PASSIVE POLARIMETRIC REMOTE SENSING OF THE OCEAN SURFACE: THE EFFECTS OF SURFACE ROUGHNESS AND WHITECAPS*

Steven C. Reising$^{(1)}$, William E. Asher$^{(2)}$, L. Allen Rose$^{(3)}$ and Mohammed A. Aziz$^{(1)}$

$^{(1)}$University of Massachusetts, 113 Knowles Engineering Building, Amherst, MA 01003-4410 USA
$^{(2)}$University of Washington, 1013 NE 40th St., Applied Physics Laboratory, Seattle, WA 98105 USA
$^{(3)}$ Naval Research Laboratory, Remote Sensing Division, Washington DC 20375 USA

ABSTRACT

Foam on the ocean surface significantly increases the brightness temperatures measured by microwave radiometers. Previous results have shown that the microwave emissivity of foam on a calm water surface is significantly less than one and depends upon polarization and incidence angle. Recent radiometric and video observations of large-scale breaking waves from the R/P FLIP during the FAIRS experiment show that the emissivity of whitecaps evolves temporally and is not constant in time. Predicted changes in brightness temperatures measured by spaceborne radiometers due solely to the presence of foam are sufficiently large to significantly affect wind direction retrievals from polarimetric radiometers.

INTRODUCTION

With its upcoming launch, WindSat will be the first spaceborne polarimetric microwave radiometer. It was developed by the U.S. Navy and the National Polar-Orbiting Environmental Satellite System (NPOESS) Integrated Program Office to demonstrate the viability of measuring the ocean surface wind vector using passive polarimetry. The WindSat sensor includes three polarimetric channels at 10.7, 18.7 and 37.0 GHz, as well as two dual-polarized channels at 6.8 and 23.8 GHz. Due to the increased retrieval accuracy required to measure wind direction at the ocean surface, this instrument motivates a renewed interest in quantitative determination of the relationship between the wind vector and surface microwave emission.

Foam on the ocean surface increases the brightness temperature measured by a microwave radiometer and is a key component of the wind speed signal measured by a horizontally or vertically polarized radiometer, such as the Special Sensor Microwave Imagers (SSM/I) aboard the DMSP satellites. Accordingly, the accurate models of sea foam emissivity are needed in order to achieve accurate retrievals using physically-based algorithms. Although the microwave emissivity of the sea surface is known to depend upon surface roughness and foam coverage, the exact form of this dependence has not been determined, primarily because of the difficulty of acquiring time series of radiometric data with concurrent measurements of the relevant air-sea interaction parameters.

PREVIOUS RESULTS

Our previously reported results include measurements of the microwave emissivity of foam conducted at the Naval Research Laboratory's Chesapeake Bay Detachment using radiometers operating at 10.8 and 36.5 GHz [1,2]. These measurements were performed at incidence angles from 30º to 60º. Foam was generated on the surface by blowing compressed air through a matrix of gas-permeable tubing supported by an aluminum frame and floats. Video micrographs were used to measure bubble size distribution and foam layer thickness. A video camera was boresighted with the radiometers to determine the beam-fill fraction of the foam generator. The results showed that foam emissivities were greater than 0.9 at vertical polarization, and relatively constant over the range of incidence angles measured. The emissivities at horizontal polarization showed a gradual decrease from approximately 0.9 to 0.8 as the incidence angle increased from 30º to 60º.

RECENT MEASUREMENTS

The foam generator experiment provided measurements of the emissivity of foam on a calm water surface [1,2], but provided no information on the time dynamics of whitecap evolution and the modulation of sea surface slopes during wave breaking. As a first step to fulfill this objective, in September and October 2000, the Fluxes, Air-Sea Interaction and Remote Sensing (FAIRS) experiment was conducted in the northeastern Pacific Ocean aboard the U.S. Navy's R/P

*This work was sponsored by the Department of the Navy, Office of Naval Research under Award #N0014-00-1-280 to UMass Amherst, Award #N00014-00-0152 to Univ. Washington, and Award #N0001400WX21032 to the Naval Research Laboratory.

FLoating Instrument Platform (FLIP). Because FLIP functions as a spar buoy of 120-m height with minimal platform motion, it was possible to acquire a long-term radiometric time series for use in studying the response in ocean surface microwave emission to changes in the environmental forcing functions.

Sea surface polarimetric microwave brightness temperatures were measured at X-band (10.8 GHz) and Ka-band (36.5 GHz) at incidence angles of 45º, 53º and 65º for wind speeds ranging from approximately 2 m/s to 15 m/s. Fractional-area whitecap and foam coverage in the field of view of both radiometers was measured using a boresighted video camera. In addition to the microwave and video data, air-sea interaction parameters such as sea-surface skin temperature and friction velocity were also observed. When combined, these data sets are well-suited for testing parameterizations of the sea surface microwave emissivity that include the effects of fractional-area foam coverage and surface roughness.

RESULTS

During FAIRS 2000, simultaneous radiometric and video measurements were recorded for several periods of actively breaking waves. Two cases are presented in this paper. In the first, a sequence of 1-Hz video images in Fig. 1 shows the evolution of a large-scale breaking wave. Fig. 2 shows the co-located X-band and Ka-band radiometric data during the same time period, at an incidence angle of 53º, and an azimuth angle of approximately 161° with respect to upwind. Even though the calibration of the horizontally polarized data at 10.8 GHz is not yet verified, these data demonstrate that the emissivity of a whitecap is not constant, and that the decaying foam patch left in the wake (at *t* = 6 sec) has higher emissivities at all polarizations than those of the actively breaking wave crest (at *t* = 1 sec). The decrease in emissivities at *t* = 4 sec is most likely caused by the partial filling of the radiometers' fields of view by foam.

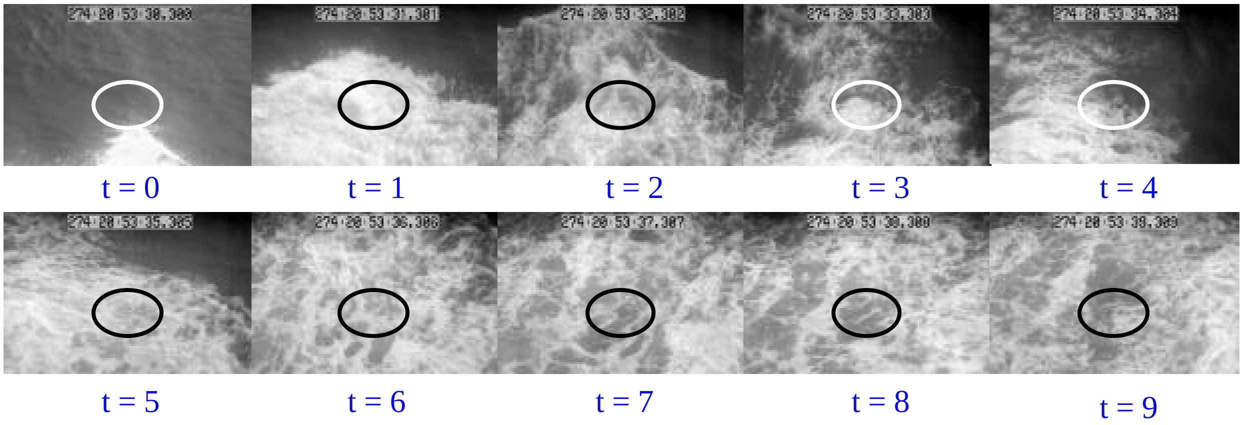

Fig. 1. Image sequence from the FAIRS experiment on 30 Sep 2000, showing a large whitecap propagating through the radiometers' field of view. The images were recorded at one-second intervals, at a wind speed of 13 m/s. The oval in the center depicts the approximate footprint of the microwave radiometers.

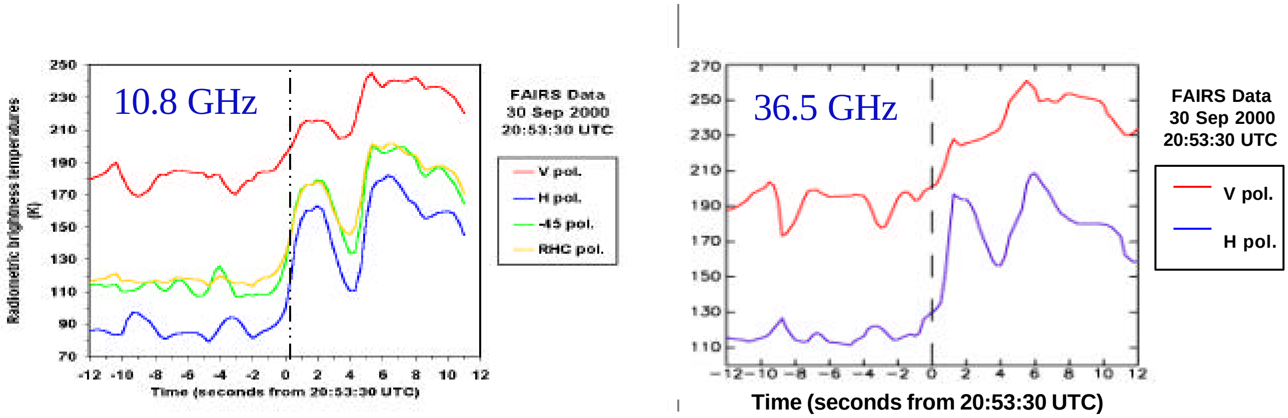

Fig. 2. Radiometric brightness temperatures at X-band (left) and Ka-band (right) over the same period (*t* = 0 to 9 s) as the image sequence in Fig. 1. The radiometers were pointed at 53º incidence and 161º azimuth angle.

A second case is illustrated in Figs. 3 and 4. Fig. 3 shows another breaking wave and subsequent decaying foam in the radiometers' fields of view. The Ka-band radiometric brightness temperatures at an incidence angle of 45º and an azimuth angle of approximately 280º are shown in Fig. 4 for the same time period. The similarities to the case in Figs. 1-2 are that the radiometric brightness temperatures increase during the actively breaking wave, decrease as the foam partially leaves the field of view, and again intensify during the decaying foam. However, in this case the decaying foam has lower emissivities than those of the actively breaking wave. These differences may be explained by an undetermined azimuth angle dependence, because of the 120º difference in azimuth of the radiometer with respect to the direction of wave breaking. Therefore, more data are needed to characterize precisely the dynamic nature of the microwave emissivity of breaking waves on the ocean.

Additional results were obtained by analyzing video images using the grayscale analysis procedure described by [3] for three geographically-diverse foam-coverage datasets at low-to-intermediate wind speeds. Results are shown in Fig. 5.

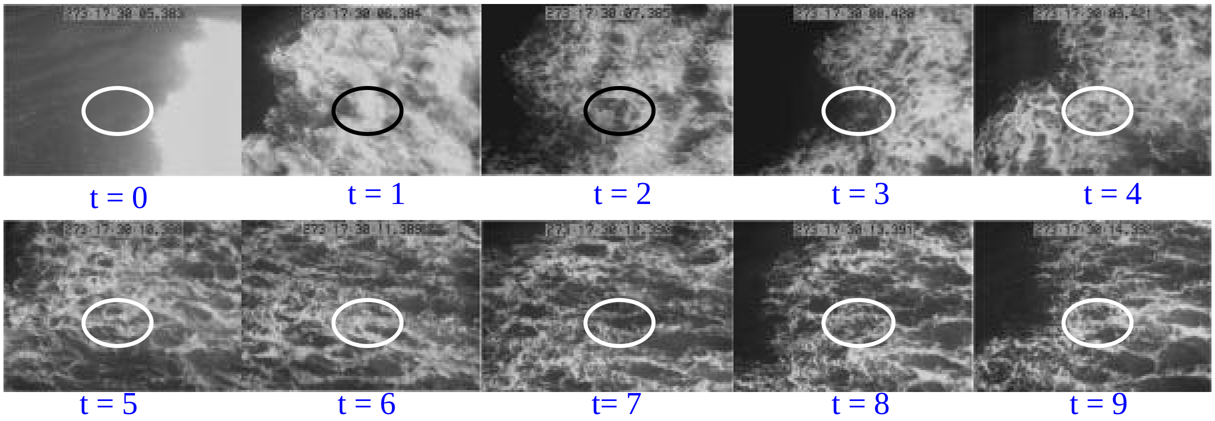

Fig. 3. Image sequence from the FAIRS experiment on 29 Sep 2000, showing a large whitecap propagating through the radiometers' field of view. The images were recorded at one-second intervals, at a wind speed of approximately 13 m/s. The oval in the center depicts the approximate footprint of the microwave radiometers.

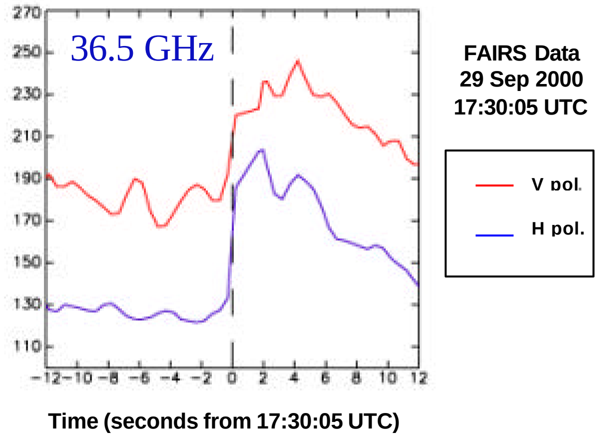

Fig. 4. Radiometric brightness temperatures at Ka-band over the same period (t = 0 to 9 s) as the image sequence in Fig. 3. The radiometer was pointed at 45º incidence and approximately 280° azimuth with respect to upwind.

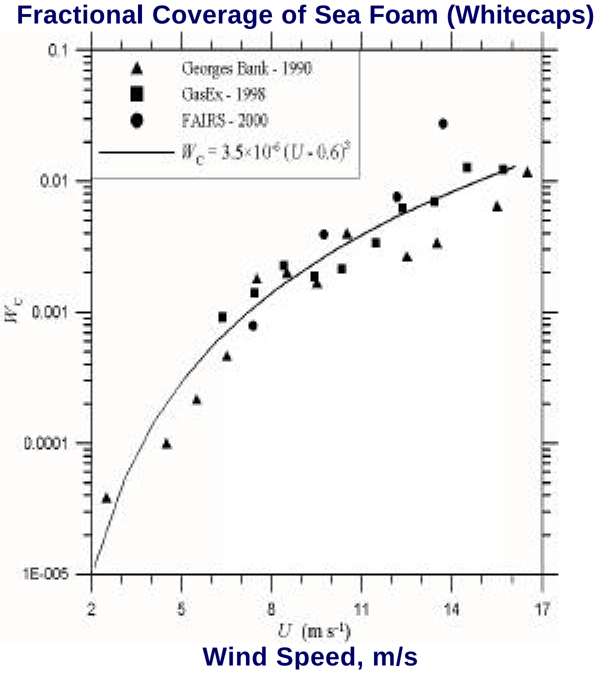

Fig. 5. The fractional coverage of sea foam observed from video images as a function of wind speed. Points show data obtained by Asher and colleagues [3], and the solid line shows a parameterization based on [4].

For these datasets, fractional-area whitecap coverage can be parameterized in terms of a cubic dependence on wind speed [4]. These parameterizations are expected to change significantly at higher wind speeds. However, for these low-to-intermediate wind speeds, the change in brightness temperature from no foam to full foam coverage observed in Fig. 2 for horizontal and vertical polarizations is multiplied by the foam coverage fraction shown in Fig. 5 to yield the expected increases in brightness temperatures due to foam alone, shown in Fig. 6, as measured by a spaceborne radiometer that averages over large spatial areas of the ocean surface.

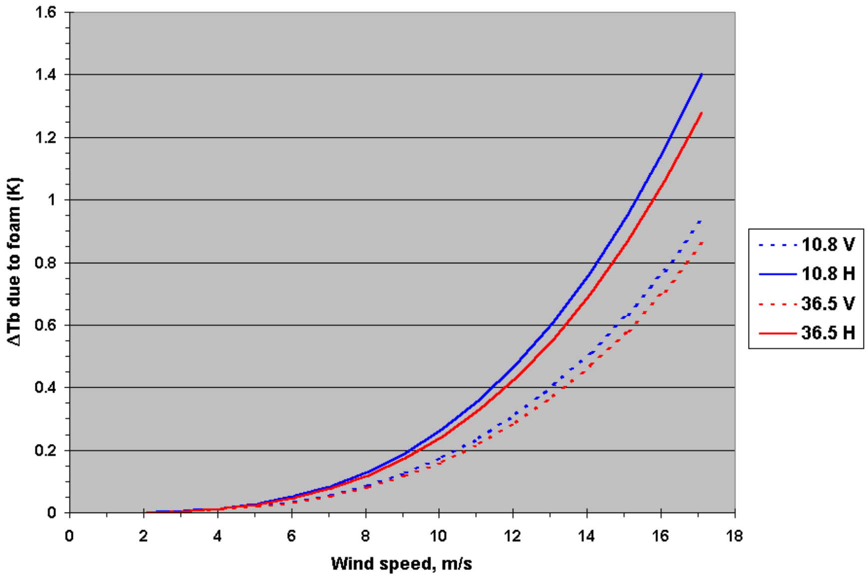

Fig. 6. The increases in brightness temperatures expected to be measured by a spaceborne radiometer, due solely to the presence of foam, at low-to-intermediate wind speeds. These values are calculated using the results shown in Figs. 2 and 5.

CONCLUSIONS

Radiometric and video observations of large-scale breaking waves from the R/P FLIP during the FAIRS experiment show that the emissivity of whitecaps evolves temporally and that it cannot be modeled accurately as a constant in time. In addition, grayscale analysis of video imagery of oceanic whitecaps show that for low-to-intermediate wind speeds, the fractional whitecap coverage can be parameterized as a cubic dependence on wind speed. At a wind speed of 15 m/s, brightness temperatures measured by spaceborne radiometers are expected to increase by approximately 0.5-1.0 K, depending on frequency and polarization. These changes are large enough to have a significant effect on the retrieval of wind direction from spaceborne polarimetric radiometers.

REFERENCES

[1] L.A. Rose, P.W. Gaiser, K.M. St Germain, D.J. Dowgiallo, W. Asher, S.C. Reising, K.A. Horgan, E.J. Knapp, and G. Farquharson, "Radiometric measurements of the microwave emissivity of foam," *Proc. 2001 Int. Geoscience and Remote Sensing Symp.*, Sydney, Australia, 2001.

[2] L.A. Rose, W. Asher, S.C. Reising, P.W. Gaiser, K.M. St Germain, D.J. Dowgiallo, K.A. Horgan, G. Farquharson, and E.J. Knapp, "Radiometric measurements of the microwave emissivity of foam," in press, *IEEE Trans. Geosci. Remote Sensing*, April 2002.

[3] W.E. Asher and R. Wanninkhof, "The effect of bubble-mediated gas transfer on purposeful dual gaseous-tracer experiments," *J. Geophys. Res.*, vol. 103, no. C5, pp. 10,555-10,560, 1998.

[4] E.C. Monahan and M. Lu, "Acoustically relevant bubble assemblages and their dependence on meteorological parameters," *IEEE J. Ocean. Eng.*, vol. 15, no. 4, pp. 340-349, 1990.