  < 40 cm s<sup>-1</sup>). We made a preliminary attempt to classify the positively identified breaking events according to

whitecap size. Since no significant correlation was found between this subjective assessment and the measured microwave parameters, all events with whitecaps approximately 0.5 m or greater were counted. A nominal criterion of a 10% false detection rate was used as a guide in evaluating the success of a given threshold. (Note that a sea spike associated with a whitecap less than 0.5 m would be classified as a false detection.) The performance of the microwave detection was evaluated in terms of the number of detected breaking events as a percentage of the total number of sea spikes attributed to breaking waves. This percentage, denoted as  $P_{ss}^i$ , is given by

$$P_{ss}^{i} = 100 \frac{\text{Number of detected events}}{\text{Number of sea spikes due to breaking waves}}$$
(2)

This performance parameter is listed in Table 2, with the superscript i indicating the different detection schemes considered. The method used to establish the denominator in the above expression is outlined in section 4.2.

#### 4.1. Polarization-Independent Events

Our first attempt to establish a radar cross section threshold based solely on the characteristics of the microwave data was to exploit the expected polarization-independent nature of returns from breaking waves. For measurements at moderate incidence angles, the average polarization ratio,  $\sigma_{VV}^0/\sigma_{HH}^0$ , of the sea surface is greater than unity owing to the dominance of the Bragg resonant scattering mechanism [Wright, 1966]. The scattering becomes polarization independent as the incidence angle decreases and the specular scattering regime is approached, resulting in a polarization ratio of unity. We used the number of sea spikes in a given record as a function of cross section threshold and polarization to establish a threshold to detect polarization-independent events.

Figure 5a shows the average number of sea spikes per hour as a function of detection threshold for a total of 48 hours of data divided into three different intervals of u. for both VV polarization (solid lines) and HH polarization (dashed lines) during the SAXON-CLT experiment. For a low threshold, more events are counted for VV than for HH because the mean polarization ratio is greater than unity. As the threshold is increased, approximately the same number of events are counted for both VV and HH over a range of  $u_*$ . If the polarization ratio for individual breaking events producing large spikes is indeed unity, then the

TABLE 2. Percentage of Sea Spike Breaking Events Detected

| Run<br>ID | <i>u</i> *,<br>cm s <sup>-1</sup> | $P_{ss}^{1}, \%$ | P <sup>2</sup> <sub>ss</sub> , % | P <sup>3</sup> <sub>ss</sub> , % | P <sup>4</sup> <sub>ss</sub> , % |
|-----------|-----------------------------------|------------------|----------------------------------|----------------------------------|----------------------------------|
| 6a        | 43                                | 28               | 49                               | 61                               | 69                               |
| 6b        | 48                                | 15               | 35                               | 60                               | 67                               |
| 11        | 30                                | 15               | 28                               | 70                               | 73                               |
| 12        | 40                                | 19               | 33                               | 66                               | 70                               |
| 12a       | 40                                | 17               | 28                               | 73                               | 76                               |
| 12b       | 34                                | 17               | 30                               | 65                               | 70                               |
| Average   | -                                 | 19               | 34                               | 66                               | 71                               |

The percentage  $P_{ss}^i$  is given by equation (2), where the superscript *i* denotes one of the following detection schemes: (1)  $\sigma_{VV}^0 \ge \sigma_{pol}^0 = -5.2 \text{ dB} (0.30)$ ; (2)  $\sigma_{VV}^0 \ge -6 \text{ dB} (0.25)$ ; (3)  $B \ge 50 \text{ Hz}$ ; (4)  $\sigma_{VV}^0 \ge -6 \text{ dB} (0.25)$  or  $B \ge 50 \text{ Hz}$ .



Fig. 5. (a) Average number of events per hour, N, in SAXON-CLT data versus radar cross section detection threshold for different  $u_*$  intervals. Near -5 dB, the same number of events are counted in VV and HH polarization. (b) Same as Figure 5a except for North Sea data; VV and HH curves begin to coincide near -6 dB.

point at which the VV and HH curves in Figure 5*a* coincide is an appropriate threshold to count polarization-independent sea spikes. (The coincidence of the VV and HH curves at slightly larger  $\sigma^0$  thresholds for larger values of  $u_*$  suggests that the minimum threshold may be a weak function of  $u_*$ .)

Results of this analysis for the preliminary measurements in the North Sea, shown in Figure 5b, are similar to those for the SAXON-CLT experiment. However, small differences are apparent in both the threshold at which the VV and HH curves coincide and the spacing of the different u. curves. For the SAXON-CLT data, the VV and HH curves in Figure 5a begin to coincide at approximately -5 dB, whereas the same point in Figure 5b for the North Sea measurements occurs closer to -6 dB. If the two figures are shifted relative to one another by the difference between these two levels, the curves for the SAXON-CLT and the North Sea data roughly line up. The scatterometers used for the two measurements were different, and thus the difference of 1 dB or so may be due to calibration uncertainty, since the accuracies of the systems are approximately ±1 dB [Jessup et al., 1990]. In the following analysis of the SAXON-CLT data, a threshold of  $\sigma_{pol}^0 = -5.2 \text{ dB} (0.30)$  was used to detect large, polarization-independent sea spikes.

From the video recordings, we found that all the sea spikes detected with the threshold  $\sigma_{pol}^0$  were due to waves that produced whitecaps meeting the 5-m distance criterion described at the start of section 4. However, the large, polarization-independent events detected with this scheme constituted, on average, only 19% of the sea spikes associated with breaking waves (see Table 2). Furthermore, we found a significant number of break-

ing events that produced discernible sea spikes of a lesser magnitude than the threshold value  $\sigma_{\text{pol}}^0$ .

# 4.2. Wave-By-Wave Analysis

To improve our detection rate, we compiled statistics on the computed microwave parameters for all sea spikes associated with the passage of a wave crest for the six different periods of video recordings listed in Table 2. The passage of an individual wave crest was taken as the time between zero upcrossings in the zero-mean time series of the mean Doppler frequency. Cycles in the Doppler frequency with a maximum excursion of less than 25 Hz (0.27 m s<sup>-1</sup>) were not considered to constitute an individual wave crest. Furthermore, a minimum threshold of  $\sigma_{pol}^0/2$  was imposed on  $\sigma_{VV}^0$  to eliminate false detections due to low-level random fluctuations. We then viewed the video recordings and classified each sea spike as being associated with either a breaking or a nonbreaking wave, using the 5-m distance criterion.

Figure 6 shows scatter plots of the peak values of  $\sigma_{VV}^0$  versus  $\sigma_{HH}^0$  for the sea spikes classified in this manner for the 1-hour period designated run 12 in Table 2. The top plot is for events



Fig. 6. Scatter plot of peak  $\sigma_{VV}^0$  versus  $\sigma_{HH}^0$  for sea spikes associated with waves identified as (top) breaking and (bottom) nonbreaking for the 1-hour video recording from run 12.

classified as being due to breaking waves, and the bottom plot is for those due to nonbreaking waves. The distribution of nonbreaking values indicates that a radar cross section threshold somewhat lower than  $\sigma_{pol}^0 = -5.2 \, dB \, (0.30)$  would continue to detect only breaking events. Furthermore, comparison between the VV and HH values in Figure 6 suggests that applying the threshold to either polarization would yield equivalent results.

Breaking events continued to be detected successfully when the VV radar cross section threshold was lowered to  $-6 \, dB$ (0.25). For this threshold, the false detection rate was less than 10% for all runs in Table 2 except for run 6a, for which it was 20%. As summarized in Table 2, an average of 34% of the breaking events identified from the video recordings was detected by the lower threshold of  $-6 \, dB$ . However, the distribution of breaking events in Figure 6 indicates that a significant number of sea spikes associated with breaking events had still lower radar cross sections. On the basis of radar cross section alone, we concluded that most sea spikes that were attributable to breaking waves were not distinguishable from sea spikes of comparable magnitude that showed no visual evidence of being due to wave breaking.

The data in the scatter plot in the top graph of Figure 6 show that many of the breaking events with a large radar cross section fall close to the line of  $\sigma_{VV}^0 = \sigma_{HH}^0$ . For most sea spikes caused by breaking waves, however,  $\sigma_{VV}^0$  is significantly greater than  $\sigma_{HH}^0$ . Furthermore, many of these events are in the same region as the nonbreaking events shown in the bottom plot of Figure 6. These results discouraged the use of the polarization ratio as a further discriminator of microwave events associated with wave breaking.

#### 4.3. Mean Doppler Frequency

The observation that the large sea spikes associated with the forward face of breaking waves occur almost simultaneously with local maxima in the mean Doppler frequency is illustrated by considering whether  $F_{max}$ , the maximum mean Doppler frequency associated with a given wave, is less than or equal to  $F_{\text{peak}}$ , the mean Doppler frequency at the time of the associated sea spike peak. (By definition,  $F_{peak}$  cannot exceed  $F_{max}$ .) Figure 7 shows scatter plots of  $F_{peak}$  versus  $F_{max}$  for breaking and nonbreaking waves identified in the 1-hour video recording designated run 12 in Table 2. Most of the points in Figure 7 are clustered near the line  $F_{peak} = F_{max}$ , indicating that many of the Doppler frequency maxima and sea spike peaks are nearly coincident. However, for both the breaking and nonbreaking distributions, a significant number of events lie below this line. The distribution of values along this line illustrates the wide range of mean Doppler frequency maxima associated with breaking events. The extent of the distribution may reflect the influence of the crest orientation on the measured line-of-sight scatterer velocity. Although we found that the mean Doppler frequency cannot be used to increase discrimination, it may contain important information about the kinematics of the breaking process, as discussed in Part 2.

We cannot readily predict the effect of the increased velocity of the active whitecap at the crest of a breaking wave on the mean Doppler frequency. The Doppler frequency due to a whitecap velocity on the order of the phase speed would be significantly larger than that due to the orbital velocity. However, since we expect the whitecap velocity to be nearly horizontal, it would contribute less than its magnitude to the measured line-of-sight velocity. In general, the combined effect of the orbital and whitecap velocities on the mean Doppler frequency





Fig. 7. Scatter plot of the Doppler frequency at the time of the sea spike peak,  $F_{\text{peak}}$ , versus the Doppler frequency maximum,  $F_{\text{max}}$ , for (top) breaking waves and (bottom) nonbreaking waves identified from the 1-hour video recording from run 12. (By definition,  $F_{\text{peak}}$  cannot exceed  $F_{\text{max}}$ .)

will depend on their relative target strengths. As is discussed in the next section, we found that the large velocities associated with active whitecaps superimposed on the orbital velocity had more effect on the Doppler bandwidth than on the mean Doppler frequency.

#### 4.4. Doppler Bandwidth

We now consider the jump in the Doppler bandwidth that often accompanied sea spikes caused by breaking waves. Unlike the mean Doppler frequency, the bandwidth maximum associated with a breaking wave generally occurred after the sea spike maximum in  $\sigma^0$ . Our comparisons of time series such as Figure 4 with simultaneous video recordings indicated that a bandwidth maximum generally occurred when the illuminated area straddled the crest region. Even for a nonbreaking wave, an increase in the bandwidth might be expected near the crest region owing to the large variation in the line-of-sight orbital velocity across the crest. However, we expect that the velocity of an active whitecap will increase the range of velocities within the illuminated area straddling the crest region more than this range would be increased as a result of the orbital velocity alone, and thus augment the bandwidth.

Indeed, the Doppler spectra computed from the archived scatterometer data indicated that the characteristic jump in the bandwidth following a sea spike was due to an increased range of velocities near the crest. Figure 8 is a 1-min time series of radar cross section, mean Doppler frequency, and Doppler bandwidth computed directly from moments of the power spectral density of the microwave backscatter. Figures 9 and 10 show Doppler spectra corresponding to the two VV sea spikes identified in the time series of Figure 8. The vertical axis is the power spectral density in decibels (re arbitrary units), and the horizontal axis is the Doppler frequency in hertz, with axis divisions of 100 Hz and zero frequency indicated by the vertical center line (the Doppler conversion is 94 Hz  $m^{-1} s^{-1}$ ). These short-term spectra, corresponding to a time record of 0.125 s, were smoothed using a weighted running average resulting in a reduction of variance equivalent to 64 degrees of freedom. The spectra in the upper plots of Figures 9 and 10 coincide in time with the maximum in the radar cross section for the two sea spikes considered. The lower spectra correspond to the bandwidth maxima for each event. The mean Doppler frequency for each spectrum is indicated by an X on the frequency axis.

The spectra for the first VV sea spike identified in Figure 8 are shown in Figure 9. The spectrum at the time of the sea spike maximum exhibits a single peak which is roughly coincident with the mean Doppler frequency. The spectrum at the time of the bandwidth maximum is quite different, showing two major peaks widely separated in frequency. (In both spectra, the negativefrequency image of the major peak is due to phase imbalance between the I and Q channels and has no physical significance; thus it was not included in the bandwidth calculation.) The mean Doppler frequency at the time of the bandwidth maximum is less than that at the time of the sea spike maximum, even though the frequency of the highest peak is significantly larger. The secondary peak lies very close to zero and shows significant contributions at negative frequencies. In contrast, the corresponding spectrum for the second sea spike identified in Figure 8, shown in Figure 10, does not have two distinct frequency peaks. However, this spectrum does include significant returns ranging from nearzero frequency to approximately 150 Hz. The broad and sometimes bimodal nature of the spectra corresponding to the bandwidth maximum indicates contributions from higher velocities within the active whitecap as well as contributions from scatterers advected by the orbital velocity. A significant amount of energy near zero frequency in these spectra suggests returns from the back side of the crest.

To establish a bandwidth threshold, we considered joint distributions of the peak VV sea spike radar cross section  $\sigma_{\text{peak}}^0$  and the corresponding maximum bandwidth  $B_{\text{max}}$ . Figure 11 is an example of one such distribution for the 1-hour period designated run 12. Surprisingly, the distribution of  $B_{\text{max}}$  suggests that a bandwidth threshold alone would unambiguously identify a larger number of breaking events than the radar cross section thresholds discussed in sections 4.1 and 4.2 above. This implication was borne out by the analysis summarized in Table 2, showing that a criterion that  $B_{\text{max}}$  exceed 50 Hz successfully detected an average of 66% of the breaking events identified from the video recording for the six different sessions viewed in detail. The false detection rate for this scheme was less than 10% for all runs in Table 2 except run 6a, which had a rate of 13%. By combining this bandwidth criterion with the radar cross section thresholds.



Fig. 8. Example of 1-min time series of  $\sigma_{VV}^0$ ,  $\sigma_{HH}^0$ , mean Doppler frequency F, and Doppler bandwidth B computed directly from Doppler spectra derived from the scatterometer data recorded on analog tape. Spectra for the two sea spikes identified in the top trace are shown in Figures 9 and 10.

hold described in section 4.2 (counting all events for which  $\sigma_{VV}^0 > -6 \text{ dB} (0.25)$  or B > 50 Hz), we increased the success rate to an average of 71%. Once again, the false detection rate was less than 10% for all runs in Table 2 except run 6a, which had a rate of 23%.

The percentages of breaking events identified by the four threshold-based detection schemes considered in this analysis are summarized in Table 2. While none of these detection schemes identified all microwave events attributable to breaking waves, scheme 4 was the most successful. Furthermore, for schemes 3 and 4 the proportion of breaking events detected was roughly the same for all runs (see Table 2). That is, for the six different periods of video recordings with 30 cm s<sup>-1</sup> <  $u_*$  < 48 cm s<sup>-1</sup>, the number of breaking events detected was roughly proportional to the total number of sea spikes caused by breaking waves. We believe that this validates the use of these detection schemes to measure the overall degree of wave breaking, even though they fail to identify all microwave events attributable to breaking waves. Note that schemes 3 and 4 may be expected to provide better statistical results than schemes 1 and 2 by virtue of the larger sample size they provide.

### 5. CONCLUSIONS

In this paper, we investigated the relationship between breaking surface waves and distinctive events in microwave backscatter at moderate incidence angles. The microwave events were characterized in terms of radar cross section, polarization ratio, and moments of the Doppler spectrum. This suite of microwave variables was used to investigate detection thresholds for identifying microwave events associated with individual breaking waves.

We found that the waves producing whitecaps in the 3-dB illuminated area were not necessarily associated with large sea spikes in  $\sigma^0$  and vice versa, i.e., that large sea spikes were sometimes unaccompanied by a whitecap in the 3-dB illuminated area. However, many of the latter events produced a whitecap "downwave" of the radar spot, that is, after the crest of the wave responsible for the sea spike had passed the center of the illuminated area. Therefore we established the criterion for a given microwave event being due to a breaking wave as the appearance of a whitecap within a distance of approximately 5 m downwave of the radar spot.

In general, the sea spikes in  $\sigma^0$  associated with breaking waves tended to be accompanied by an increased mean Doppler frequency and large jumps in bandwidth. The majority of sea spikes in  $\sigma^0$  associated with breaking occurred on the steep forward face of waves that ultimately formed a whitecap. From this observation, we concluded that these sea spikes were primarily due to the change in local incidence angle. However, some sea spikes occurred almost simultaneously with the passage of a long wave crest through the center of the illuminated area.

The large sea spikes in  $\sigma^0$  associated with the forward face of breaking waves were nearly simultaneous with a maximum in the mean Doppler frequency. The jump in the Doppler bandwidth tended to be delayed with respect to the sea spike maximum and generally occurred when the illuminated area straddled the crest region. From time series of Doppler spectra, we attributed the



Fig. 9. Doppler spectra S(f) for the first VV sea spike identified in Figure 8 (time 02:45.76) corresponding to (top) the sea spike peak and (bottom) the associated bandwidth maximum at time 02:46.13. The mean frequency is marked with an X on the frequency axis (an image of the dominant peak reflected about zero frequency is evident on the left in each spectrum.) The mean Doppler frequency of the upper spectrum is roughly coincident with the peak frequency, while that of the lower spectrum is significantly less.

bandwidth increase to the large range of velocities associated with the crest region of waves in the process of breaking.

Criteria based on polarization independence and the radar cross section detected an average of only 19% and 34%, respectively, of the sea spikes associated with breaking waves. The polarization ratio and the mean Doppler frequency also proved to be inadequate as consistent indicators of breaking. A somewhat surprising result was that a jump in the Doppler bandwidth caused by breaking waves was the most successful detection parameter. Nearly three out of four breaking waves producing detectable microwave events were successfully identified by a threshold-based scheme utilizing both radar cross section and bandwidth information.

This investigation has shown that characteristics of microwave backscatter from breaking waves can be used to detect individual events reliably. None of the detection schemes tested could identify all microwave events attributable to breaking waves. However, for the schemes utilizing bandwidth, the proportion of those events that were detected was roughly the same regardless of friction velocity. That is, the number of breaking events counted was roughly proportional to the number of sea spikes caused by breaking waves.

The results encourage further research into utilizing microwave techniques to quantify the role of wave breaking in the upper ocean. Because the mean radar cross section decreases with increasing incidence angle, detection may be enhanced as the incidence angle is increased. Laboratory measurements might help to establish the source of the bandwidth increase and clarify



Fig. 10. Same as Figure 9 except for the second VV sea spike peak identified in Figure 8 (time 03:06:13).

the importance of both the stage of development and the location of the radar spot with respect to the phase of the wave. Further research on the source of the bandwidth increase associated with wave breaking may lead to an objective basis for a bandwidth threshold.

## **APPENDIX: INTEGRATION TIME ISSUES**

Because a portion of the unprocessed output of the scatterometer was recorded on analog tape, the processing done in real time during the experiment could be repeated with a different integration time. To investigate the effect of a shorter integration time, we chose an integration time equal to one-half that used in the field, or  $T_i = 0.125$  s.

Comparison of the time series of  $\sigma_{VV}^0$  and  $\sigma_{HH}^0$  for the two different integration times showed that the characteristics of some of the large sea spikes were indeed changed by the use of a shorter integration time. In general, the amplitude of the random fluctuations was greater in the time series with  $T_i = 0.125$  s than in those with  $T_i = 0.25$  s. The large radar cross section sea spikes tended to increase in maximum amplitude and exhibit amplitude fluctuations that were larger than the overall increase in background noise. Furthermore, the increase in maximum amplitude appeared to be greater for HH spikes than for VV spikes.

These observations of the effect on individual sea spikes are reflected in Figure A1, which shows the result of the threshold analysis described in section 4.1 repeated on 22 hours of data reprocessed with the shorter integration time. Comparison of Figure A1 with Figure 5a indicates that for a given threshold, a larger number of sea spikes are detected for the data processed with a shorter integration time. For large threshold values, the number of detected events tends to increase more for HH polarization than for VV polarization. As a result, the VV and HH curves in Figure A1 no longer converge as they do in Figure 5a.



Fig. 11. Scatter plot of peak sea-spike  $\sigma_{VV}^0$  versus  $B_{max}$  for (10p) breaking waves and (bottom) nonbreaking waves identified in the 1-hour video recording from run 12.

The fact that the VV and HH polarization curves in Figure 5*a* roughly converge at large threshold values was used as the basis for choosing the threshold level  $\sigma_{pol}^0$  to detect polarizationindependent events. That the HH curves in Figure A1 rise significantly above the VV curves for large threshold values implies that a substantial number of sea spikes are produced by a scattering mechanism for which  $\sigma_{1HH}^0$  exceeds  $\sigma_{VV}^0$ . Interpreting this result using a shorter integration time is complicated by uncertainty in the absolute calibration of the scatterometer. Note that shifting the VV and HH curves in Figure A1 by a few tenths of a decibel would cause them to converge at large threshold values. Because the accuracy of the SAXON-CLT radar cross section measurements is approximately ±1 dB, the events for which  $\sigma_{HH}^0$  exceeds  $\sigma_{VV}^0$  might be the result of calibration uncertainty.

On the other hand, the events for which the polarization ratio is less than unity are consistent with wedge diffraction [Lyzenga et al., 1983]. Furthermore, discrepancies between measurements and theoretical modeling of the polarization characteristics of the radar cross section have been reported by various authors. Most recently, Sylvester et al. [1989, 1990] reported that maximum



Figure A1. Threshold analysis in Figure 5a repeated with an integration time of  $T_i = 0.125$  s. Note that the number of HH events exceeds that of VV events at large threshold values.

values of  $\sigma_{HH}^0$  exceeded those of  $\sigma_{VV}^0$  for a significant percentage of measurements at incidence angles of 28°, 40°, and 56° with the Seasat-A satellite scatterometer. Although the Seasat measurements are not necessarily directly comparable to the SAXON-CLT data, tower-based measurements have been used to calibrate space-based scatterometer systems [e.g., *Keller et al.*, 1989]. The results reported by *Sylvester et al.* [1989, 1990] indicate the importance of understanding events for which  $\sigma_{HH}^0$  exceeds  $\sigma_{VV}^0$ .

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#### References

- Alpers, W.R., D.B. Ross, and C.L. Rufenach, On the detectability of ocean surface waves by real and synthetic aperture radar, J. Geophys. Res., 86(C7), 6481-6498, 1981.
- Banner, M. L., and E. H. Fooks, On the microwave reflectivity of smallscale breaking water waves, Proc R. Soc. London, Ser A, 399, 93-109, 1985.
- Blanc, T.V., Variation of bulk-derived surface flux, stability, and roughness results due to the use of different transfer coefficient schemes, J Phys. Oceanogr., 15, 650-669, 1985.
- Donelan, M., and W.J. Pierson Jr., Radar scattering and equilibrium ranges in wind-generated waves with application to scatterometry, J. Geophys. Res., 92(C5), 4971-5092, 1987.
- Doviak, R. J., and D. S. Zmic, Meteorological radar signal processing, in Doppler Radar and Weather Observations, pp. 91-120, Academic, San Diego, Calif., 1984.
- Duncan, J.R., W.C. Keller, and J.W. Wright, Fetch and wind speed dependence of Doppler spectra, *Radio Sci.*, 9, 809-819, 1974.
- Ewell, G. W., M. T. Tuley, and W. F. Horne, Temporal and spatial behavior of high resolution sea clutter 'spikes,' in *IEEE Radar '84 Conference*, pp. 100-104, Inst. of Elect. and Electron. Eng., New York, 1984.

- Jessup, A.T., Microwave detection and characterization of deep-water wave breaking, M.S. thesis, Mass. Inst. of Technol., Cambridge, 1988.
- Jessup, A. T., Detection and characterization of deep water wave breaking using moderate incidence angle microwave backscatter from the sea surface, Ph.D. thesis, 344 pp., Joint Program in Oceanogr. and Oceanogr. Eng., Mass. Inst. of Technol./Woods Hole Oceanogr. Inst., Woods Hole, Mass., 1990.
- Jessup, A.T., W.C. Keller, and W.K. Melville, Measurements of sea spikes in microwave backscatter at moderate incidence, J. Geophys. Res., 95(C6), 9679-9688, 1990.
- Jessup, A. T., W. K. Melville, and W. C. Keller, Breaking waves affecting microwave backscatter, 2. Dependence on wind and wave conditions, J. Geophys. Res., this issue.
- Kalmykov, A. I., and V. V. Pustovoytenko, On polarization features of radio signals scattered from the sea surface at small grazing angles, J. Geophys. Res., 81, 1960-1964, 1976.
- Katzin, M., On the mechanism of radar sea clutter, Proc. IRE, 45, 44-54, 1957.
- Keller, W.C., and W.J. Plant, Cross sections and modulation transfer functions at L and K<sub>u</sub> bands measured during the Tower Ocean Wave and Radar Dependence experiment, J. Geophys. Res., 95(C9), 16.245-16.262, 1990.
- Keller, W. C, W. J. Plant, and G. R. Valenzuela, Observations of breaking ocean waves with coherent microwave radar, in *Wave Dynamics and Radio Probing of the Sea Surface*, edited by O. M. Phillips and K. Hasselmann, pp. 285-293, Plenum, New York, 1986.
  Keller, W. C., C. V. Wissman, and W. Alpers, Tower-based measurements
- Keller, W. C., C. V. Wissman, and W. Alpers, Tower-based measurements of the ocean C band radar cross section, J. Geophys. Res., 94(C1), 924-930, 1989.
- Kwoh, D.S., and B.M. Lake, A deterministic, coherent, and dualpolarized laboratory study of microwave backscattering from water waves, 1, Short gravity waves without wind, *IEEE J. Oceanic Eng.*, *OE-9*(5), 291-308, 1984.
- Kwoh, D. S., B. M. Lake, and H. Rungaldier, Microwave scattering from internal wave modulated surface waves: A shipboard real aperture coherent radar study in the Georgia Strait Experiment, J. Geophys. Res., 93(C10), 12,235-12,248, 1988.
- Large, W.G., and S. Pond, Open ocean momentum flux measurements in moderate to strong winds, J. Phys. Oceanogr., 11, 324-336, 1981.
- Lewis, B. L., and I. D. Olin, Experimental study and theoretical model of high-resolution radar backscatter from the sea, *Radio Sci.*, 15, 815-828, 1980.
- Loewen, M.R., and W.K. Melville, Microwave backscatter and acoustic radiation from breaking waves, J. Fluid. Mech., 224, 601-623, 1991.
- Long, M. W., On the two-scatterer theory of sea echo, IEEE Trans. Antennas Propag., AP-22, 667-672, 1974.

- Long, M. W., Radar Reflectivity of Land and Sea, pp. 170-206, Artech House, Dedham, Mass., 1983.
- Lyzenga, D.R., A.L. Maffett, and R.A. Shuchman, The contribution of wedge scattering to the radar cross-section of the ocean surface, *IEEE Trans. Geosci. Remote Sens.*, GE-21(4), 502-505, 1983.
- Melville, W.K., M.R. Loewen, F.C. Felizardo, A.T. Jessup, and M.J. Buckingham, Acoustic and microwave signature of breaking waves, *Nature*, 336, 54-59, 1988.
- Phillips, O. M., Radar returns from the sea surface—Bragg scattering and breaking waves, J. Phys. Oceanogr., 18, 1065-1074, 1988.
- Plant, W. J., W. C. Keller, and A. Cross, Parametric dependence of ocean wave-radar modulation transfer functions, J. Geophys. Res, 88(C14), 9747-9756, 1983.
- Rapp, R.J., and W.K. Melville, Laboratory measurements of deep-water breaking waves, *Philos. Trans. R. Soc. London, Ser. A*, 331, 735-800, 1990.
- Smith, S. D., Coefficients for sea surface wind stress, heat flux, and wind profiles as a function of wind speed and temperature, J. Geophys. Res., 93(C12), 15,467-15,472, 1988.
- Sylvester, W.B., W.J. Pierson, Jr., and S. R. Breitstein, Techniques for evaluating the performance of models of radar backscatter from the ocean surface: Suggestions for their development, in IGARSS '89 (International Geoscience and Remote Sensing Symposium), 12th Canadian Symposium on Remote Sensing Proceedings, vol. 5, IEEE Publ. 89CH2768-0, pp. 2991-2996, Inst. of Elect. and Electron. Eng., New York, 1989.
- Sylvester, W. B., W. J. Pierson, Jr., and S. R. Brentstein, Further results on "techniques for evaluating the performance of models of radar backscatter from the ocean surface: Suggestions for their improvement," in Remote Sensing for the Nineties, IGARSS '90 (International Geoscience and Remote Sensing Symposium), vol. 3, *IEEE Publ.* 90CH2825-8, pp. 2149-2155, Inst. of Elect. and Electron. Eng., New York, 1990.
- Wright, J. W., Backscattering from capillary waves with application to sea clutter, *IEEE Trans. Antennas Propag.*, AP-14, 749-754, 1966.

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