

# **Field Measurement of the Effects of Foam and Roughness on Microwave Emissivity**

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## **LONG-TERM GOALS**

The development of more accurate wind vector retrieval algorithms for use with satellite-borne polarimetric microwave radiometers that correctly account for the effects of ocean surface foam on microwave emissivity.

## **OBJECTIVES**

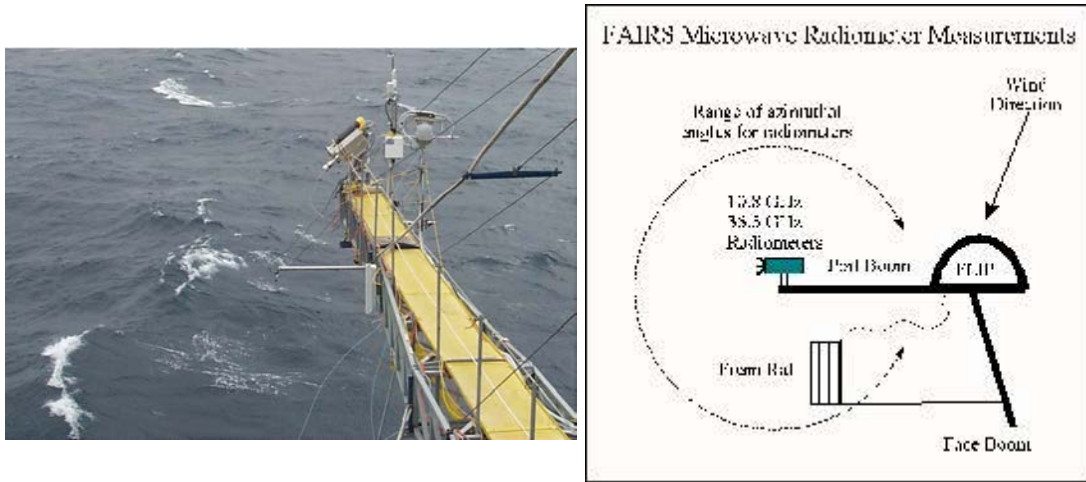
Characterize the polarimetric microwave properties of foam on the ocean surface and characterize the properties of the foam in terms of its temporal and spatial evolution on the sea surface, its bubble size spectra, its void fraction, and its thickness.

## **APPROACH**

Satellite-mounted polarimetric microwave radiometers such as WindSat could provide an effective method for remote measurement of the ocean surface wind vector. Accurate retrieval of the wind vector from microwave brightness temperature, especially at high wind speeds, requires that the emissivity of foam is known. In collaboration with Drs. P. Gaiser, K. St. Germain, and A. Rose from the Naval Research Laboratory in Washington D.C. and Prof. S. Reising from the University of Massachusetts we have made the first detailed measurements of the microwave polarimetric properties of a foam-covered water surface. Our first experiment was a detailed series of measurements of the polarimetric microwave emissivities of a stable, beam-filling patch of foam generated by a specially constructed foam generator. These measurements, conducted from a pier at the Naval Research Laboratory, Chesapeake Bay Detachment (CBD) in May, 2000, have shown that the microwave emissivity of foam is significantly less than unity [Rose *et al.*, 2001], which contradicts the common assumption that foam behaves as a blackbody at microwave frequencies. In addition, the microwave emissivity of a wind-roughened ocean surface was measured as a function of both foam coverage and azimuthal angle with respect to the wind vector. These measurements were made as part of the Fluxes, Air-sea Interaction and Remote Sensing (FAIRS) experiment conducted in September and October of 2000 aboard the R/P *FLIP*. Data from both these experiments are currently being used by Prof. L. Tsang and co-workers at the University of Washington in modeling the electromagnetic properties of foam at microwave frequencies.

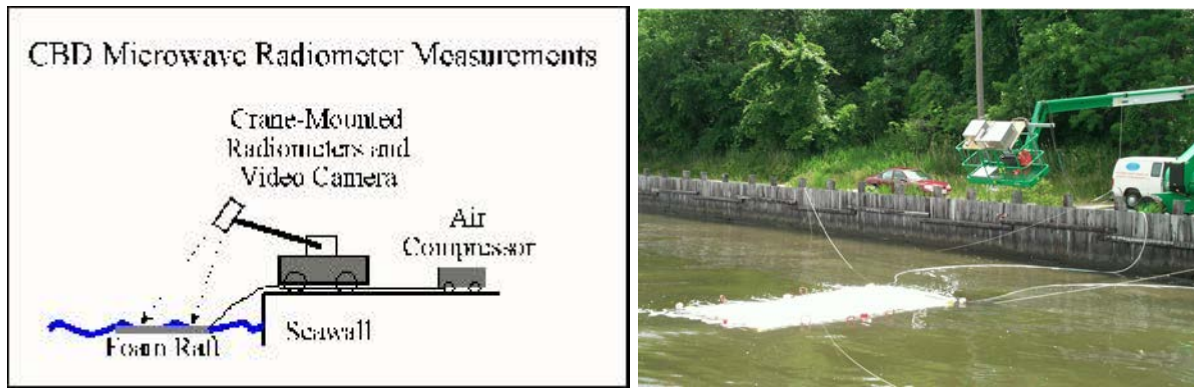
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During FAIRS, the Naval Research Laboratory deployed a polarimetric radiometer operating at a frequency of 10.8 GHz and the University of Massachusetts deployed a 36.5 GHz polarimetric radiometer. As shown in Figure 1, both radiometers were mounted on the port-side boom approximately 8 m above the water surface and could be scanned azimuthally with respect to the wind direction over the azimuthal angle range  $160^{\circ}$ - $360^{\circ}$ - $10^{\circ}$  (where  $360^{\circ}$ ( $0^{\circ}$ ) is upwind). During the FAIRS experiment, sea-surface video images were recorded using a camera bore-sighted with the microwave radiometers. These images were analyzed to give the average fractional area foam coverage for the naturally occurring whitecaps during the FAIRS experiment. In addition, image sequences of individual large-scale breaking waves were also acquired to allow investigation of the time-evolving structure of a whitecap and how that structure affected the scene brightness temperature.



**Figure 1. The radiometers and video camera deployed from the port boom of the R/P FLIP during FAIRS. The left-hand image shows the location of the instruments on the boom. The right-hand diagram shows the range of azimuthal angles scanned.**

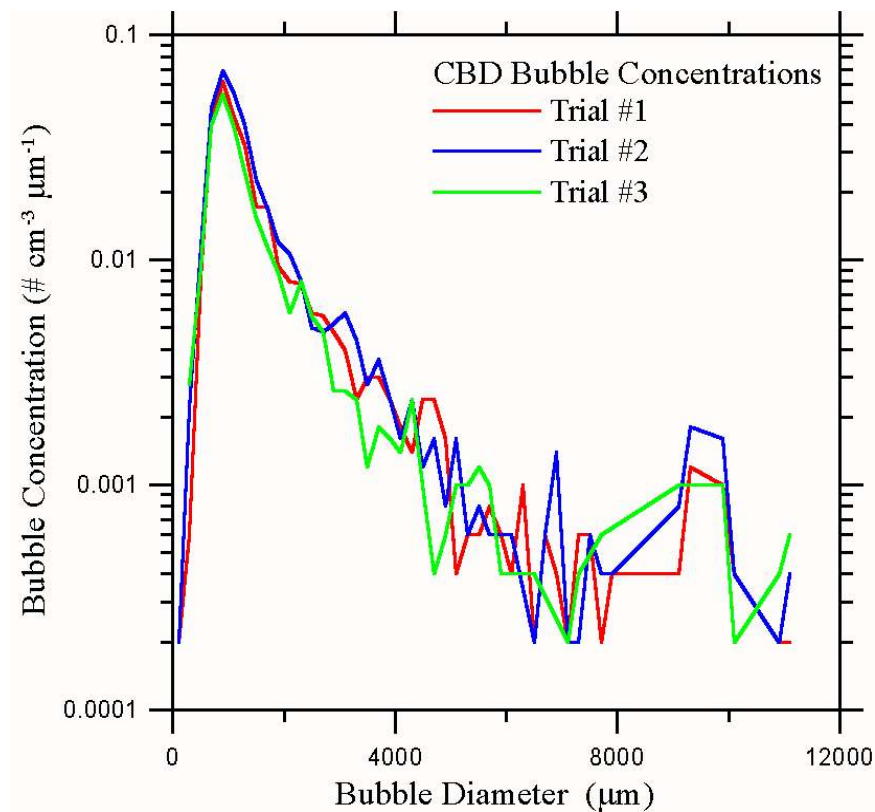
The experiment conducted at CBD was designed to provide a high-quality data set of microwave polarimetric emissivities for use in testing electromagnetic models of the emissivity of foam. This was achieved by generating a beam-filling patch of foam with temporally invariant properties. The foam patch was produced by blowing compressed air through a grid of gas permeable tubing mounted to an aluminum frame suspended just below the water surface (i.e., a foam raft). Both radiometers used during the FAIRS experiment were also deployed during the CBD measurements, except they were mounted to a man-lift crane so that they could view the foam at varying incidence angles and maintain the same slant-range (see Figure 2). Video images of the foam patch were used to verify that the foam was beam-filling. In addition, the bubble size spectra of the foam, the foam void fraction, and the foam thickness were measured using an underwater video camera.



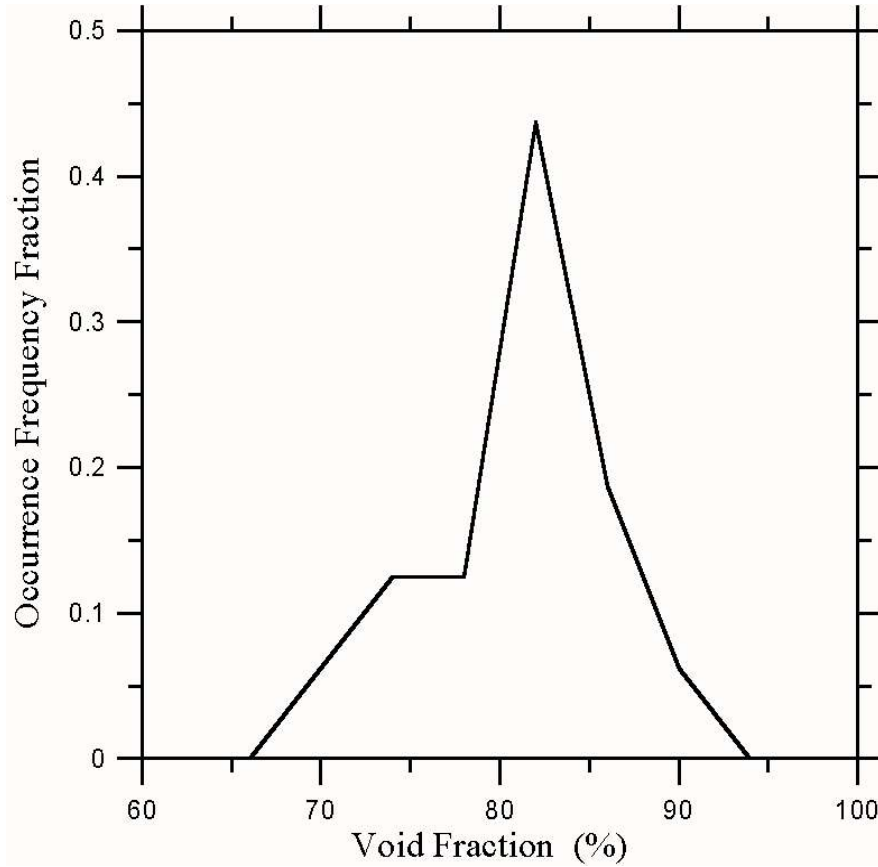
**Figure 2.** *Schematic diagram and photograph of the CBD radiometry experiment showing crane used to mount the radiometers and the foam raft that generated the stable patch of foam on the water surface.*

## WORK COMPLETED

We have completed analysis of the underwater video images from the CBD experiment. These analyses have provided the size-segregated bubble densities in the foam (number of bubbles of a given radius per unit volume of foam) (see Figure 3) and the average bubble void fraction (see Figure 4).



**Figure 3.** *Bubble concentrations measured in the foam generated by the foam raft during the CBD measurements.*



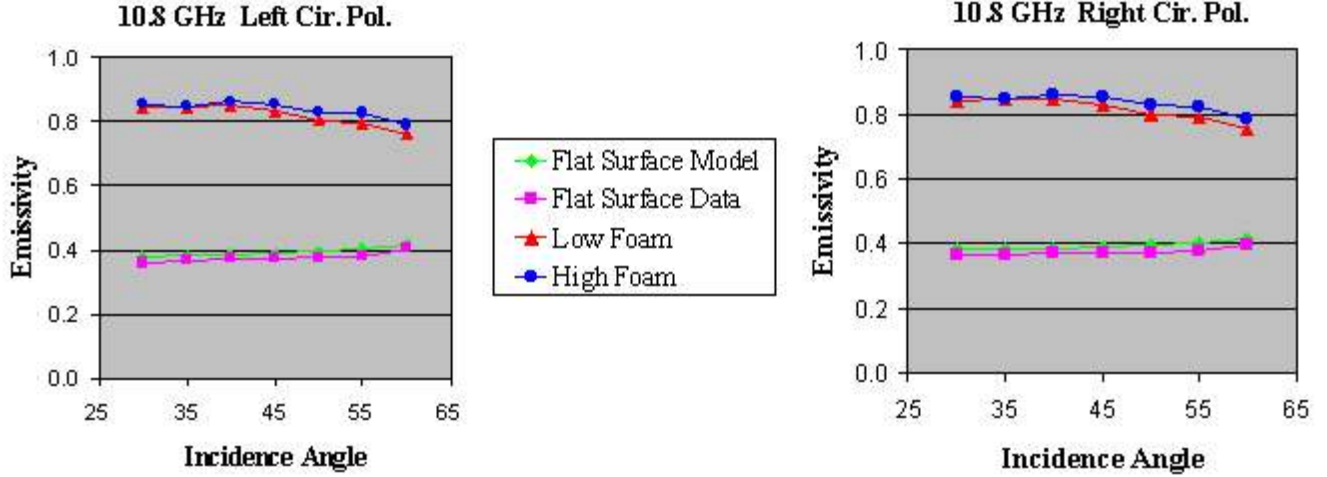
**Figure 4. Void fraction measured in the foam generated by the foam raft during the CBD measurements. Data is shown as a frequency distribution of the observed values (i.e., approximately 50% of the data show a foam void fraction between 80% and 85%).**

We have completed the analysis of the CBD data and are in the process of preparing a peer-reviewed paper discussing the results. Included in these data are the first reported measurements of the polarimetric emissivities of a foam-covered water surface (see Figure 5). The CBD data are also being used by Prof. Tsang's group for modeling the microwave emissivity of foam on a water surface.

We have completed the analysis of the ocean surface video images acquired during the FAIRS experiment. Images have been analyzed to give both average fractional area coverage as a function of wind speed and to give information on the time evolution of foam coverage for large-scale breaking waves (see Figure 6).

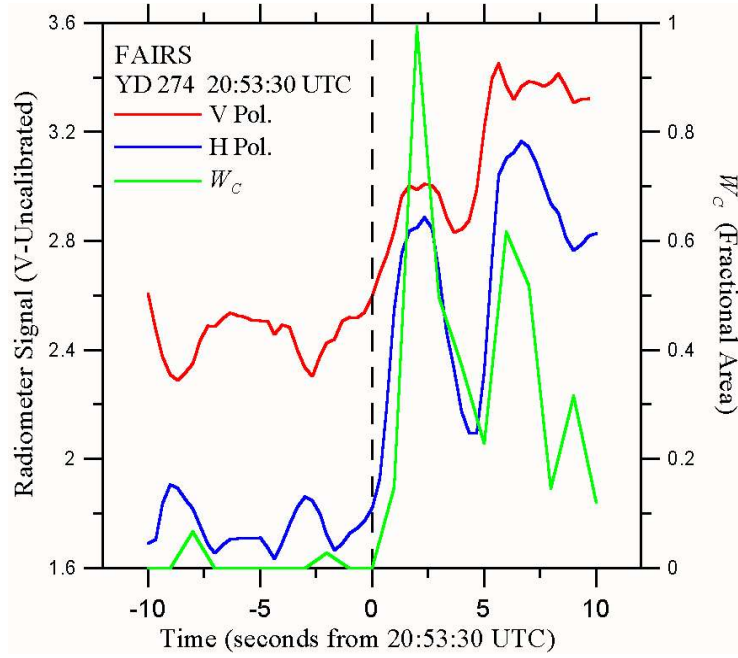
## RESULTS

The data from the CBD measurements demonstrate that the polarimetric emissivity of foam at microwave frequencies is significantly less than one (see Figure 5). This contradicts the assumption that sea surface foam behaves as a blackbody at microwave frequencies. These are the first direct measurements of the polarimetric emissivities of foam at microwave frequencies.



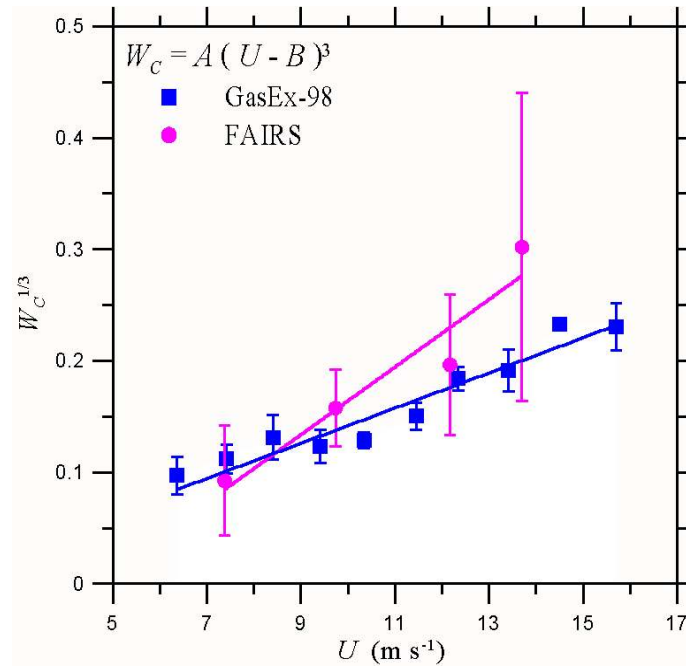
**Figure 5. Seawater foam emissivity for left and right circular polarizations as measured at 10.8 GHz plotted as a function of incidence angle. Measurements were made for beam-filling foam during the NRL-CBD experiments.**

The analysis of the time series of fractional area foam coverage from the FAIRS experiment has shown that the emissivity of the foam patch generated by a breaking wave is not constant over the life of whitecap. Figure 6 shows a time series of signal voltage for both V and H polarizations from the 10.8 GHz radiometer (signal voltage is proportional to brightness temperature) plotted with the corresponding time series for foam coverage,  $W_C$ , in the radiometer field of view determined from a video image sequence of the breaking wave. Note that at 2 s the breaking wave foam patch is beam filling (i.e.,  $W_C = 1.0$ ) corresponding to a local maximum in the brightness temperature. However, several seconds later the foam coverage has decreased to  $W_C = 0.6$ , yet the brightness temperature is higher than for the beam-filling foam. The data show that foam brightness temperatures, and therefore emissivities, are a function of the age of the foam in the plume.



**Figure 6.** A time series of radiometer signal voltages from the 10.8 GHz radiometer measured during the FAIRS experiment. Also shown in the figure is a time series of fractional area foam coverage as determined from a collocated video image sequence.

The whitecap coverage data resulting from the FAIRS experiment provides further evidence that fractional area whitecap coverage scales as the cube of wind speed (see Figure 7).



**Figure 7.** The cube root of fractional area whitecap coverage determined from sea surface video images taken during the FAIRS experiment plotted versus wind speed as suggested by Monahan [1993]. Also shown for reference are whitecap coverage data recorded in the N. Atlantic during the GASEX-98 experiment.



## IMPACT/IMPLICATION

The detailed measurements of the foam structure on the water surface will be useful in modeling the emissivity of foam. Some of the results from the initial data analysis of the foam structure have already been used in a model for predicting the microwave emissivity of foam developed by Prof. L. Tsang and co-workers at the Department of Electrical Engineering, University of Washington. The emissivity data shown in Figure 5 will be of great use in further validating this model.

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.

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