Azimuthal Variation of the Microwave Emissivity of Foam

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Introduction: Successful naval operations require excellent knowledge of the ocean wind speed and direction. In addition, the global ocean wind vector is a key element for weather forecasting and for climate and oceanography studies. WindSat, a satellite-borne multifrequency polarimetric microwave radiometer developed by the Naval Research Laboratory, has demonstrated the ability to remotely sense the global ocean wind vector from space.[1] The wind direction signal measured by WindSat is about two orders of magnitude smaller than the background scene, and only a little larger than the radiometer noise floor. Therefore, any small uncertainties in the geophysical model used to retrieve the wind direction will introduce errors in the retrieved wind vector. One such uncertainty is the contribution of sea foam on the wind direction signal.

Down-looking radiometers, such as WindSat, receive energy emitted from the ocean surface and the atmosphere. The energy from the ocean surface, quantified as the brightness temperature, is related to surface physical temperature by

$$T_B = e_S \cdot T_W,$$

where T_B is the brightness temperature, T_W is the physical temperature of ocean water surface, and e_S is surface emissivity, which depends on the measurement frequency, polarization, incidence angle, and the azimuth angle between wind direction and the direction from which observations are made. The emissivity of the sea surface also depends on physical properties of the water surface such as temperature, salinity, and surface roughness, which is primarily wind-driven.

The presence of foam and roughness created by wind and breaking waves greatly increases the surface emission at microwave frequencies. The surface emissivity is sometimes written as

$$e_S = f \cdot e_F + (1 - f) \cdot e_R,$$

where f is the fraction of the surface covered with foam, e_F is the emissivity of foam, and e_R is the emissivity of the foam-free, rough water surface.

Past studies of e_F have focused on incidence angle, frequency, and polarization dependencies.[2] To better understand the azimuthal dependence of e_F, we conducted the Polarimetric Observations of the Emissivity of Whitecaps EXperiment (POEWEX) in 2002 and 2004. POEWEX involved simultaneous radiometric and video measurements of breaking waves at microwave frequencies of 6.8, 10.8, 18.7, and 36.5 GHz, which match those used by WindSat.

Outdoor Wave Tank Experiment: Since breaking waves and foam on the open ocean are intermittent and highly variable, POEWEX was conducted under controlled conditions in the Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) in Leonardo, New Jersey.[3] The outdoor saltwater wave tank uses a mechanical wave generator to produce waves with a period of about 2 s. An artificial shoal in the center of the tank causes reproducible breaking waves at the same location. In situ physical measurements with an underwater video camera and conductivity probe agreed well with similar measurements of breaking waves in the ocean. Thus, the radiometric emission observed in the wave tank is representative of that from breaking waves in the open ocean.

Figure 4 shows the experimental setup, with the radiometers suspended beneath the cradle of a boom-lift crane observing a breaking wave. The drawing in Fig. 4 shows the five azimuth angles from which observations were made. A video camera bore-sighted with the radiometers provided video images from which the fractional coverage of foam in the radiometer field of view (FOV) was determined.

Results: Figure 5 presents results at 53 deg incidence angle and 90 deg azimuth. The upper part of the figure shows video images of the breaking waves. The artificial shoal creating the breaking point is seen as a black rectangle, and overlaid circles define the radiometer FOVs. The lower part of Fig. 5 plots time series of the antenna temperatures at 10.8, 18.7, and 36.5 GHz for the vertical (red) and horizontal (blue) polarizations and for the foam fraction (yellow). Maximum and minimum values of antenna temperature and foam fraction can be seen at approximately 2.5 and 4 s, respectively. By observing the radiometer antenna temperatures for the two cases when the foam fraction is maximum and minimum, the foam emissivity can be expressed as[3]

$$e_F = \frac{(1 - f_2)\,(Ta_1 - T_{sky}) - (1 - f_1)\,(Ta_2 - T_{sky})}{(f_1 - f_2)\,(T_W - T_{sky})}.$$

Here Ta_1 and Ta_2 are, respectively, the maximum and minimum values of antenna temperature when the

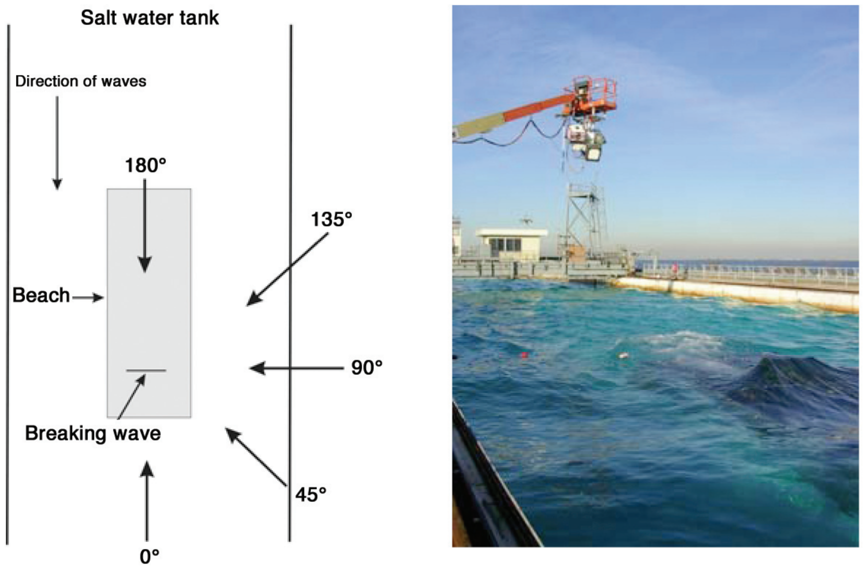

FIGURE 4
On the right: radiometers observing waves at OHMSETT. On the left: drawing showing azimuth angles from which observations were made.

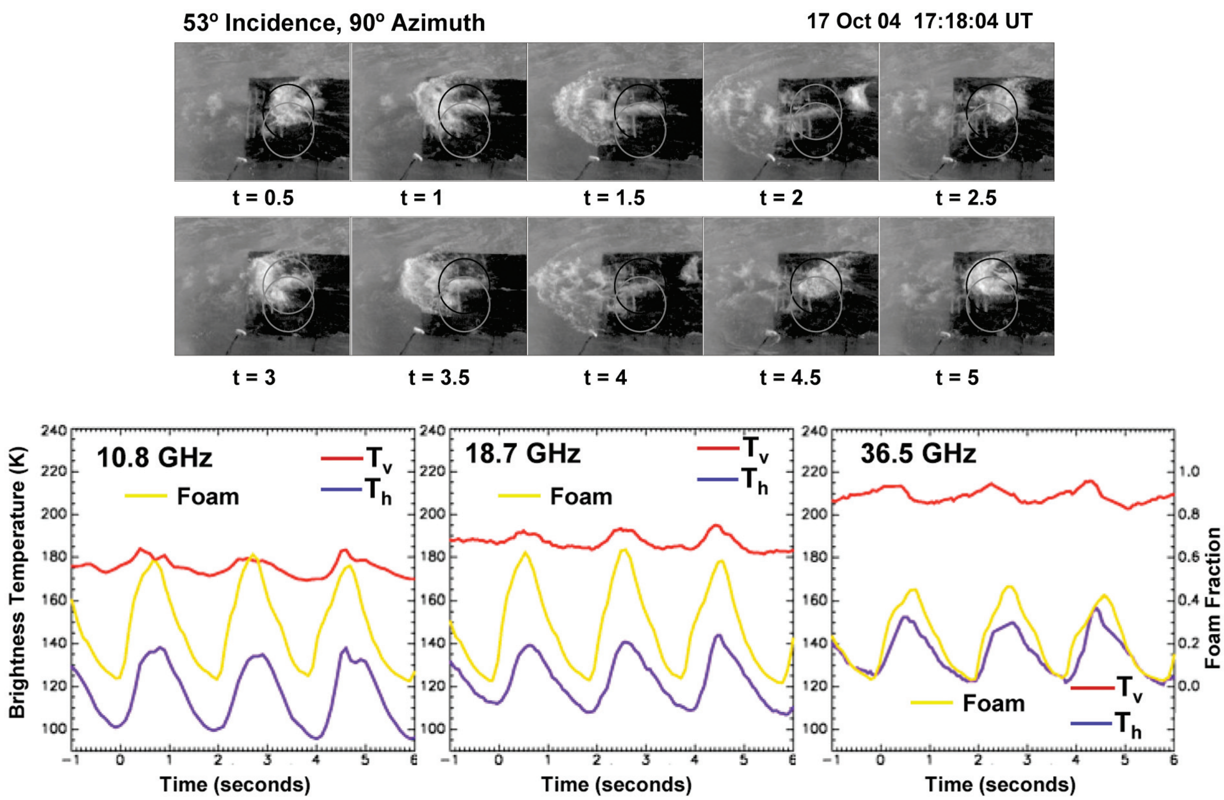

FIGURE 5
Video images of breaking waves on the shoal in the outdoor test tank and plots of antenna temperature and foam fraction vs time.

breaking wave is in the FOV on the shoal, f_1 and f_2 are the foam fractions corresponding to the maximum and minimum values of antenna temperature, and T_{sky} is the brightness temperature of downwelling sky radiation.

Figures 6 and 7 show the emissivity of foam at an incidence angle of 53 deg as a function of azimuth angle for all four frequencies in the vertical and horizontal polarization. At all frequencies, both plots show variation of emissivity with azimuth angle, but the

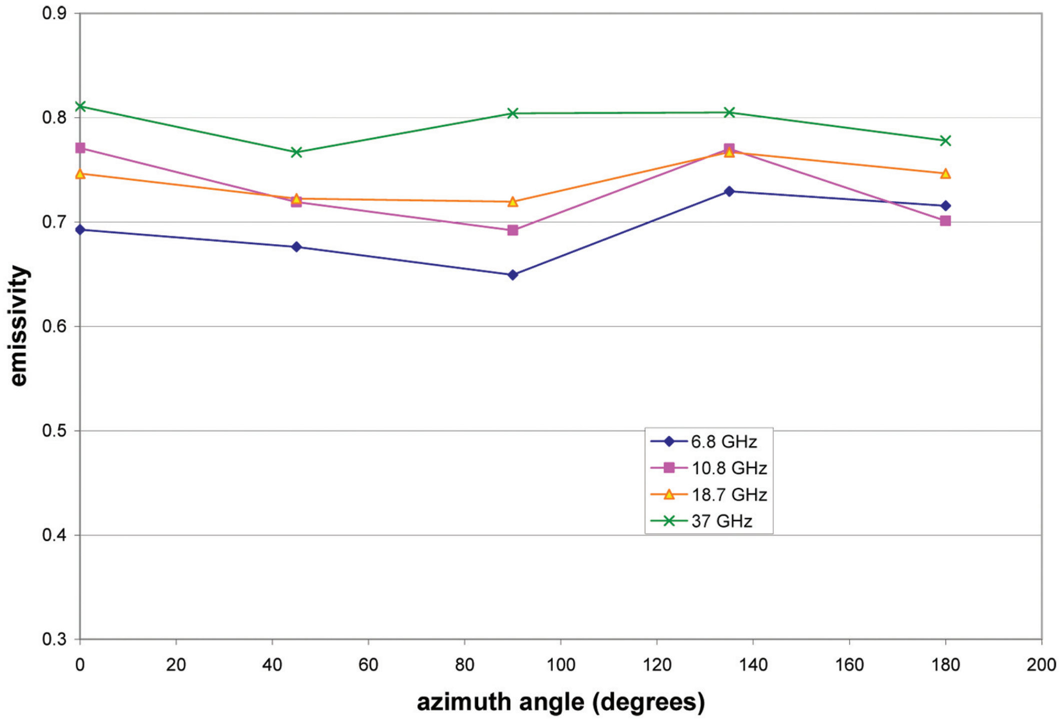

FIGURE 6
Foam emissivity vs azimuth angle, vertical polarization.

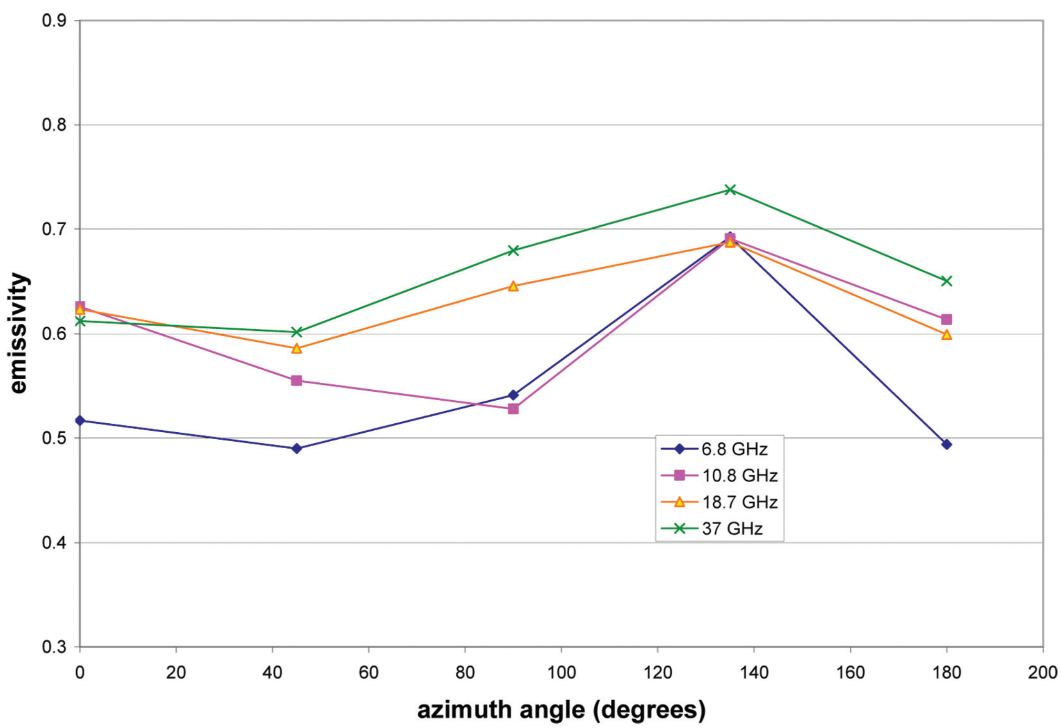

FIGURE 7
Foam emissivity vs azimuth angle, horizontal polarization.

variation is more pronounced for the horizontal polarization. This is the first experimental evidence of an azimuthal variation in foam emissivity.

Azimuthal variations in foam emissivity are most probably explained by the asymmetric distribution of foam on the wave slopes. Newly formed foam on the forward face of the wave covers much less area than the decaying foam in the wave's trough. Although perhaps not as dominant, some contribution to the azimuthal asymmetry of foam emissivity may also come from the different thickness of new and old foam. We continue to investigate these effects. Characterizing the azimuthal dependence of the microwave foam emissivity has the potential to improve the accuracy of wind vector retrievals from physically based algorithms.

[Sponsored by IPO]

References

[1] P.W. Gaiser, et al., "The WindSat Spaceborne Polarimetric Microwave Radiometer: Sensor Description and Early Orbit Performance," *IEEE Trans. Geosci. Rem. Sens.* **42**, 2347-2361 (2004).

[2] L.A. Rose, et al., "Radiometric Measurements of the Microwave Emissivity of Foam," *IEEE Trans. Geosci. Remote Sens.* **40**(12), 2619-2625 (2002).

[3] S. Padmanabhan, et al., "Effects of Foam on Ocean Surface Microwave Emission Inferred from Radiometric Observations of Reproducible Breaking Waves," *IEEE Trans. Geosci. Rem. Sens.*, WindSat Special Issue (Feb. 2006). ★