The Emissivity of Sea Foam at 19 and 37 GHz

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Abstract—An airborne experiment was conducted over the Nantucket Shoals with the purpose of determining the emissivity of sea foam at 19 and 37 GHz, vertical and horizontal polarizations. Nine whitecaps were identified as providing 100-percent coverage for at least part of their signatures. The emissivities of these whitecaps were calculated based on the peak brightness temperature recorded at 37 V, 37 H, and 19 V. The mean values of the emissivities at the respective frequencies and polarizations lie within 3 percent of the values predicted by the model of Stogryn [5]. The 37-GHz emissivities vary by 25 to 30 percent of the mean while the 19-GHz values lie within 15 percent of the mean. The data are consistent with a single parameter model depending on an effective foam fraction. The emissivities of foam for the respective channels are linearly related to each other for the same scene. The 37-H channel exhibits twice the sensitivity to foam as the 37- and 19-V channels.

I. INTRODUCTION

ALTHOUGH SEA foam typically covers only 3 percent of the sea surface [1] it has a profound effect on the average microwave brightness of the sea, due to its very high emissivity relative to the background. In fact, for wind speeds greater than 15 m/s, foam brightness may provide as much as half of the wind speed signature to an orbiting microwave radiometer. The frequency polarization, and incidence angle dependence of foam emissivity has been the subject of many investigations. Williams [2] found that the emissivity of foam at X-band was a strong function of bubble layer depth and a weak function of bubble size. He measured emissivities (based on reflectivity) of foam in a waveguide that reached values as high as 1.0 for 6 mm of foam thickness. Droppleman [3] developed a theory for the emissivity of a layer of foam over a substrate of sea water. Parameters were foam depth and the mixture ratio of air to total volume. The theory predicts that the emissivity for the idealized case approaches 1.0 as the depth/wavelength and the mixture ratios approach 1.0. Hollinger [4] measured the emissivity of artificially generated foam in a tank at 19 GHz and found some polarization dependence for incidence angles greater than 30 degrees. He observed emissivities as high as 0.8. Stogryn [5] collected the results of aircraft, laboratory, and surf measurements and derived an expression for the foam emissivity as a function of frequency and incidence angle, using a least squares fit of a polynomial to the data. The scatter of the data points about the best fit curve sug-

gests that the foam should not be characterized by a single emissivity but by a range of emissivities.

This report describes the result of an airborne experiment to determine the emissive properties of foam at 50 degrees incidence and at 19 and 37 GHz, vertical and horizontal polarizations. These frequencies represent those channels of the Special Sensor Microwave Imager (SSM/I) which are used to estimate the sea surface wind speed. Previous scanning multichannel microwave radiometers (Ex: SMMR on board both Nimbus-7 and Seasat satellites) used microwave emissivity models of a foam covered sea developed by Wilheit [6] and Pandey and Kakar [7] for geophysical parameter retrieval.

II. EXPERIMENT

In order to determine the emissivity of sea foam, the experiment site must offer large, beam-filling breakers and the breakers must be representative of deep ocean conditions. Nantucket Shoals was chosen as a site for foam emissivity measurements due to the predictable nature of the breaking there, the proximity to an airstrip, the relatively deep water, and the size of the breakers under strong wind conditions. The data presented here were collected on March 15, 1986. A cold front had moved offshore in the morning, bringing 15-m/s winds from the NW. Two flights were conducted, lasting from 1100 to 1200 and from 1600 to 1730, local time.

The aircraft was outfitted with two microwave radiometers: a 37-GHz radiometer that recorded both vertical and horizontal polarization simultaneously, and a 19-GHz radiometer that could be operated at only one polarization at a time. The radiometers were a Spacek Labs Model RM-37VH and a Honeywell Model PMR-19, respectively. The latter radiometer was placed in the horizontal mode during the morning flight and the vertical mode during the afternoon flight. Both radiometers were bore-sighted in the after direction with an incidence angle of $50^\circ \pm 2^\circ$. The beam width of each antenna was 7° , resulting in a half-power footprint of 30 m by 13 m at an aircraft height of 100 m. The integration time was set at 200 ms and the data was digitized at 20 Hz.

The 19-GHz antenna is a 12.5-cm-diameter parabolic reflector with side lobes 20 dB down from the main beam. The 37-GHz antenna is a conical horn 7.5 cm in diameter. The horn is not corrugated, i.e., the E-plane pattern and H-plane patterns differ slightly.

In addition, a still frame Hasselblad camera and a video camera were installed, pointing in the nadir direction. The

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Fig. 1. The aircraft flight path (line A) crosses over four submerged ridges on the Nantucket Shoals. Steady wave breaking occurs over the ridges as the result of the ambient wave field interacting with tide-related currents.

Fig. 2. Lines of breakers as seen from the aircraft cockpit. The view is toward the west with Nantucket Island to the upper right.

photographic image was formed about 1.5 s before the whitecap was detected by the radiometers. The Hasselblad was operated at a frame rate of 1 frame per 5-s interval, resulting in an area coverage of 40 percent. Video tape records were used to fill in the gaps. The flight altitude was 130 m for the morning flight and 100 m for the afternoon flight. The nominal speed of the aircraft was 70 m/s.

The aircraft flew a fixed flight track normal to several submerged sills. The flight path relative to the bottom topography is shown in Fig. 1. Waves break over the sills at all times and under all wind conditions due to wave and

current interactions. Breaking was particularly intense under the high wind conditions prevailing on the day of the experiment. Fig. 2 shows the influence of the submerged sills on the breaking as viewed from the aircraft cockpit.

III. CALIBRATION

Normal calibration procedures were followed using microwave absorber immersed in liquid nitrogen and microwave absorber at ambient temperature as reference sources at 77 and 281 degrees Kelvin, respectively. The cold temperature calibration appeared somewhat erratic compared to the warm temperature calibration voltages, and the cold

temperature calibration for the afternoon flight of March 15 predicted anomalously high emissivities. The LN temperatures were considered to be biased high, probably due to the high wind conditions, and were deemed useless for the purpose of calibration.

In lieu of the liquid nitrogen reference temperature I model the brightness temperature over the foam-free area of the sea surface using atmospheric data collected at the Chatham Coast Guard Station, 30 km to the north, and data from a NOAA data buoy 30 km to the south as model inputs. The model incorporates the effects of wave slope steepness, atmospheric moisture, temperature, and pressure profiles and the sea water dielectric properties as determined by the sea surface temperature and salinity. Absent is the effect of sea foam, which is normally included when analyzing data from a satellite borne microwave radiometer [6].

I omit the foam effect for the following reason. A review of the video tape shows that, in areas of weak wave breaking (i.e., away from the crests of the submerged ridges), the breakers were separated by distances of between 70 and 400 m. The foam-free background, under these conditions, is easily resolved by the 13 m by 30 m antenna footprint. The flat, low noise radiometric signal in these areas reflects the effect of this high intermittence between whitecaps. Since the model-derived temperatures are used to compare against the radiometric signal in these "quiet" regions, the foam effect should not be included in the model.

The atmospheric data were collected at 1800 local time, about 1 h following the evening flight. The buoy reported a wind speed of 10 m/s and a sea water temperature of 278°K at 1700 local time. The model used combines the scattering model of Stogryn [8] and the well-known atmospheric radiative transfer theory such as is described by Ulaby *et al.* [9]. The results of the model are shown in Table I for each of the three channels used in the afternoon flight. The sky temperature at 50° incidence angle was calculated from the model to be 21°K. This result will be used below to remove the effect of reflected sky radiation from the sea foam.

The values of gain for the 37-V and 37-H channels are approximately equal, always occurring in the same ratio, independent of the gain values, themselves. After applying this constraint to the calibration obtained above I obtain best-fit background temperatures of 133°K (6°K above the modeled temperature) and 187°K (4°K below the modeled temperature) for the 37-H and 37-V channels, respectively. Since a similar constraint could not be imposed on the single-channel 19-GHz radiometer, the modeled sea surface temperature was assumed correct for the sea surface background temperature. These temperatures were used for the cold reference temperatures.

Since the gain ratio constraint reveals an inconsistency of approximately 6°K, a conservative error estimate would be 10°K or about 3 percent in the emissivity.

Between 1720 and 1730 the 37-H and 37-V channels experienced a gradual cooling of about 6°K and 3°K, re-

TABLE I
MODEL-PREDICTED BRIGHTNESS TEMPERATURES FOR MAR 15, 1986 AT
1800, LOCAL TIME

Channel	Reflected Brightness (°K)	Emitted Brightness (°K)	Total Scene Brightness (°K)
37V	11	180	191
37H	22	105	127
19V	10	158	168

spectively. Using [10] and adjusting for the location of the experiment site relative to the local time meridian, I calculate sunset to be at 1816, local time. Hence, the drop in temperature was observed to commence 56 min before sunset. Since the effect is most pronounced in the horizontal channel, a drop in the atmospheric brightness temperature, perhaps near the horizon, is the most likely cause.

IV. TWO CANDIDATE MODELS

An actively breaking sea is strewn with foam in varying stages of development. "New" foam is a product of a wave that has recently broken and that has entrained air as the crest of the wave plunges forward. Many of the bubbles, thus created, roll forward on the surface as a bubble "raft" and look quite bright to the eye. These bubbles give the strongest microwave brightness signal. However, as the wave plunges forward it also carries entrained air to depth, and, after a short time, these bubbles return to the surface as a "boil". This I call "old" foam since it lasts much longer than the bubble rafts. The "old" foam exhibits a lower brightness temperature.

Therefore, the emissivity of foam can be expected to vary from whitecap to whitecap and, indeed, from point to point on any given whitecap. It may be dependent on some measurement of the foam depth and air-water volume ratio of the foam as detailed by Droppleman [3] and may also depend on such factors as the bubble size spectrum and the overall bubble density. Therefore, a microwave radiometer mounted on a satellite or high-flying aircraft would sense both the fraction of sea surface covered with foam and some average property of the foam.

The brightness of the partially foam covered surface of the sea, due only to emitted radiation, can be expressed

$$T_b^f = [E_w^f(1 - Fr) + E_{fm}^f Fr] T_s \quad (1)$$

where T_s is the sea surface temperature, E_w^f is the emissivity of a rough, but foam-free, sea surface [8], Fr is the fraction of sea surface covered by foam, and E_{fm}^f is the emissivity of the foam. The superscripts f and p denote the dependence on frequency and polarization, respectively. Equation (1) represents a one parameter model of foam emission, where E_{fm}^f is considered to be a constant.

A second parameter Q can be introduced in the following way. If E_{fm} varies over the surface of the foam, it could be expressed as a product

$$E_{fm}^f = a^f Q \quad (2)$$

where Q is the "quality" of the foam and varies between

0 and 1 and a^{fp} contains the dependence of the emissivity on frequency, polarization, and incidence angle.

V. ANALYSIS

The video and photographic data from the afternoon aircraft flights on Mar. 15, 1986 were reviewed to determine, for which of the strong, foam-induced radiometer peaks recorded, the antenna pattern 3-dB contour was likely to have been completely subtended by foam. Analysis was restricted to this set, since the role of foam fraction Fr might then be minimized as a factor contributing to the variability of T_b . From the video data nine strong peaks were identified to have satisfied this beam-filling criteria. Table II lists the peak brightness temperatures for each of these whitecaps.

The brightness temperature due to both emissions from the sea and reflections from the sky can be expressed as

$$T_b = ET_s + (1 - E)T_{sky} \quad (3)$$

where E is the emissivity, T_s is the sea surface temperature, and T_{sky} is the sky brightness temperature (21°K) evaluated from the model. (An assumption inherent in (3) is that the sea foam reflects incident radiation as a flat, specular surface. Since T_{sky} is relatively uniform in the neighborhood of 50°, incidence, this assumption can be relaxed to allow reflections from a variety of angles.) Solving (3) for E

$$E = \frac{T_b - T_{sky}}{T_s - T_{sky}} \quad (4)$$

Whitecap emissivities were calculated according to (4) using the peak brightness temperature of each of the nine whitecaps. Table III lists the mean, standard deviation, maximum, and minimum values of these emissivities. The value of the emissivity predicted by the empirical relation developed in [5] is included in the table for comparison.

One measure of the sensitivity of the various channels to sea foam is a comparison of the individual ΔE 's (differential emissivity rise above the background, due to foam). Since the background E 's vary from channel to channel, the ordering of the sensitivities (ΔE 's) is not necessarily the same as for the absolute emissivities. ΔE 's for a typical whitecap are listed below in Table III. The 37-H channel, for the example shown, is almost twice as sensitive to foam as the other channels.

Fig. 3 is a sample time series plot of the 37-V, 37-H, and 19-V channels during the afternoon flight. Points "A" denote radiometric signatures of gravity waves. The wavelength of the swell, inferred from the speed of the aircraft, is about 210 m. From the model developed in [8], the sensitivity of brightness temperature to wave slope dT/dm is 1.6°K/°slope at 37-V, 50°, incidence. The amplitude of the wave signature in Fig. 3 is about 5°K and represents twice the slope ak where k is the swell wavenumber and a is its amplitude. The angle of slope is, then, about 1.6° and the wave amplitude should be about 90 cm, a reasonable value under the conditions. Point "B" denotes the signature of old foam. Note the nearly

Fig. 3. Brightness temperature time series for the 37-V, 37-H, and 19-V channels. Points A are the signature of the swell, point B is old foam, and point C is a breaking wave. The 19-V signature differs slightly from the 37-V, since the antenna footprints are offset by 3 m.

TABLE II
PEAK BRIGHTNESS TEMPERATURES FOR NINE WHITECAPS IDENTIFIED AS BEAM-FILLING

$T_{37H}(^{\circ}K)$	$T_{37V}(^{\circ}K)$	$T_{19V}(^{\circ}K)$
181	225	213
170	215	193
198	235	209
167	204	197
183	225	199
203	240	217
217	249	220
207	243	212
209	244	213

flat nature of the maximum. Point "C" denotes a breaking wave and exhibits the highest temperature in the series.

Fig. 4(a) is a sample time series of the 37-GHz microwave brightness as the aircraft over-flew the whitecap shown in Fig. 4(b). The photo field of view is about 140 m. The brightness rises sharply on the breaking (left) side of the whitecap and returns slowly to the background brightness on the trailing side. Hence, the plunging portion of the breaker is brighter than the older bubble rafts on the tail of the whitecap. Since this example is from the morning flight the calibration is questionable, however the time series exhibits the essential features of the calibrated series obtained during the afternoon flight.

Following the one parameter model we may write down the two equations

$$T_b^{37V} = [E_w^{37V}(1 - Fr) + E_{fm}^{37V}Fr]T_s \quad (5)$$

and

$$T_b^{37H} = [E_w^{37H}(1 - Fr) + E_{fm}^{37H}Fr]T_s \quad (6)$$

If Fr is eliminated from (5) and (6) we are left with the equation

$$T_b^{37V} = AT_b^{37H} + B \quad (7)$$

where

$$A = \frac{(E_{fm}^{37V} - E_w^{37V})}{(E_{fm}^{37H} - E_w^{37H})} \quad (8)$$

Fig. 4. (a) The 37-GHz brightness temperature time series as the aircraft over-flies the whitecap in Fig. 4(b). Note that the data was collected during the morning flight and the calibration is questionable. (b) The 3-dB antenna contour was superimposed on the whitecap recorded in Fig. 4(a).

and

$$B = (E_w^{37V} - E_w^{37H} A) T_s.$$

On a plot of T_b^{37V} versus T_b^{37H} , (7) describes a straight line passing through the foam-free point ($Fr = 0$) and the 100-percent foam point ($Fr = 1$).

The peak brightness temperature data of Table II is shown plotted on a graph of T_b^{37V} versus T_b^{37H} in Fig. 5. The best-fit straight line is shown as the solid line in the figure, and the equation of this line is

$$T_b^{37V} = 0.815 T_b^{37H} + 74. \quad (9)$$

The 19-V data is regressed against the 37-H data in Fig. 6. The linear regression expression that best fits this data is

$$T_b^{19V} = 0.360 T_b^{37H} + 138. \quad (10)$$

The plots of Figs. 5 and 6 show that the data fit the regression curves quite well with a correlation of 0.96 for (9) and 0.80 for (10). Both regression curves pass very close

Fig. 5. Plot of 37-V versus 37-H peak brightness temperatures for beam-filling whitecaps. The solid line is the linear regression on the data marked by '+'s. No-foam point corresponds to the foam-free brightness temperatures predicted by the model.

Fig. 6. Plot of 19-V versus 37-H brightness temperatures for beam-filling whitecaps. The solid line is the linear regression on the data denoted by '+'s.

to the foam free point as would be expected for a one parameter model in the form of (1).

E_{fm}^{37V} and E_{fm}^{37H} are linearly related through (8) if the single parameter model of (1) is assumed. Taking the value of A in (8) to be 0.815 from the results of the linear regression (9) we obtain, from (8)

$$E_{fm}^{37V} = 0.815 E_{fm}^{37H} + 0.340. \quad (11)$$

The analog to (7) can be derived for E_{fm}^{19V} and E_{fm}^{37H} . Similarly, we can assign the value, 0.360, from (10) to A , in this case, to obtain a linear relation between these two emissivities

$$E_{fm}^{19V} = 0.360 E_{fm}^{37H} + 0.433. \quad (12)$$

VI. DISCUSSION

The mean values for emissivity derived from the peak brightness temperatures of the whitecaps lie remarkably

close to the predictions of [5]. The variance in emissivities is shown to be greater at 37 GHz than at 19 GHz. This would imply that the 37-GHz channel is more sensitive to variations in bubble density, bubble layer thickness, or other factors that give rise to the variability in foam emissivity. The hierarchy of foam T_b 's, $37\text{ V} > 19\text{ V} > 37\text{ H}$, at 50° incidence, found in this experiment, is consistent with previous findings. As indicated in Table III under the column titled " ΔE (typical)," the sensitivity to change in scene brightness due to foam is greatest in the 37-H channel. If it were desirable to retrieve foam as a separate parameter, as distinct from the RMS wave slope, the heightened sensitivity of the 37-H channel could be exploited.

The mechanism for the much-enhanced brightness of sea foam remains an open question. The forward plunging side of the breaker exhibits distinctly warmer temperatures than the trailing side where bubbles are returning to the surface. Both regions can appear equally as white in a photographic image. As was pointed out by Williams [2], the plunging breaker may so distort the underlying sea surface that the resulting convoluted "holes" serve as an effective trap for microwave radiation, producing multiple reflections within the cavities. Thus, it may not be the foam itself that produces anomalously high temperatures, but the associated distortion in the sea surface topography.

By assumption, all of the points in Figs. 5 and 6 represent 100-percent foam coverage cases. That is, if the regression curve were parameterized by foam fraction Fr , the " $Fr = 1$ " point would occur at some temperature, cooler than that of the lowest data point. At temperatures warmer than the " $Fr = 1$ " point, foam properties would presumably dominate, and the curves in Figs. 5 and 6 might take on a different slope or even a different shape as the temperatures increased beyond this point. We see, however, that the data points representing 100-percent foam coverage fall on the extension of the straight line representing partial coverage (7). We are led to conclude, then, that either 1) the assumption of 100-percent foam coverage is false, i.e., that "visible" foam coverage is somewhat greater than "microwave" foam coverage or that 2) foam properties such as bubble density, air/water fraction, bubble layer depth, etc. have the same incremental effect on T_b as does fractional coverage. This might occur, for example, if the foam properties entered the equations as a factor in the value of the emissivity as was expressed by (2). Equation (7) would, then, be of the same form except that E_{fm}^{pq} would take on the form $a^{fp}Q$ where now a^{pq} would be a true constant for given p and q and Q would contain the physical properties of the foam.

Since the foam emissivities enter into the expression for the slope (8) and the data has shown that slope to be a constant, independent of the value of the emissivity of foam, then those emissivities must be related by (8) with A , a constant. Equations (11) and (12) are just such relationships if the slope is determined by the best fit straight line through the data.

TABLE III
THE MEAN, STANDARD DEVIATION, MAXIMUM, AND MINIMUM VALUES OF SEA FOAM EMISSIVITY AS CALCULATED USING (4) AND THE DATA FROM TABLE II

Channel	E	σ_E	$E_{\max}$	$E_{\min}$	$E_{\text{Stogryn (1972)}}$	ΔE (Typical)
37V	.82	.060	.89	.68	.79	.15
37H	.67	.069	.76	.57	.66	.28
19V	.73	.037	.77	.67	.72	.15

(The values predicted by the model of [5] are listed in the sixth column followed by some typical values for the increase of emissivity due to the presence.)

If conclusion 1) is correct, then this experiment hasn't provided sufficient spatial resolution to resolve the 100-percent foam covered areas that must be smaller than the 13 m by 40 m antenna footprint, employed. We could not determine, then, on the results obtained here, whether another parameter describing foam properties is necessary in order to properly model the effects of foam. It should be noted, however, that the highest T_b reached was close to 250°K over a 278°K sea. There remains only 28°K or 100 percent of the entire thermal range in which to achieve a 100-percent foam coverage, i.e., if we have not achieved 100-percent coverage, then we must be very close.

If, on the other hand, conclusion 2) is correct then we need only specify the single parameter Fr , the effective foam fraction, in order to properly model the data. This was the conclusion reached in [7].

The 19-V versus 37-H data shown in Fig. 6 exhibits a decreased sensitivity of the 19-GHz channel to what the 37-GHz channel sees as foam fraction in Fig. 5. A greater spread exists in this data since the 19-V and 37-H antennas were displaced by about 3 m and, hence, the antenna footprints were not exactly congruent.

VII. CONCLUSIONS

The measured emissivities of nine selected whitecaps exhibit a good deal of spread in values despite efforts to screen them for 100-percent coverage. Foam properties such as bubble density, thickness, and, perhaps, the shape of the underlying surface play a role in the variability of the emissivities. The peaked nature of all the strong jumps in brightness suggest a variation in properties within the whitecaps themselves. None of the breakers showed any tendency to saturate in microwave brightness.

The mean values of emissivities at all three channels, 37 V, 37 H, and 19 V, showed good agreement with the model developed in [5]. The emissivities at 37 GHz were more variable (25 and 29 percent of the mean) than the 19-GHz channel (15 percent of the mean).

The 37-H channel is the most sensitive to changes in emissivity due to foam. The average increase in emissivity due to foam was nearly twice the value of the increases at 37 and 19 V for the same whitecap.

The effects of changes in foam properties are seen as changes in fractional coverage. A single parameter model, employing only foam fraction as a parameter fits the data well. Within the range of the measured emissivities the

trend of the data was not toward the sea surface temperature as would be the case if foam radiation tended to a black body.

Finally, the emissivities of foam at the three channels are linearly related to one another. These relationships are embodied in (11) and (12).

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