

A Detailed Study of the Effect of Breaking Waves on Microwave Polarimetric Emissivities

William E. Asher

Applied Physics Laboratory, University of Washington

1013 NE 40th Street

Seattle, WA 98105

phone: (206) 543-5942

facsimile: (206) 543-6785

e-mail: asher@apl.washington.edu

Award Number: N00014-00-1-0152

<http://www.apl.washington.edu>

LONG-TERM GOALS

Our long-term goals are to provide polarimetric microwave data that can be used to test models for predicting the microwave electromagnetic response of a foam-covered water surface and to develop better wind vector retrieval algorithms for satellite-mounted microwave radiometers.

OBJECTIVES

We will provide a detailed look at the physical processes affecting the microwave radiometric signal from breaking waves and foam patches by measuring the microwave polarimetric emissivity and microphysical structure of reproducible breaking waves in a saltwater surf pool.

APPROACH

Recent data have indicated that wind speed and direction can be measured using passive microwave radiometers [*Piepmeyer and Gasiewski*, 2001; *Wentz*, 1992; *Wick et al.*, 2000; *Yueh et al.*, 1999; *Yueh et al.*, 1997; *Yueh et al.*, 1995]. Multi-frequency radiometers are an attractive method for satellite-based wind measurements because they also provide estimates of sea surface temperature, sea-ice coverage, rain rate, water vapor concentration, and cloud water content. For this reason, the Office of Naval Research is the lead agency responsible for developing the WindSat microwave polarimeter satellite. WindSat is designed to provide a demonstration of the efficacy of measuring the wind vector by passive radiometry. Because the radiometric signals needed for retrieving the wind direction are only a few degrees Kelvin at most, accurate retrieval of vector wind fields from microwave radiometric data requires understanding how microwave emissivity is determined by ocean surface properties. It is also critical to understand how this emissivity varies as a function of azimuthal look angle of the radiometer with respect to the wind vector. Although it is known that the ocean surface emissivity is primarily a function of the surface roughness and the fractional area coverage of breaking waves and foam, the dependence of the emissivity of foam on both incidence angle and azimuthal angle have not been characterized.

In collaboration with Dr. L. A. Rose from the Naval Research Laboratory in Washington D.C. and Prof. S. Reising from the University of Massachusetts, we made a field experiments that have provided a more thorough understanding of the relationship between foam, breaking waves, surface roughness, and microwave emissivity. The first of these experiments was conducted in May 2000 on the

Report Documentation Page			Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 2002		2. REPORT TYPE		3. DATES COVERED 00-00-2002 to 00-00-2002	
4. TITLE AND SUBTITLE A Detailed Study of the Effect of Breaking Waves on Microwave Polarimetric Emissivities				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Applied Physics Laboratory, University of Washington,,1013 NE 40th Street,,Seattle,,WA, 98105				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Our long-term goals are to provide polarimetric microwave data that can be used to test models for predicting the microwave electromagnetic response of a foam-covered water surface and to develop better wind vector retrieval algorithms for satellite-mounted microwave radiometers.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 8	19a. NAME OF RESPONSIBLE PERSON
a REPORT unclassified	b ABSTRACT unclassified	c THIS PAGE unclassified			

Chesapeake Bay using a specially designed foam generator. The foam generator consisted of a 3-m $\times$ 7-m grid of gas permeable tubing mounted to an aluminum frame. The grid was suspended just below the water surface and compressed air was blown through the tubing. This generated a uniform, stable patch of foam on the water surface. A crane was used to position an X-band (10.8 GHz) and a Ka-band (36.5 GHz) radiometer over the foam raft so that the emissivity of beam-filling foam could be measured as a function of radiometer incidence angle. The data show that for all polarizations and incidence angles measured, the foam emissivity is significantly less than one, which implies that ocean surface foam should not be modeled as a blackbody with an emissivity of one [Rose *et al.*, 2002].

The foam raft allowed measurement of the polarimetric emissivities of beam-filling foam as a function of incidence angle at both X-band and Ka-band. However, these measurements were not designed to provide information on how the dynamics of whitecap evolution and modulation of surface slopes during wave breaking influence the emissivity of foam. They also leave unresolved the question of whether the emissivity of foam is a function of the azimuthal look angle with respect to the direction of wave breaking. In order to collect data to investigate the polarimetric emissivities of breaking waves, in September 2000, radiometric, foam coverage, and air-sea interaction data were collected from the R/P FLIP during the Fluxes, Air-Sea Interaction and Remote Sensing (FAIRS) experiment for wind speeds of up to 15 m/s with concomitant large-scale breaking waves. Figure 1 shows Ka-band radiometric data taken at an incidence angle of 53° and an azimuthal angle of 180° (downwind) while a large wave was breaking in the footprint of the radiometers. Figure 2 shows similar data, except at an incidence angle of 45° and an azimuthal angle of 270° (crosswind). In both cases, the change in brightness temperatures demonstrate that the emissivity of the whitecap is not constant. Furthermore, the data also suggest that the decaying foam patch left in the wake has a higher emissivity than the actively breaking crest. Despite these general similarities, there are subtle differences between the data sets in terms of the change in brightness temperature as the breaking process evolves.

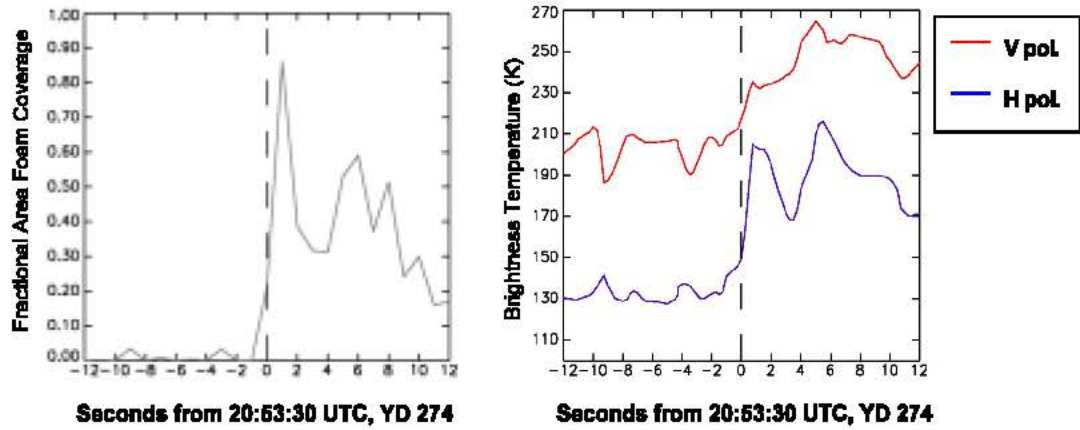


Figure 1: The time series of fractional area foam coverage of a large scale breaking wave in the radiometer field of view (left-hand plot) and the brightness temperature at 36.5 GHz measured at an incidence angle of 53° and an azimuthal angle of 180° -downwind (right-hand plot). The rapid rise in signal from $t=0$ to $t=3$ s corresponds to the actively breaking crest propagating through the radiometer field of view. The decrease in signal at $t=4$ s corresponds to the wake moving out of the footprint with the subsequent rise due to the wake moving back into the field of view.

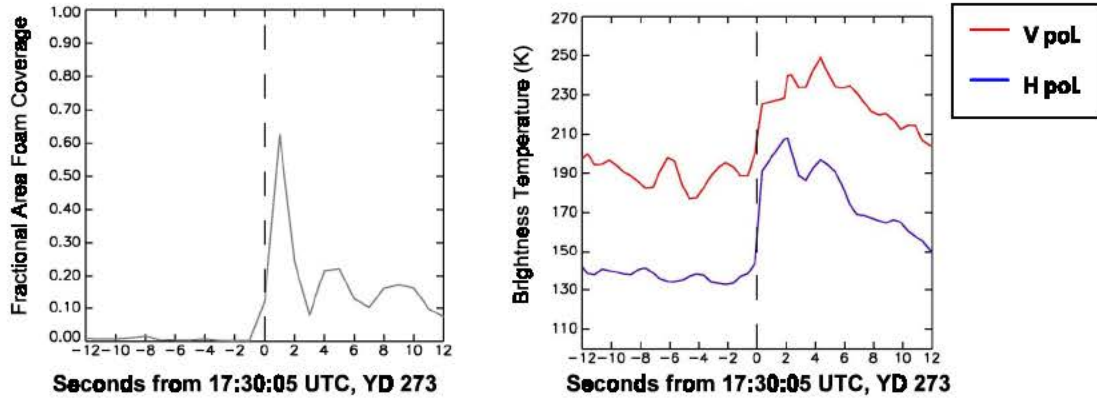


Figure 2: The time series of fractional area foam coverage of a large scale breaking wave in the radiometer field of view (left-hand plot) and the brightness temperature at 36.5 GHz measured at an incidence angle of 45° and an azimuthal angle of 270°-crosswind (right-hand plot). The rapid rise in signal from $t=0$ to $t=1$ s corresponds to the actively breaking crest propagating through the radiometer field of view. The decrease in signal at $t=3$ s corresponds to the wake moving out of the footprint with the subsequent rise due to the wake moving back into the field of view.

The intermittent and spatially sparse nature of oceanic breaking waves make it difficult to acquire repeated measurements of beam-filling foam. (For example, at a wind speed of 15 m/s, the fractional area whitecap coverage is of order 10^{-3} , which means on average one beam-filling whitecap will be observed for every 1000 s of sampling time. Although it might seem that one could simply sample for long periods of time to collect enough images of breaking waves to give good statistics, limits on data storage capacity, daylight hours available for photography, and wind duration often restrict sampling so that at best only a few whitecaps per high wind speed event are imaged.) Coupled with the problem of simply acquiring enough samples of breaking waves is the inherent variability in breaking dynamics for each individual whitecap (i.e., it is virtually impossible to view the same breaking wave simultaneously from different azimuthal look angles). These considerations make detailed analysis of the effect of breaking waves on microwave emissivity extremely difficult because the intermittancy and variability necessitate long sample times. When comparing wave breaking events as in Figures 1 and 2, it is not clear whether the differences between the brightness temperature time series reflect a dependence of the whitecap's emissivity on azimuthal angle or are simply the manifestation of variability of breaking dynamics between different whitecaps. Resolution of this issue is critical in understanding how breaking waves affect microwave remote sensing of the ocean surface and in improving algorithms for retrieving environmental data. We believe significant advances in modeling the microwave emissivity of breaking waves could be made if the emissivities of whitecaps could be studied under more controlled conditions.

As the next step in assessing the effect of breaking waves on ocean remote sensing using passive microwave instruments, the main goal of this project has been to measure the polarimetric microwave emissivities of breaking waves as a function of the incidence angle, azimuthal look angle and time evolution of the breaking wave. Rather than attempt these measurements in the open ocean for wind-driven breaking waves, which would require a sizeable investment in time and money, it was decided

to study the breaking of mechanically generated waves in a surf pool. Because surf pools generate reproducible breaking waves at a known location, they have been found to be an extremely cost-effective method of acquiring detailed information on the relationship between breaking waves, air-water gas exchange, and microwave brightness temperature [Asher *et al.*, 1995; Asher *et al.*, 1998].

WORK COMPLETED

One major effort completed in the past fiscal year was the planning and set-up required for the Polarimetric Emissivity of Whitecaps Experiment (POEWEX) conducted in October 2002 at the OHMSETT wave basin in Leonardo, New Jersey. After a lengthy search for a suitable facility to conduct a microwave radiometric study in saltwater, we selected OHMSETT because it was the only site identified that was outdoors, big enough (200-m long by 20-m wide) and, most importantly, filled with seawater. A removable shoal was built and installed in OHMSETT to generate breaking waves. Specific tasks completed were the design and construction of a concrete shoal for the wave basin that caused the waves to break at a predetermined location in the tank and the installation and check-out of a complete suite of wave characterization instruments used for the experiment. The POEWEX wave-characterization instruments deployed were two acoustic-Doppler anemometers, an array of three precision pressure transducers for recording wave height profiles in the breaking zone, two void fraction meters for measuring air entrained by the breaking waves, an underwater camera for measuring the bubble size spectra, and a 14 GHz Doppler radar for estimating surface roughness. Three fully polarimetric microwave radiometers were used, a 10.8 GHz unit from the Naval Research Laboratory, and two radiometers from the University of Massachusetts, one at 19 GHz and one at 36.5 GHz. Figure 3 shows an overview of the breaking waves and the crane used to mount the microwave radiometers.



Figure 3: Overview photograph of the OHMSETT wave basin showing the radiometers, mounting crane, and breaking waves generated on the shoal. The shoal is visible in the photograph as the dark shadow behind the breaking wave in the center of the tank.

The second major task completed in FY2002 was the analyses of the radiometric and environmental forcing function data sets from FAIRS. We presented the results of this effort at the Progress in Electromagnetics Research Symposium in July, 2002 (Cambridge, Massachusetts).

RESULTS

Figure 4 shows the apparent microwave brightness temperature of the sea surface at vertical and horizontal polarization, T_V and T_H , respectively, measured at 36.5 GHz plotted as a function of friction velocity, u^* for three separate incidence angles from the data collected during FAIRS. Figure 5 shows T_V and T_H plotted as a function of fractional area whitecap coverage, W_C . We have also investigated the correlation of brightness temperature with significant wave height, wind speed, latent heat flux, and sensible heat flux. This analysis shows that friction velocity, which parameterizes wind stress, and whitecap coverage are the primary correlates for microwave brightness temperature.

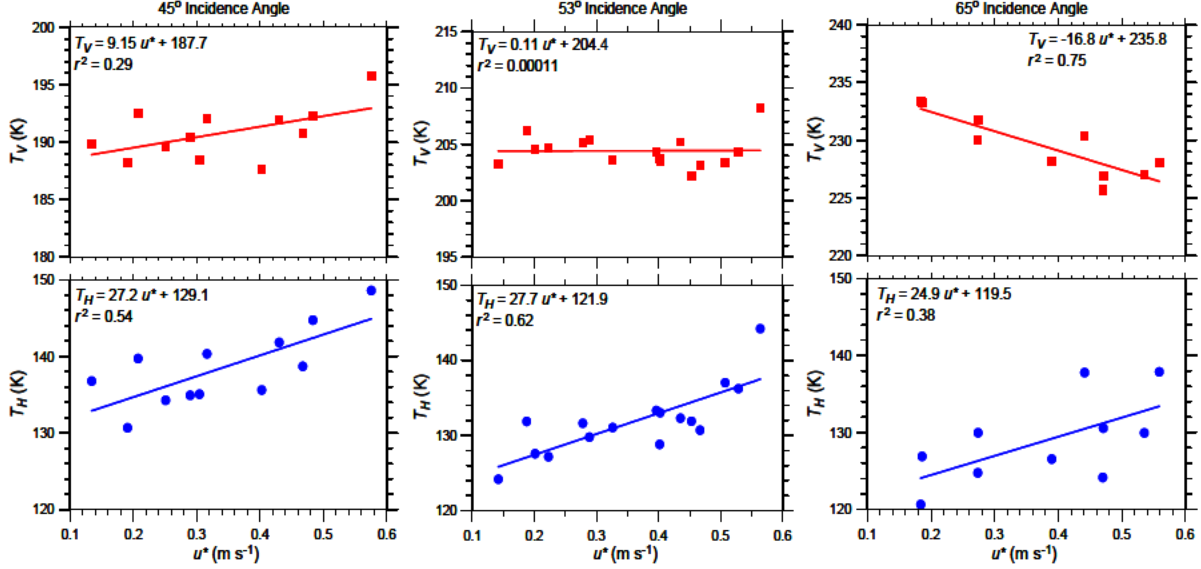


Figure 4: Plot of apparent microwave brightness temperature as a function of the friction velocity u^* and incidence angle for data collected during FAIRS.

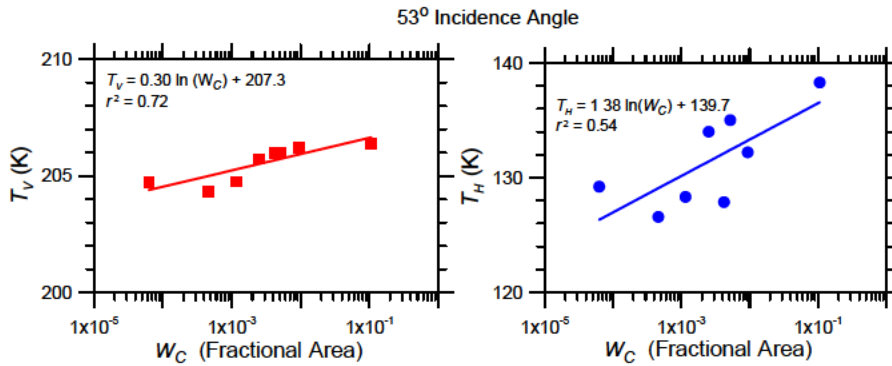


Figure 5: Plot of apparent microwave brightness temperature as a function of fractional area whitecap coverage, W_C for data collected during FAIRS.

IMPACT/IMPLICATION

The data from the FAIRS experiment will be useful in determining the sea surface emissivity over a variety of wind-wave conditions. The availability of whitecap coverage along with the azimuthal scans performed by the NRL and University of Massachusetts research teams will be used in developing models for validating microwave polarimetric satellite instruments.

POEWEX provides the first detailed study of the polarimetric microwave emissivities of breaking waves. As such, the data will be valuable for developing parameterizations of the emissivities of oceanic breaking waves, and in designing future experiments for calibrating and validating the performance of the WindSat microwave polarimeter.

REFERENCES

- Asher, W., L. Karle, B. Higgins, P. Farley, C. Sherwood, W. Gardiner, R. Wanninkhof, H. Chen, T. Lantry, M. Steckley, E. Monahan, Q. Wang, and P. Smith, Measurement of gas transfer, whitecap coverage, and brightness temperature in a surf pool: An overview of WABEX-93, in *Air-Water Gas Transfer*, edited by B. Jähne, and E.C. Monahan, pp. 205-216, Aeon Verlag, Hanau, 1995.
- Asher, W.E., Q. Wang, E.C. Monahan, and P.S. Smith, Estimation of air-sea gas transfer velocities from apparent microwave brightness temperature, *Mar. Tech. Soc. J.*, 32, 32-40, 1998.
- Piepmeyer, J.R., and A.J. Gasiewski, High-resolution passive polarimetric microwave mapping of ocean surface wind vector fields, *IEEE Trans. Geosci. Rem. Sensing*, 39, 606-622, 2001.
- Rose, L.A., W.E. 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, *IEEE Trans. Geosci. Rem. Sensing*, in press, 2002.
- Wentz, F.J., Measurement of oceanic wind vector using satellite microwave radiometers, *IEEE Trans. Geosci. Rem. Sensing*, 30, 960-972, 1992.
- Wick, G.A., J.J. Bates, and C.C. Gottschall, Observational evidence of a wind direction signal in SSM/I passive microwave data, *IEEE Trans. Geosci. Rem. Sensing*, 38, 823-837, 2000.
- Yueh, S.H., W.J. Wilson, F.K. Li, and S.J. Dinardo, Polarimetric microwave brightness signatures of ocean wind direction, *IEEE Trans. Geosci. Rem. Sensing*, 37, 949-959, 1999.
- Yueh, S.H., W.J. Wilson, F.K. Li, S.V. Ngheim, and W.B. Ricketts, Polarimetric brightness temperatures of sea surfaces measured with aircraft K- and Ka-band radiometers, *IEEE Trans. Geosci. Rem. Sensing*, 35, 1177-1187, 1997.
- Yueh, S.H., W.J. Wilson, F.K. Li, W.B. Ricketts, and S.V. Ngheim, Polarimetric measurements of sea surface brightness temperatures using an aircraft K-band radiometer, *IEEE Trans. Geosci. Rem. Sensing*, 33, 85-92, 1995.

PUBLICATIONS

Chen, D., L. Tsang, L. Zhou, S. C. Reising, W. Asher, L. A. Rose, K. H. Ding, and C.-T. Chen, 2002. "Microwave Emission and Scattering of Foam based on Monte Carlo Simulations of Dense Media," submitted to *IEEE Trans. Geosci. Remote Sensing*.

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

Guo, J., L. Tsang, W. Asher, K.-H. Ding, and C.-T. Chen, 2001. "Applications of Dense Media Radiative Transfer Theory for Passive Microwave Remote Sensing of Foam Covered Ocean," *IEEE Trans. Geosci. Rem. Sens.*, **39**, 1019-1027.

CONFERENCE PRESENTATIONS

Reising, S. C., W. E. Asher, L. A. Rose, and M. A. Aziz, "Passive polarimetric remote sensing of the ocean surface: The effects of surface roughness and whitecaps," *Proceedings of the 27th General Assembly of the International Union of Radio Science (URSI)*, Maastricht, Netherlands, August 2002.

Asher, W. E., S. C. Reising, and L. A. Rose, "The effect of surface roughness and whitecaps on sea surface microwave emissivity" *Progress in Electromagnetics Research Symposium*, Cambridge, Massachusetts, July 2002.

Reising, S. C., K. A. Horgan, M. A. Aziz, W. E. Asher, and L. A. Rose, "The effects of surface roughness and whitecaps on sea surface microwave emissivity," *IEEE International Geoscience and Remote Sensing Symposium*, Toronto, Canada, June 2002.

Reising, S. C., K. A. Horgan, and E. J. Knapp, W. E. Asher, L. A. Rose, K. M. St. Germain, P. W. Gaiser, and D. J. Dowgiallo, "Passive polarimetric measurements of the effects of foam and roughness on microwave emissivity," Paper F4-5, *2002 National Radio Science Meeting*, Boulder, Colorado, January 2002.

Reising, S. C., W. E. Asher, L. A. Rose, P. W. Gaiser, K. M. St. Germain, D. J. Dowgiallo, K. A. Horgan, and E. J. Knapp, "Passive polarimetric measurements of the effects of foam and roughness on microwave emissivity" *Specialist Meeting on Microwave Remote Sensing*, Boulder, Colorado, November 2001.