Radiometric Measurements of the Microwave Emissivity of Reproducible Breaking Waves

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Abstract— **In a recent experiment the microwave emissivity of foam on calm water was measured to be 0.75 to 0.95 and dependent on polarization [1]. Microwave radiometric measurements of breaking waves on the open ocean showed that the emission due to wave breaking varies with the time dynamics of the wave, as well as with radiometer polarization and viewing angle [2]. However, the inherent intermittency and sparseness of breaking waves makes it very difficult to perform repeatable measurements on the open ocean. Therefore, the authors conducted a wave basin experiment in which reproducible breaking waves were generated every 1-2 seconds. This paper reports preliminary results of the combined observations of polarimetric brightness temperatures and physical characteristics of these waves and foam. These and future results will provide input parameters to bound numerical electromagnetic models for prediction of foam emissivities [3].**

I. Introduction

The U.S. Navy and the NPOESS Integrated Program Office launched WindSat in January 2003, the first polarimetric microwave radiometer in space, to retrieve the ocean surface wind vector. Azimuthal variations in brightness temperatures with wind direction have been observed in horizontally and vertically polarized radiometric measurements from space [4-5] and in polarimetric measurements from aircraft [6-7]. Since these azimuthal variations are small, typically 0.5-2 K, it is essential to account for other geophysical effects, including surface roughness, surfactants, whitecaps, temperature, salinity and atmospheric parameters. Near surface measurements quantitatively identify these relationships because they observe smaller areas of the ocean surface, under conditions of increased homogeneity.

The high emissivity of foam significantly increases the microwave emission from the sea surface. Therefore at moderate to high winds, foam due to breaking waves is likely to modify brightness temperature azimuthal variations due to wind direction.

Several models have been developed to characterize the effect of foam on the ocean surface emission [8-9]. Wilheit modeled foam emission empirically as a function of wind speed and frequency, assuming that foam emissivity was independent of polarization [8]. Kunkee and Gasiewski included the effect of time-varying foam coverage as the wave breaks [9]. However, most empirical models have not considered physical parameters of foam such as the bubble size spectrum and foam thickness.

In a recent experiment, the microwave emissivity of foam on calm water was measured at X-band and Ka-band at the Chesapeake Bay Detachment (CBD) [1]. Beam-filling, stable foam was generated to allow characterization of the polarimetric emissivities of beam-filling foam as a function of incidence angle and polarization. The emissivity of foam was measured to be less than one, polarization dependent, and decreasing with incidence angle (for horizontal polarization) [1].

Guo et al. formulated an electromagnetic scattering and emission model of foam and applied dense media radiative transfer theory (DMRT) to analyze the effects of foam on passive remote sensing measurements [10]. The experimental results measured at CBD in turn motivated further modeling of foam by Chen et al. [3], in which Monte Carlo simulations of ensembles of foam bubbles using DMRT showed good agreement with the CBD results. However, the CBD experiment provided no information on how the microwave emission is affected by the time evolution of whitecaps and by the surface slope spectrum.

The time evolution of radiometric emission due to wave breaking was studied during the Fluxes, Air-Sea Interaction and Remote Sensing (FAIRS) experiment. Simultaneous measurements of brightness temperature and video imagery were obtained from the R/P FLIP in the Pacific Ocean. Although several cases of wave breaking were studied in detail, the spatially variable nature of ocean breaking waves makes it very difficult to capture repeatable measurements of breaking waves on the open ocean. As described in the following section, brightness temperature measurements of reproducible breaking waves are expected to allow assessment of the effects of time dynamics, polarization, elevation and azimuth angles on the microwave emissivity of foam.

II. Experimental Description

The POlarimetric Emissivity of Ocean Waves EXperiment (POEWEX) was conducted in October 2002 in the wave basin at the Ohmsett facility in Leonardo, NJ, owned by the Minerals Management Service, U.S. Department of the Interior. The Ohmsett facility features an outdoor wave basin measuring 203 m x 20 m x 3.4 m, filled with 2.6 million gallons of seawater with a controlled salinity of 35 ppt. A mechanical wave generator produces waves up to one meter in height. For

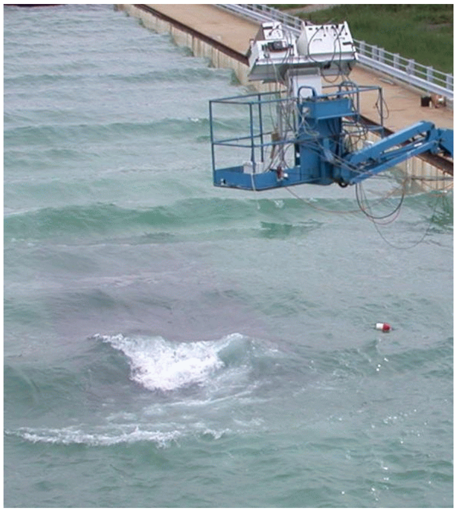

Fig. 1. Radiometers observing a breaking wave at the Ohmsett facility during POEWEX.

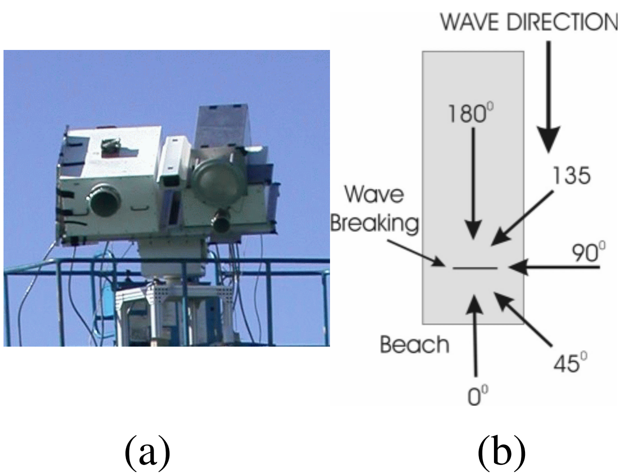

Fig. 2. (a). NRL and UMass polarimetric radiometers with a boresighted video camera in the basket of a boom lift crane. (b). The five azimuthal positions of the radiometer.

the experiment, an underwater concrete beach was installed to cause wave breaking near the same location in the wave basin as shown in Fig. 1. The NRL X-band (10.8 GHz), and the University of Massachusetts K-band (18.7 GHz) and Ka-band (36.5 GHz) polarimetric radiometers were mounted atop a pan-tilt positioner, in the bucket of a boom-lift crane, as shown in Fig. 2(a).

A bore sighted video camera was used to aim the radiometers at the center of the breaking waves. The wave generator produced waves that propagated linearly down the direction of the tank. For this experiment, 0° azimuthal angle was defined to be the direction opposite to wave propagation, and 180° degrees the direction along wave propagation. Fig. 2(b) shows the five azimuth angle positions for which measurements were performed, at each of the incidence angles of 45°, 53° and 60°. The boom lift was positioned so that the slant range of the three radiometers was 12 m in every azimuth position.

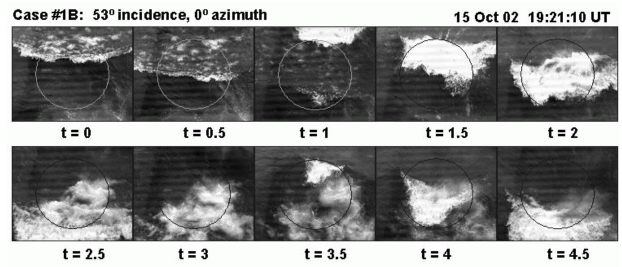

Fig. 3. A time series of video images (every half-second) of several breaking waves measured by a bore sighted video camera for azimuth angle of 0° and incidence angle of 53°.

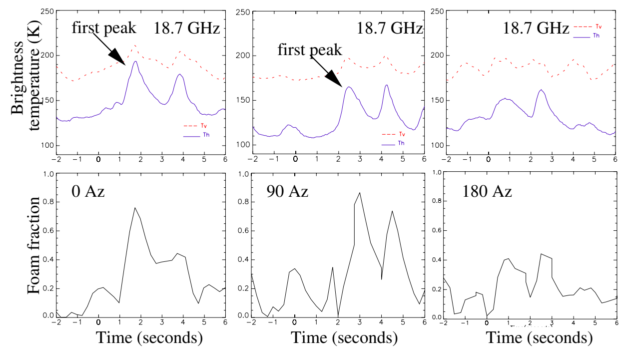

Fig. 4. The top row consists of time series of radiometric brightness temperatures, T_v and T_h shown as dotted and solid lines, respectively, for azimuth angles 0°, 90° and 180°, from left to right. The bottom row consists of foam coverage time series recorded simultaneously. The plots on the left correspond to the video images shown in Fig. 3.

Before and after each azimuthal angle measurement, all three radiometers performed external calibration using liquid nitrogen and ambient loads. In addition, tipping curves provided a stable cold reference load using the cosmic background radiation. Internal calibration was performed every 45 seconds by measuring the internal noise sources in each of the radiometers. Radiometric data was collected for both calm water and breaking waves for each incidence and azimuth angle combination. Boresighted video data was collected simultaneously to measure the foam coverage in the radiometers' field of view.

In-situ wave and foam measurements were performed by the University of Washington using acoustic Doppler velocimeters, void fraction probes, pressure transducers and an underwater video camera. The void fraction probes and underwater camera measured the microphysical characteristics of foam, whereas the pressure transducers and a scatterometer measured the macrophysical wave properties. The field of view of each radiometer was calculated using the 90% power radiation beamwidth, as shown by the ellipses in Fig. 3.

III. Results

Calibrated brightness temperatures were obtained using both internal and external calibration [11], as described in Section II. The measured calm water brightness temperatures were in good agreement with model values [12]. Fig. 4 shows an example of the time evolution of several breaking wave

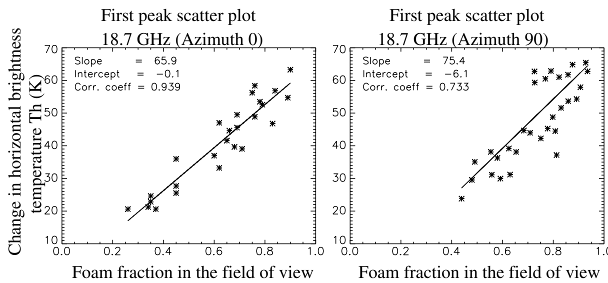

Fig. 5. Scatter plots of the change in horizontal brightness temperature versus foam fraction for azimuth angles 0° and 90°.

events measured by the boresighted video camera. Images were recorded at a rate of 4 Hz, and every other image is shown in Fig. 3. The corresponding radiometric and foam fraction data are shown in the left column of Fig. 4. At t = 1 sec, the approaching breaking wave causes a gradual increase in the brightness temperatures. The brightness temperatures peak just after t = 1.5 sec and subsequently decay until t = 3 sec.

A second wave breaks in the field of view at t = 4 sec, and the brightness temperatures subsequently decay. For this experiment, each breaking wave event is characterized by two or three peaks. Fig. 5 shows the dependence of the change in horizontal brightness temperature on foam fraction in the field of view for the first peak of all breaking wave events observed at azimuth angles of 0° and 90°. A high degree of correlation is observed for the first peaks of all breaking wave events.

IV. Discussion

The foam fraction in the K-band field of view and the K-band brightness temperatures exhibit similar time signature features (Fig. 4, leftmost column). The foam fraction for the same time period was estimated using grayscale analysis for an appropriate brightness threshold [13]. The T_h brightness temperature time signature is observed to track the foam fraction signature better than the T_v. There are two reasons to expect this behavior. First, the change in microwave emissivity from calm water to beam filling foam on a flat water surface is larger for T_v than T_h. Second, the effect of the reduction in local incidence angle by the front face of gravity waves is to decrease T_v and increase T_h. Therefore, the effect of foam on T_v is partially mitigated by the effect of long waves. Conversely, for T_h the predominant effect of gravity waves is to augment the effect of foam. Measurements of foam fraction in the field of view and of void fraction in the underwater bubble will allow comparison of the radiometric signatures of individual breaking waves with their physical properties on a case-by-case basis. The first peak of every group of breaking waves will be used to investigate the azimuthal dependence of the emissivity of foam since the first wave in each group breaks after bubble plumes from previous waves have decayed. The dependence of brightness temperatures of foam on elevation and azimuth angles and time will be found through analysis of ensembles of breaking waves. The combined radiometric and foam measurements provide quantitative information to bound numerical electromagnetic models of the microwave emissivity of foam, in terms of its time dynamics, polarization and radiometric viewing angle [3].

Acknowledgments

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