Polarimetric Observations of the Emissivity of Whitecaps Experiment (POEWEX' 04) to Characterize the Azimuthal Variation of the Microwave Emission from Foam Generated by Breaking Waves

S. Padmanabhan, S. C. Reising
Microwave Systems Laboratory, Electrical and Computer Eng. Dept., Colorado State University, Fort Collins, CO 80523
W. E. Asher
Applied Physics Laboratory, Univ. of Washington Seattle, WA 98105
L. A. Rose, P. Gaiser, J. Bobak, D. Dowgiallo and T. VonRentzell
Naval Research Laboratory, Washington, DC 20375

ABSTRACT:

WindSat, the first polarimetric microwave radiometer on orbit, and the NPOESS Conical Microwave Imager/Sounder, scheduled for launch in 2010, are both designed to retrieve the ocean surface wind vector from radiometric brightness temperatures. Available observations and models show that the wind direction signal is only 1-3 K peak-to-peak at 19 and 37 GHz, much smaller than the wind speed signal. Therefore, quantitative knowledge of the dependence of the ocean surface emissivity on properties such as surface roughness and wave breaking is critical for wind vector retrieval. The dependence of surface emission on roughness has been addressed by many studies, but the azimuthal dependence of the microwave emission from breaking waves and foam has not been adequately addressed. Recently, a number of experiments have been conducted to quantify the increase in sea surface microwave emission due to foam. The Polarimetric Observations of the Emissivity of Whitecaps EXperiment (POEWEX'04) was conducted during November 2004 to measure the azimuthal dependence of reproducible breaking waves in order to improve wind vector retrieval from spaceborne radiometric measurements, especially at wind speeds of 7 m/s and higher. The emissivity of breaking waves was shown to vary as a function of azimuth angle at four different WindSat frequencies.

INTRODUCTION:

WindSat, the first polarimetric microwave radiometer on orbit, was launched in January 2003 to demonstrate retrieval of the sea surface wind vector using passive microwave remote sensing. The NPOESS Conical Microwave Imager/Sounder (CMIS), planned for first launch in 2010, is designed to retrieve the ocean surface wind vector as one of its six key environmental data records. Aircraft and satellite measurements have shown that the wind direction dependence of brightness temperatures at 10, 19 and 37 GHz is small, typically less than 3K peak-to-peak [1-4]. However, retrieval of the wind direction with an accuracy of approximately 20º or better necessitates the quantification and removal of geophysical uncertainties in sea surface emission to an accuracy of approximately 0.1-0.3 K. To date, some two-scale models have characterized the increase in microwave emission with wind speed as an aggregate effect of both surface roughness and foam [5]. Since foam substantially increases ocean microwave emission [6] with a wind speed dependence that changes in different wind speed regimes, microwave emission from foam needs to be characterized separately. Nevertheless, the relationship between the microwave emission from foam and azimuth angle with respect to the wind direction is not well understood. Understanding how breaking waves and foam affect microwave emissivity as a function of wind speed and observation angle is critical to improving retrieval of wind direction from passive polarimetric microwave observations.

PREVIOUS MEASUREMENTS:

Recent experimental investigations have provided new quantitative information on the increase in surface microwave emission due to breaking waves. Near-surface measurements provide the capability to distinguish changes in sea surface emission caused by breaking waves and foam from those resulting from other factors. Open ocean measurements have shown that emission due to foam depends on the incidence and/or azimuth angles of observation [7]. It was also found that the temporal intermittency and spatial variability of breaking waves on the open ocean make it difficult to study the dependence of foam emission on observation angle in a reproducible way. Therefore, it is necessary to measure the microwave emission from

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reproducible breaking waves to characterize its dependence on incidence and azimuth angles of observation.

The Polarimetric Observations of the Emissivity of Whitecaps EXperiment (POEWEX ‘02), was conducted during October 2002 at the OHMSETT wave basin in Leonardo, New Jersey [8]. OHMSETT is a 200 m long by 20 m wide by 2.4 m deep wave basin filled with saltwater at a salinity of 35 ppt. A submerged shoal was installed in the wave basin to cause waves to break in the same location every 1-2 seconds, as shown in Fig. 1. The water depth at the area of breaking was 45±1 cm. The wave basin was equipped with two instrument carriages spanning the width of the tank that were moved along its length. These carriages were used for mounting an underwater video camera, capacitance void fraction probe, and acoustic Doppler velocimeters. Microwave radiometers were mounted in the basket of a boom-lift crane so that they could be positioned to view the water surface at a range of incidence and azimuth angles. For this experiment, the 0º azimuth angle was defined to be looking into the direction of wave propagation, and 180º degrees was viewing along the direction of wave propagation, as shown in Fig. 2. Radiometric measurements were performed at the WindSat polarimetric frequencies at X-band (10.7 GHz), K-band (18.7 GHz) and Ka-band (37 GHz) [1]. The radiometers operating at 18.7 and 37 GHz were Dicke-switched and measured at horizontal and vertical polarization. The Naval Research Laboratory 10.8 GHz polarimetric radiometer was total power and measured at horizontal, vertical, +45º linear, -45º linear, left hand circular and right hand circular polarizations. Brightness temperatures were measured for calm water (no waves produced) and for breaking waves. At each azimuth angle of observation during POEWEX ’02, i.e. 0º, 45º, 90º and 180º, brightness temperatures were measured at incidence angles of 45º, 53º and 60º. The radiometers were positioned so that the slant range to the water surface was always 12 m.

Physical measurements were used to verify that the general features of the breaking waves in the wave basin were similar to those in the open ocean. The bubble size spectrum measured in the wave basin was compared to an oceanic bubble size spectrum reported by Deane and Stokes [9], showing excellent agreement between the two data sets over the size range of 0.3 mm to 3 mm. This suggests that the bubble populations generated by the breaking waves in the wave basin were comparable to those on the open ocean. Similarly, the time series of void fraction, V_F, measured by the two void probes exhibited the expected decrease in V_F with increasing depth, but more importantly, the maximum value measured by the shallower probe, i.e. 25%-30%, agrees well with previous measurements made by Lamarre and Melville [10] and Deane [11]. The agreement in bubble size spectrum and the similarity in void fraction between the breaking waves in the wave basin and those on the ocean suggest that similar radiometric emission would be expected from breaking waves in both cases.

Results of the POEWEX ’02 experiment were used to estimate the effect of breaking waves and foam on brightness temperatures measured by a satellite microwave radiometer at low to moderate wind speeds. Measurements of whitecap coverage with respect to wind speed provide empirical fit parameters to the Monahan and Lu [12] model for foam coverage. Since the WindSat accuracy requirement for wind direction is ±20º over 3-25 m/s, the 1-3 K peak-to-peak wind direction signal at these frequencies requires brightness temperature accuracies of approximately 0.1-0.3 K.

The increase in brightness temperatures due to breaking waves and foam is expected to affect wind direction retrievals significantly at or above 7 m/s wind speed. The effect of foam on brightness temperatures was shown to vary with azimuth angle. As a quantitative example, for the Stramska and Petelski model [13] of whitecap coverage, at a wind speed of 15 m/sec,

Figure 1. Microwave radiometers observing a breaking wave at the WindSat polarimetric frequencies (10.7, 18.7 and 37 GHz) at the OHMSETT wave basin during the POEWEX’02 experiment.

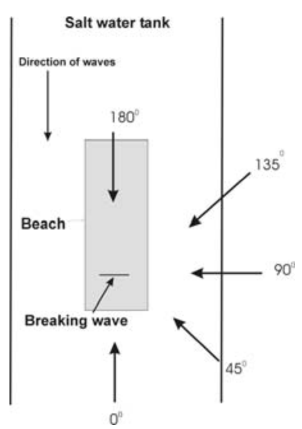

Figure 2. The five azimuthal viewing directions of the radiometers.

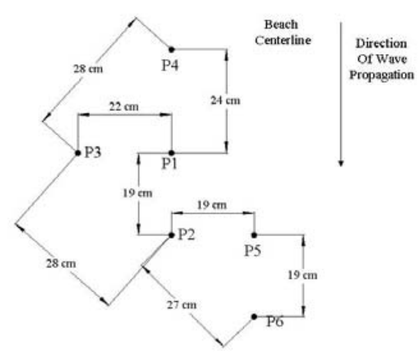

Figure 3. The position of the pressure transducers in the wave tank.

the increase in the brightness temperatures measured by a spaceborne radiometer due to breaking waves is predicted to be 4.5 and 7 K at 10.8 GHz, and 3 K and 6 K at 37 GHz at vertical and horizontal polarization respectively, showing a significant frequency dependence.

POEWEX'04:

The POEWEX'02 measurements demonstrated that, in addition to the radiometric brightness temperature and foam fraction in the field of view, a number of additional physical parameters are required to obtain an accurate quantitative estimate of the azimuthal variation of the microwave emission from foam generated by breaking waves. Knowledge of the wave slope spectrum during wave breaking is required to characterize more fully the effects of the wave field and sea state on the increase in emission between a foam-free rough water surface and a partially foam-covered rough water surface. In addition, analysis of radiometric time series from the POEWEX'02 experiment showed that it is important to measure not only foam-free calm water but also foam-free rough water over a substantial length of time with no breaking waves in the field of view.

The Polarimetric Observations of the Emissivity of Whitecaps Experiment (POEWEX '04) was conducted during Nov. 2004 and focused on the characterization of azimuthal dependence of microwave emissivity of foam. The new measurements during POEWEX'04 included horizontal and vertical polarized brightness temperatures at 6.8 GHz, roughened surface emission with no breaking waves in the field of view and foam thickness. In addition, slope modulation due to gravity waves was measured using a 2-D array of pressure transducers (Fig. 3) to measure the instantaneous wave field in the radiometers' field of view.

Microwave radiometers at 6.8, 10.7, 18.7 and 37 GHz were suspended below the basket of a boom-lift crane and positioned to view the water surface at azimuth angles of 0˚, 45˚, 90˚, 135˚ and 180˚ and incidence angles of 45˚, 53˚ and 65˚. The fractional area foam coverage in the field of view of the radiometers was found by analyzing the bore-sighted video measurements using the grayscale method of Asher and Wanninkhof [14]. This involves measuring the fraction of pixels in the field of view of the radiometer antennas that exceed the brightness threshold distinguishing the breaking wave from the water background. The resulting fractional area foam coverage may include both actively breaking crests and decaying bubble plumes, and is called the foam fraction here for brevity.

RESULTS:

Pressure transducer power spectra (Fig. 4) show that the large-scale wave field in the wave tank was consistent from day to day. The average video brightness of the area sampled by the void probe at 10 cm depth peaks ~1 sec before the peak measured by the void probe, as shown in Fig. 5. In addition, the void fraction enhancement is significantly shorter in duration than the video brightness enhancement. Therefore, an increase in optical brightness due to foam must be principally due to foam on the surface.

Fig 6 shows increase in horizontal (left) and vertical (right) emissivities at all frequencies due to foam. The increases in emissivity vary as a function of azimuth angle, and this variation is more significant for horizontal polarization than for vertical polarization.

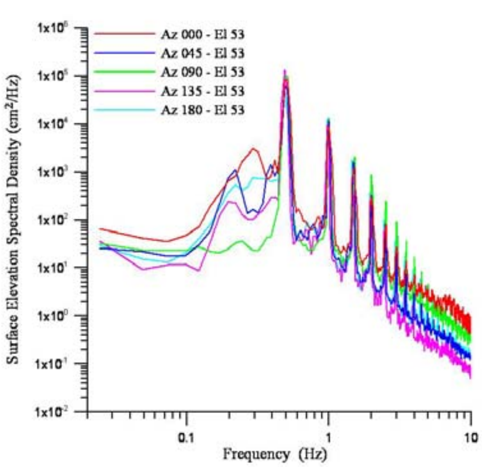

Figure 4. Surface elevation spectral density measured by the pressure transducers.

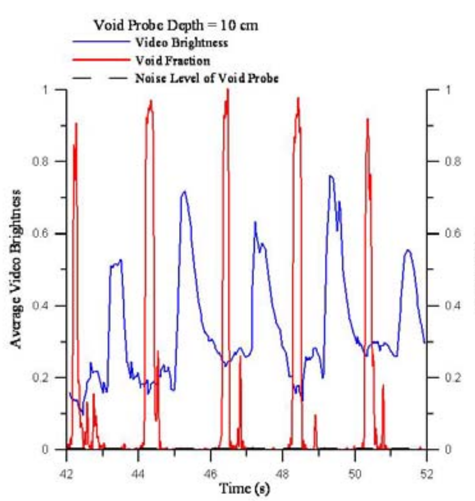

Figure 5. Average video brightness sampled by the void probe at 10 cm depth.

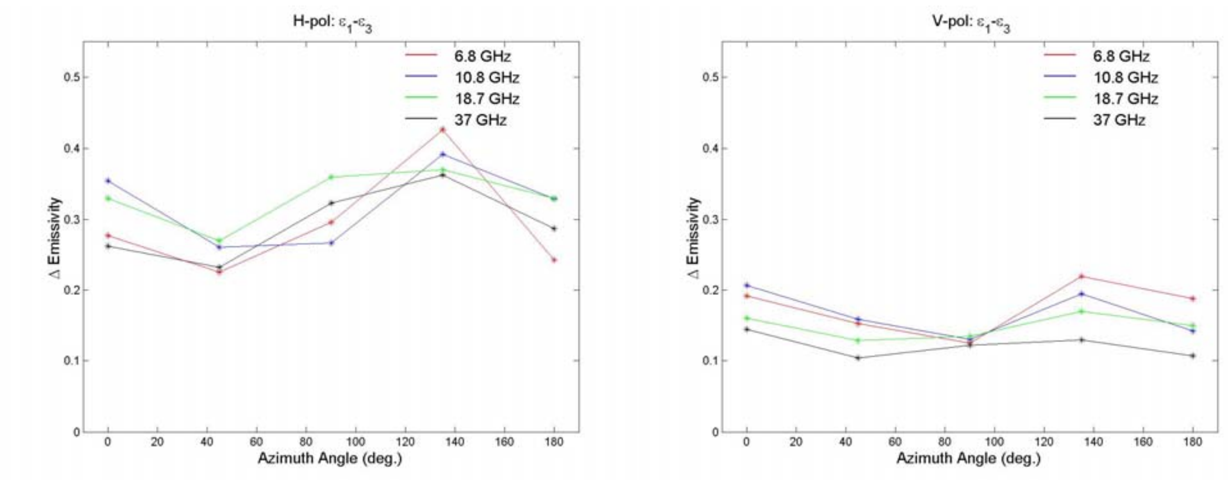

Figure 6. The increase in emissivity due to foam at horizontal (left) and vertical (right) polarizations as a function of azimuth angle at all frequencies.

Additionally, it was observed that the mean and azimuthal variations of the increases in the emissivity vary with frequency. For the increases in emissivity measured at 6.8, 10.7, 18.7 and 37 GHz, the azimuthal variations as a percentage of the mean vary from 13.3% to 25.1% for vertical polarization and from 11.4% to 44.7% for horizontal polarization.

The azimuthal averages of the increases in emissivities from POEWEX'04 measurements were also used to estimate the brightness temperature expected to be measured by a satellite radiometer. The estimated increases in brightness temperatures were significant at wind speeds greater than 7 m/s.

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