Parameterization of Microwave Emission due to Foam to Improve the Accuracy of Satellite-based Retrieval Algorithms

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Abstract—**WindSat, the first polarimetric microwave radiometer on orbit, has as its primary objective the demonstration of robust retrieval of the sea surface wind vector from measured brightness temperatures. The ocean surface wind vector is one of the key environmental data records for the NPOESS Conical Microwave Imager/Sounder (CMIS) instruments, first planned for launch in 2009. To date, aircraft and satellite measurements, as well as modeling results, indicate that brightness temperature variations with wind direction are small, on the order of 1-3 K peak-to-peak. Therefore, quantitative understanding of the dependence of the ocean surface emissivity on properties such as surface roughness and wave breaking is critical for wind vector retrieval. Despite the importance of this, some basic physical properties such as the azimuthal angle dependence of the microwave emission from foam have not been well characterized to date. Recent measurements from the R/P FLIP indicated that the increase in ocean surface emission due to breaking waves may depend on both the incidence and azimuthal angles. The need to quantify this dependence motivated systematic measurement of the emissivity of reproducible breaking waves at varying incidence and azimuthal angles. Results from these recent field measurements provide the first parameterization with wind speed of the change in brightness temperatures due to breaking waves.**

Keywords-microwave radiometer; ocean surface; wind vector; foam; breaking waves; microwave emissivity

I. INTRODUCTION

WindSat, the first polarimetric microwave radiometer on orbit, was launched in January 2003 as a proof-of-concept for retrieval of the full sea surface wind vector using passive microwave remote sensing. The NPOESS Conical Microwave Imager/Sounder (CMIS), planned for first launch in 2009, is designed to retrieve the ocean surface wind vector as one of its six key environmental data parameters. Aircraft and satellite measurements have indicated that the wind direction dependence of brightness temperatures is small, on the order of 1-3 K 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 excess microwave emission due to wind speed as an aggregate effect of both surface roughness and sea-foam [5]. To consider these two effects separately, several experimental studies were designed and conducted to measure the enhancement in sea surface microwave emission due to foam.

Recent experimental investigations by the authors have provided new quantitative information on excess microwave emission due to breaking waves. In the first experiment, a 3 m x 6 m foam generator suspended just below a calm water surface on the Chesapeake Bay produced uniform foam coverage that nearly filled the fields of view of two microwave radiometers at 10.7 and 37 GHz [6-7]. Results of radiometric measurements at incidence angles from 30˚ to 60˚ showed that the emissivity of foam in this experiment was greater than ~0.9 at vertical polarization, and decreased with incidence angle from ~0.9 to ~0.75 at horizontal polarization. The foam emissivity was observed to be similar at X-band and Ka-band. However, these measurements of foam on calm water did not include the dynamics of whitecap evolution or the modulation due to long wave slopes during wave breaking. In addition, they did not measure the dependence of the emissivity of foam on azimuthal angle with respect to the direction of wave breaking.

The need to improve retrieval of wind speed and direction from WindSat and the upcoming NPOESS Conical Microwave Imager Sounder (CMIS) through more accurate forward modeling of sea surface emission, as well as to study the effects of air-sea interactions, motivated the passive microwave component of the Fluxes, Air-Sea Interaction and Remote Sensing (FAIRS) Experiment [8]. Passive polarimetric observations were performed from the R/P FLIP at wind speeds of up to 16 m/s with concomitant large scale breaking waves. The FAIRS experiment lasted for 27 days in the northeastern Pacific Ocean, where FLIP started at 36.96˚ N, 123.60˚ W and was allowed to drift freely, ending at 34.83˚ N, 123.25˚ W. The data from the FAIRS experiment suggest that emission due to foam depends strongly on incidence and/or azimuth observation angles. However, it was also found that the intermittency of breaking waves on the open ocean makes it difficult to acquire reproducible measurements of beam-filling foam, which are necessary to form useful conclusions about the look angle dependence of emission due to breaking waves. Understanding how breaking waves and foam affect microwave emissivity is critical to improving retrieval of wind direction from passive microwave observations.

II. EXPERIMENT DESCRIPTION

Because of the difficulties in performing oceanic radiometric measurements, the authors focused on systematic measurements of the microwave emission from waves in a wave basin that were made to break in a reproducible location. This experiment, the Polarimetric Observations of the Emissivity of Whitecaps EXperiment (POEWEX), was conducted during October 2002 at the OHMSETT wave basin in Leonardo, NJ [9-10]. OHMSETT is a 200 m long by 20 m wide by 2.4 m deep wave basin filled with saltwater with a concentration of 35 ppt. A shoal was designed and built to cause waves to break in the same location every 1-2 seconds.

Radiometric measurements were performed at X-band (10.7 GHz), K-band (18.7 GHz) and Ka-band (37 GHz) of both calm water (no waves produced) and breaking waves at each incidence and azimuthal angle combination. Simultaneous optical imagery was recorded using a bore-sighted video camera to measure the fractional foam coverage in the radiometers' fields of view. The bubble size spectra and thickness of the foam covering the water were characterized using an underwater video camera. Void fraction probes measured the total volume of air entrained by the breaking waves. Wave heights and subsurface turbulence were measured using pressure transducers and acoustic Doppler velocimeters, respectively. Relative changes in the small-scale roughness features of the water surface were measured using a 14-GHz scatterometer mounted at an incidence angle of 70 degrees. These measurements of foam, roughness, and breaking wave properties, along with radiometric measurements, are needed to bound emission and scattering electromagnetic models, as in Chen et al. [7].

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 [11]. This procedure measures the fraction of pixels in the field of view of the antenna that exceed a brightness threshold. This result is the fraction of the radiometer's field of view covered by breaking waves, which may include both actively breaking crests and bubble plumes. In this paper, the result is called the foam fraction for brevity.

External calibrations using liquid nitrogen and ambient loads were performed before and after each set of radiometric measurements. Tipping curves were used to infer the cosmic background temperature as an additional calibration reference. The K-band and Ka-band radiometers measured internal noise sources and matched loads every 45 seconds to correct for gain fluctuations due to small changes in the internal temperature of the systems. Calm water observations were performed before each set of breaking wave measurements to validate the calibration by comparing the measured data with the Ellison et al. [12] and Klein and Swift [13] models of calm water emissivity.

III. EXPERIMENT RESULTS

To obtain the measured antenna temperatures due to surface emission, the reflected atmospheric downwelling radiation was removed using the method described by Rose et al. [6]. The precise fields of view of the three radiometers were calculated using the 90˚ power beamwidths of their respective antenna patterns.

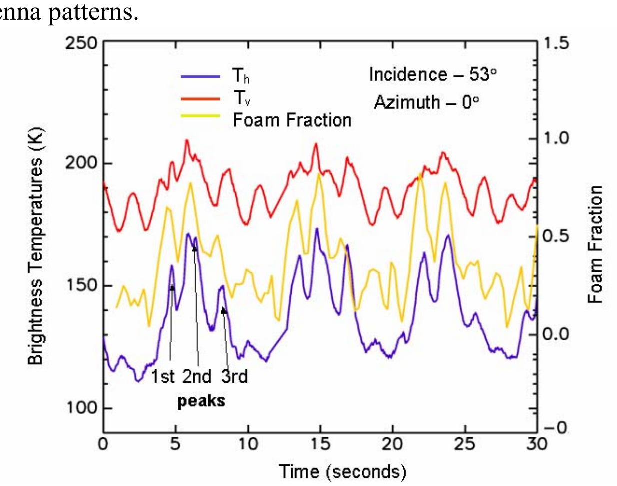

Figure 1. Radiometric brightness temperature at 19 GHz of groups of breaking waves measured at an incidence angle of 53º and azimuthal angle of 0º (looking into the direction of breaking) during POEWEX.

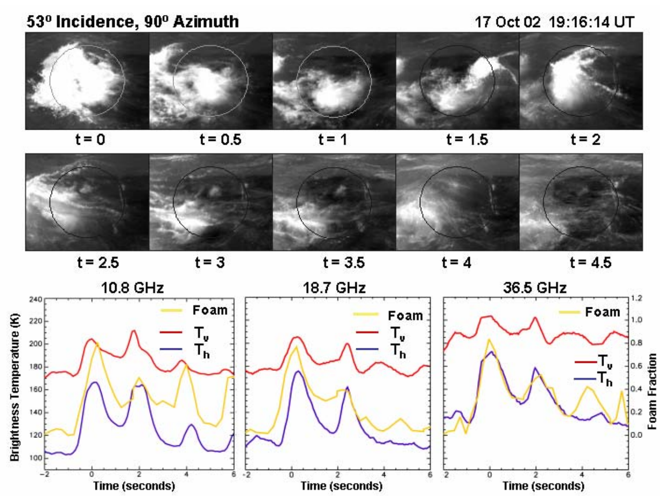

Figure 2. The top panel shows a time series of video images at a rate of 2 Hz with one of the boresighted radiometers' fields of view shown by an ellipse. The bottom panel shows the time series of vertical (red) and horizontal (blue) brightness temperatures and foam fraction in the field of view (yellow), at frequencies of 10.8, 18.7 and 37 GHz at an incidence angle of 53º and an azimuth angle of 90º. The t=0 on the lower time axes corresponds to the time of the top left video image.

In this experiment, the seiche modes of the tank caused two or three breaking waves to occur in succession, followed by a delay of 3-4 seconds. Fig. 1 shows an example time series observed at an incidence angle of 53˚ and azimuth angle of 0˚. An azimuth angle of 0º was defined as looking into the breaking wave, and 180º as opposite to the direction of wave breaking. The red and blue curves in Fig. 1 show the measured vertical and horizontal brightness temperatures measured at 19 GHz, respectively, while the yellow curve is the foam fraction in the field of view. In Fig. 1, T_h is more closely correlated with foam fraction than T_v. This was found to be true for all azimuth angles and frequencies measured, as was expected because of two effects. First, Rose et al. [6] show that the increase in emissivity from a calm water surface to beam filling foam is larger for T_h than T_v. Second, the reduction in the local incidence angle by the front face of gravity waves decreases T_v and increases T_h. Therefore, during the initial stages of the wave breaking process the effect of the increasing foam coverage on T_v is partially mitigated by the effect of the long wave slope. These two effects both contribute to a smaller increase in T_v as compared to the increase in T_h during wave breaking.

Fig. 2 shows an example of a group of breaking waves observed at 53º incidence and 90º azimuthal angle. The lower plots in the figure represent the radiometric measurements, showing vertical (red) and horizontal (blue) brightness temperatures in comparison to fractional foam coverage in the field of view (yellow), and the upper images show the video measurements, recorded at a rate of 4 Hz, with every other image shown. We observe that the brightness temperature peaks at t=0 sec due to a wave breaking in the field of view and subsequently decays until t=1 sec. A second wave breaks in the field of view at t=2 sec, and the brightness temperature decays until t=3 sec. For all of the breaking wave measurements, the correlation coefficient between the increase in brightness temperature and the foam fraction in the field of view was found to be larger for the first peak than for second and third peaks. The first peak was expected to be more highly correlated since it was least affected by previous breaking waves. Therefore, only the first peak in each group of breaking waves was used to study the azimuthal dependence of the emissivity of foam.

In order to calculate the increase in brightness temperatures due to breaking waves in the field of view, a baseline temperature, i.e. the brightness temperature of the water surface minimally affected by breaking waves, was needed. In each case, the baseline was determined by finding the minimum measured brightness temperature before each group of breaking waves, following a 3-4 second delay, as described previously. This baseline brightness temperature was similar to the calm water brightness temperature. The increase in brightness temperature at all three frequencies was calculated from measurements of approximately 30 "first peaks" at each azimuth angle, i.e. 0º, 45º, 90º and 180º. Figs. 3 and 4 show the increase in brightness temperatures due to foam (as defined earlier) as a function of the foam fraction in the field of view at horizontal and vertical polarizations, respectively. The increase in brightness temperature at 10 GHz for all azimuth angles is greater than that at 19 and 37 GHz.

IV. DISCUSSION

When measuring the emissivity of breaking waves using a microwave radiometer, the change in the brightness

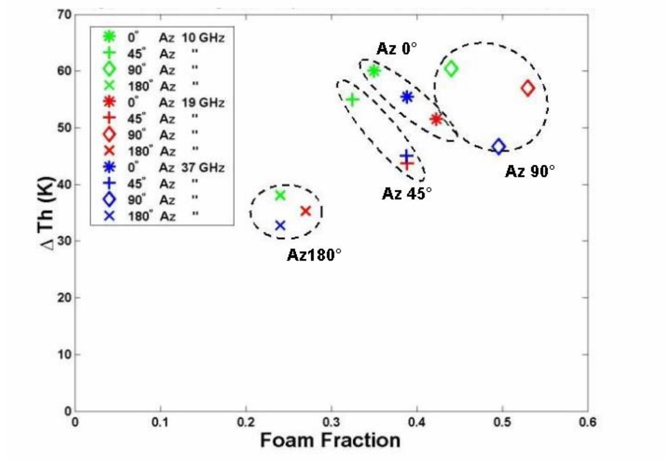

Figure 3. Measured increase in horizontal brightness temperature due to foam for three different frequencies and at four azimuth angles, all at 53º incidence angle.

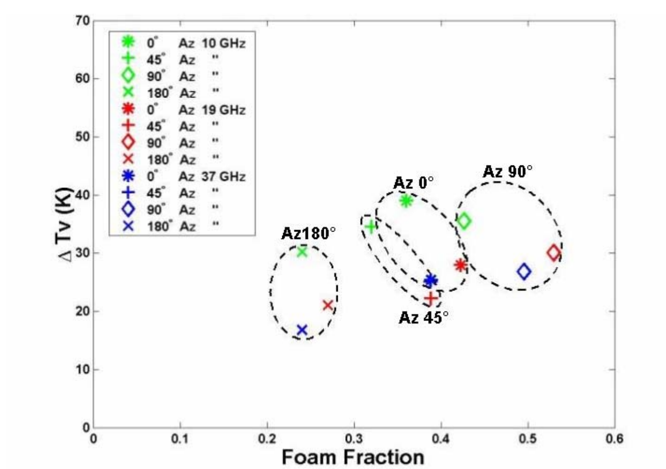

Figure 4. Same as Figure 3 except for vertical polarization.

temperature includes effects of both actively breaking crests and decaying bubble plumes. Wind speed and wind stress significantly affect the fraction of the sea surface covered by actively breaking crests and decaying bubble plumes. For low to moderate wind speeds, fractional-area whitecap coverage can be parameterized as an approximately cubic dependence on wind speed [14]. A series of measurements from ships and the R/P FLIP showed very good agreement with the Monahan and Lu model and provided a fit for the physical constants as

$$f = 3.5 \cdot 10^{6} (U_{10} - 0.6)^{3} \quad (1)$$

where f is the foam fraction and U_{10} is the wind speed measured at 10 m height. The increase in brightness temperature shown in Figs. 3 and 4 is azimuthally averaged and normalized to 100% foam coverage. This increase for 100% foam coverage is multiplied by the foam fraction predicted by (1) to obtain the predicted increase in brightness temperature due to foam as measured by a space-borne radiometer at 53º incidence at 10, 19 and 37 GHz, as shown in Figs. 5, 6 and 7, respectively.

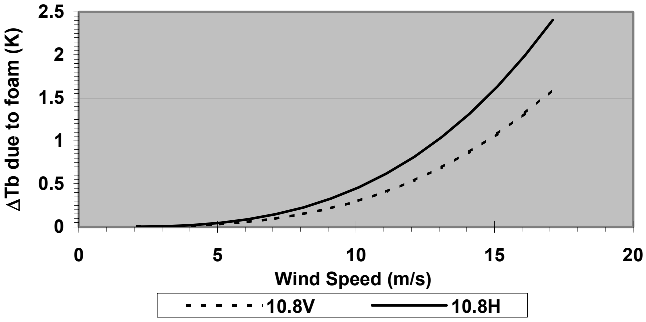

Figure 5. The increases in brightness temperatures at 10.8 GHz expected to be measured by a spaceborne radiometer, at low-to-intermediate wind speeds.

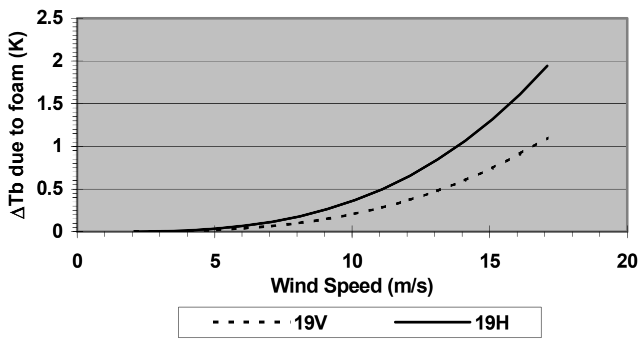

Figure 6. Same as Figure 5 except at 19 GHz.

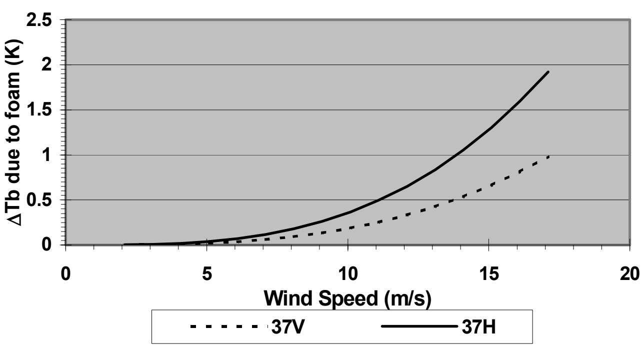

Figure 7. Same as Figure 5 except at 37 GHz.

V. SUMMARY

Radiometric and video observations of mechanically generated reproducible breaking waves during POEWEX show that the increase in brightness temperature due to breaking waves changes with azimuthal angle. As a quantitative example, at a wind speed of 15 m/sec, approximately 1% of the sea surface is found to be covered with foam, and the increase in the brightness temperatures measured by a spaceborne radiometer due to breaking waves is expected to be approximately 0.7—1.0 K at vertical polarization and 1.3—1.6 K at horizontal polarization at 10, 19 and 37 GHz, with a small but significant variation with frequency.

ACKNOWLEDGMENT

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