The Emissivity of Sea Foam at Microwave Frequencies

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A consistent picture of the emission characteristics of sea foam at microwave frequencies has emerged from a survey of published radiometric measurements. The results are summarized, as functions of frequency and angle, by means of simple equations. Available data on the reflection properties of foam are also examined and shown to be qualitatively, but not quantitatively, in agreement with the radiometric results.

Presently available evidence indicates that the two primary features of the ocean surface that are responsible for microwave brightness temperature departures from those characteristic of a specular surface are waves and foam. A theoretical treatment of wave effects has been given by *Stogryn* [1967] and has received partial confirmation in the experimental work of *Hollinger* [1970, 1971]. Further work on the effect of waves is in progress and will be discussed elsewhere. The significance of foam on the water's surface seems to have first been recognized by *Williams* [1969] and several subsequent experiments performed by various groups have verified its importance. Although an interesting attempt at a theoretical description of the emissivity of foam was made by *Droppleman* [1970], it is clear that the complexity of the electromagnetic boundary value problem has precluded the construction of a physically and mathematically convincing theoretical model. Thus, at least for the present, complete reliance must be placed on experimental data in studies relating to the effects of foam.

To date, the published data on the microwave radiometric properties of foam have been quite sparse and no attempt seems to have been made to correlate the various measurements that are available. In view of the importance of this problem in connection with the interpretation of many proposed remote sensing experiments, a synthesis of known data is attempted in this work.

Some Basic Relationships

The brightness temperature $T_p(\nu, \theta)$ of radiation with polarization p and frequency ν propagating away from the surface S (see Figure 1) may be expressed as

$$T_p(\nu, \theta) = \epsilon_p(\nu, \theta)T_w + T_p^r(\nu, \theta) \qquad (1)$$

where $\epsilon_p(\nu, \theta)$ is the emissivity in the direction θ, T_w is the thermal temperature of the water and foam, and $T_p^r(\nu, \theta)$ is the temperature of the reflected sky radiation. To write equation 1, it is assumed that the brightness temperature is measured near the surface so that certain additional atmospheric contributions to $T_p(\nu, \theta)$, which are sometimes of importance, may be ignored. Further, an implicit assumption is made that azimuthal variations in the incident sky-brightness temperatures and emissivity can be ignored. This hypothesis seems to be quite reasonable for sea foam since foam generally has a statistically isotropic structure and, for the data to be discussed below, atmospheric conditions also appeared to be isotropic.

As is customary in microwave radiometric studies, the two independent polarization directions p will be taken to be horizontal (h) and vertical (v). *Peake* [1959] has shown that the term $T_p^r(\nu, \theta)$ in (1) may be expressed by means of a set of bistatic scattering coefficients $\gamma_{ij}(\nu, \theta, \theta', \varphi')$ ($i, j = h$ or v) in the form

$$T_p^r(\nu, \theta) = \frac{1}{4\pi} \int [\gamma_{ph} + \gamma_{pv}]T_{sky}(\nu, \theta') \cdot \sin \theta' \, d\theta' \, d\varphi' \qquad (p = h \text{ or } v) \qquad (2)$$

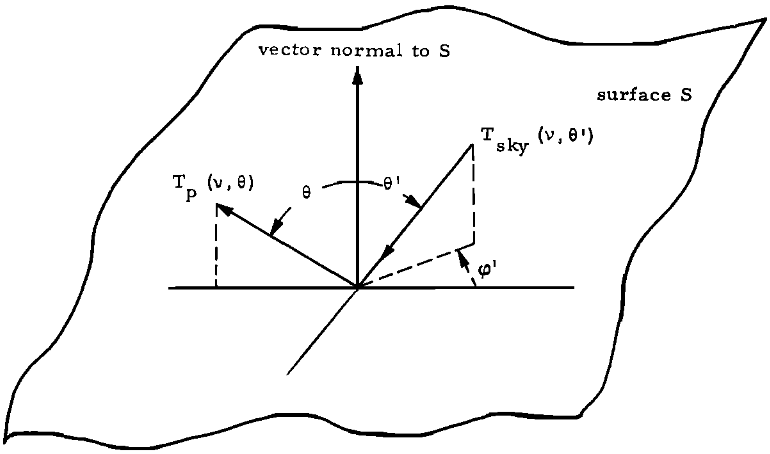

Fig. 1. Geometry for determining emissivity.

where T_{sky} is the incident sky-brightness temperature. Further, the same scattering coefficients are closely related to the emissivity by the equation

$$\epsilon_p(\nu, \theta) = 1 - \frac{1}{4\pi} \int [\gamma_{ph} + \gamma_{pv}] \cdot \sin \theta' \, d\theta' \, d\varphi' \qquad (p = h \text{ or } v) \qquad (3)$$

The above formulation shows that a complete description of the microwave properties of foam is contained in the scattering coefficient γ_{ij}. Thus, either active (scattering) measurements or passive (radiometric) measurements may be used in principle to deduce the emissivity of foam. Scattering experiments to determine γ_{ij} as a function of both the incident and scattering angles have the further advantage of providing an accurate means for calculating the reflected contribution to T_p (ν, θ). However, currently available information is far from adequate to determine the form of these coefficients. In fact, to interpret the radiometric data discussed below, the simplest possible hypothesis will be used (namely, that the angular dependence of γ_{ij} contains a delta function part of the form $\delta(\theta\text{-}\theta')\delta(\varphi')$). In this approximation, (1) reduces to

$$T_p(\nu, \theta) = \epsilon_p T_w + [1 - \epsilon_p] T_{sky}(\nu, \theta) \qquad (4)$$
$$(p = h \text{ or } v)$$

The use of (4), while not exact, will allow at least a first-order correction for sky-temperature effects to be applied to the data. This correction is most important at large angles of observation.

Before proceeding to a discussion of the data, it will be reiterated that the goal of this study is to specify the properties of a water surface covered completely with foam. Thus, in analyzing some measurements obtained over surfaces only partially foam covered, it was necessary to assume that the total brightness temperature may be decomposed into

$$T_p = (1 - f)(T_p)_w + f(T_p)_f \qquad (5)$$

where f is the fractional foam coverage, $(T_p)_w$ is the brightness temperature due to a foam-free water surface, and $(T_p)_f$ is the brightness temperature due to a 100% foam-covered surface. The assumptions under which (5) holds are quite mild and do not impose any practical restrictions for typical operational conditions. Conversely, in applying the results obtained below to actual experiments, (5) must be taken into account since water surfaces are generally completely foam covered only in exceptional circumstances.

Data obtained by passive and active electromagnetic experiments are discussed separately below.

PASSIVE MEASUREMENTS

Table 1 shows a list of measurements on foam. Unfortunately, all of the reported data was not found to be suitable for quantitative comparisons. Two primary considerations determined

TABLE 1. Reported Radiometric Measurements on Foam

Reference	Frequency, GHz	Polarization	Angle, degrees	Foam Cover, %	Remarks
Edgerton et al. [1970]	13.4, 37	*h, v*	20	100	Artificially generated foam in a large tank of water (salinity = 33 ‰)T_w = 295°K
	13.4, 37	*h, v*	50	100	Measured in surf zone at beach. Wave height ≤ 1 ft, $T_w \approx 286$°K
	37	*h, v*	$5 \leq \theta \leq 90$	~100	Scan over surf zone near shore at Newport Beach, Calif. Considerable fluctuations due to variable foam cover and breaking waves, T_w = 288°K
Hollinger [1970]	8.36, 19.34	*h, v*	$20 \leq \theta \leq 55$	?	Natural and artifically generated foam observed at Argus Island. Obtained lower bounds to foam effects.
Nordberg et al. [1969]	19.4	*h*	0	?	Measurement over Salton Sea. T_w = 294°K, wind speed ~15m/sec
Nordberg et al. [1971]	19.4	*h*	0	0–100	Flights over North Atlantic Ocean and North Sea.
	19.4	*h*	$0 \leq \theta < 70$	~25	Flight over North Sea. T_w = 277°K, wind speed = 25 m/sec (case F in reference)
Williams [1969]	9.4, 15.8, 22.2, 34	?	20°	100	Artificially generated foam in tank of water. Radiometer calibrations not established. Antenna pattern effects also present in data. Some data relating to Hurricane Beulah (1967)

the choice of data to be analyzed. The first consideration was the availability of information that related to the absolute calibration of the radiometers. This factor is critical in any comparison because absolute calibration errors greater than 70°K are apparent in some cases. A neglect of such brightness-temperature shifts can obviously conceal any correlations that could exist. Second, the foam cover on the water surface was required. For surfaces with 100% foam cover, this does not present any difficulty. On the other hand, it appears that the determination of foam coverage from optical photographs can be quite subjective and uncertain when the foam cover is small (even when there is a clearly established brightness temperature change). Thus, the error in extrapolating such results to 100% coverage may be quite large. For this reason, cases exhibiting complete foam coverage were preferred and, in fact, only one example with less foam was used to establish the basic form of the emissivity curves.

The data by *Edgerton et al.* [1970] at 37 GHz provides an illustration of the brightness-temperature characteristics of foam. Figure 2 is a plot of the scan over the surf zone taken at Newport Beach, California. The data for $5 < \theta < 90°$ refer to the foam, while for angles greater than 90°, the radiometer observed the sky temperature ($\theta = 180°$ corresponds to zenith). The sky-temperature data is important for checking the absolute calibration of the radiometer. Large fluctuations in the brightness temperature are evident in the figure and are ascribed to the constantly changing foam coverage as well as to breaking waves that have the effect of changing the local angle of incidence θ. Although the magnitude of the brightness temperature for horizontal polarization differs markedly from that of a smooth-surfaced water body, it is interesting to note the same qualitative decrease in temperature with increasing angle that is characteristic of all specular surfaces out to angles where the sky temperature dominates ($\theta \geq 80°$). The vertically polarized temperature behaves quite differently. Instead of increasing with increasing θ, as is typical of specular surfaces for angles less than the Brewster angle, the brightness temperature is seen to generally decrease until $\theta = 55°$ from which point it increases up to an angle not too different from the Brewster angle of a smooth-surfaced body of water. It is also interesting to observe that foam differs considerably from examples of very rough surfaces that have been discussed in the literature. In particular [*Peake*, 1959; *Chen and Peake*, 1961], it is known that surfaces covered with vegetation such as grass and weeds tend to exhibit the same behavior for both horizontal and vertical polarization and no Brewster angle effects are observed.

The data in Figure 2 represent the only information on the brightness temperature of foam for vertical polarization known to the author that covers angles greater than $\theta = 55°$. For this reason, the observed interesting behavior at large angles will not be supported by other direct evidence although tentative confirmation is provided by scattering data to be discussed below.

To convert the measurements exhibited in Figure 2 into emissivity data, the absolute calibration must be established and sky temperature effects extracted. In this example, the measured sky temperatures are consistent with known atmospheric conditions that prevailed at the time of the experiment and the difference between the measured sky temperatures as the radiometer was switched between the vertical and horizontal polarization modes is sufficiently small so as to establish some confidence in the calibration. Thus, using the known water temperature $T_w = 288°K$ and (4) it is possible to compute ϵ_p ($p = h$ or v) or, equivalently, the product $\epsilon_p T_w$. The latter quantity seems to be a better parameter to use at this time because the different experiments to be compared were performed at different water temperatures. If the hypothesis is made that $\epsilon_p T_w$ for foam behaves in the same way with T_w as for water in bulk form, then $\epsilon_p T_w$ should be rather insensitive to the water temperature in the frequency range to be considered [*Stogryn*, 1967]. Results of a partial subjective smoothing of the data to eliminate the effects of varying foam coverage and breaking waves (which were mentioned above) are shown in Figure 3.

The results of other measurements at 37 GHz [*Edgerton et al.*, 1970] are also shown in Figure 3. The tank experiment resulted in a tem-

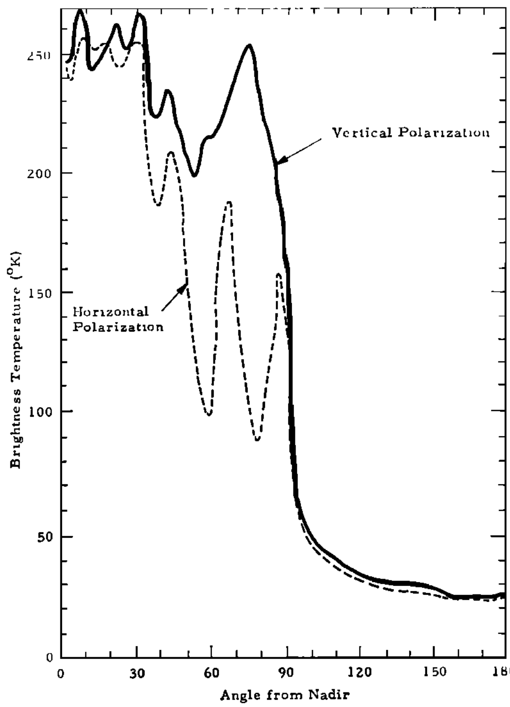

Fig. 2. Brightness temperature of surf zone at 37 GHz.

perature increase of 104°K for horizontal polarization and 104°K for vertical polarization over that of a specular water surface. The calibration check over a specular water surface, which was made during the experiment, resulted in a temperature of 134°K for horizontal polarization that is 11°K lower than a calculation with a realistic model atmosphere yielded. Since the properties of a smooth water surface can be calculated with high accuracy, it was assumed that an absolute calibration error of 11°K existed in the horizontally polarized data. After applying the calibration data as well as extracting the effect of the incident sky temperature, $\epsilon_h T_w$ was found to be 245°K for foam. A similar treatment of the vertically polarized data showed a calibration error of 18°K and resulted in $\epsilon_v T_w = 257°K$. It is apparent that although the foam in the tank was generated artifically by blowing air through the water, the results are entirely consistent with those obtained at Newport Beach. The surf zone data at $\theta = 50°$ was treated in a similar manner and yields corrected estimates of 201°K and 234°K for $\epsilon_h T_w$ and $\epsilon_v T_w$ respectively.

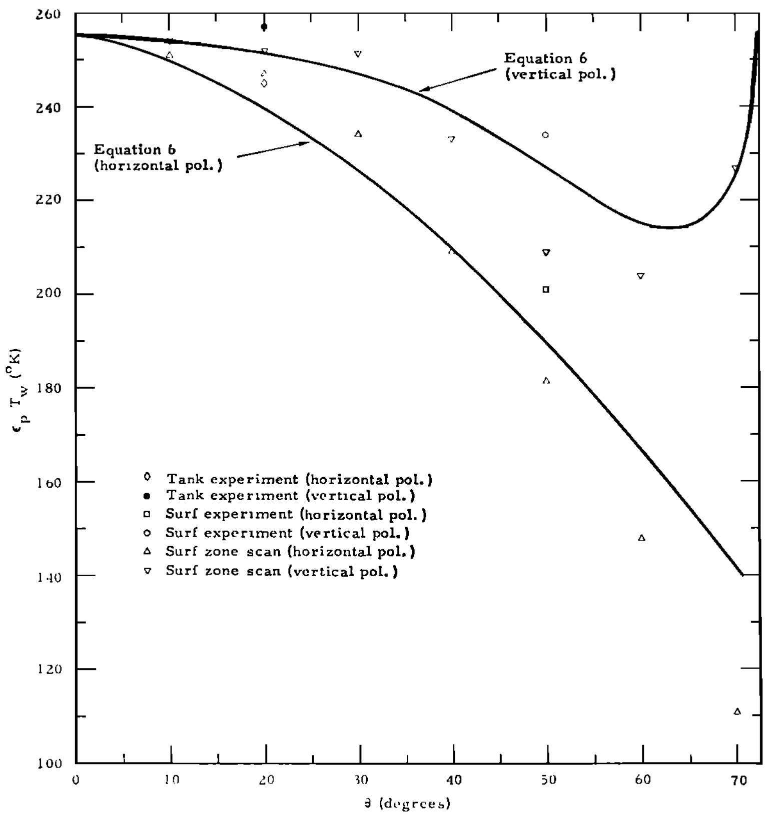

Fig. 3. Emitted temperature of foam at 37 GHz.

Data from *Edgerton et al.* [1970] at 13.4 GHz, after calibration and sky temperature corrections, are shown in Figure 4.

The experiments of *Nordberg et al.* [1971] at 19.4 GHz were performed for horizontal polarization only. The authors estimated an absolute calibration error in the range 10°–15°K. On the basis of a comparison of their computed smooth sea curve and their case B, a calibration error of 15°K will be assumed here. A model atmosphere which produces a zenith sky temperature of 19°K at 19.4 GHz is consistent with the atmospheric effects described in the reference for $\theta = 0$ and provides the basis for making atmospheric corrections at other angles. Two measurements are of particular interest here. The first was an observation of a large foam patch that filled the radiometer beam at $\theta = 0°$ and resulted in a temperature of 220°K. After the above mentioned calibration correction is applied and a small sky-temperature contribution is extracted, it is found that $\epsilon_h T_w = \epsilon_v T_w =$ 232°K at $\theta = 0°$. The second measurement to be considered here is a scan over the range $0 < \theta < 80°$ (case F of Nordberg et al.). Although the foam cover was far less than 100% for this case, it warrants attention because it provides data on angular variations at 19.4 GHz. Several interesting questions that relate to the interpretation of wave effects also arise in connection with this example.

To determine the emissivity of the foam at 19.4 GHz from the case F curve in Nordberg et al., it is necessary to estimate the foam coverage and deviations in the brightness temperature from a specular surface due to the waves on the sea surface. The foam coverage was determined by means of (5) in connection with the (corrected) measured temperatures of 132°K and 157°K at $\theta = 0$ for cases B and F, respectively, of the reference. Assuming that the difference between these cases is entirely due to foam (see remarks below), it is found that $f =$ 0.243 if use is made of the measured increase

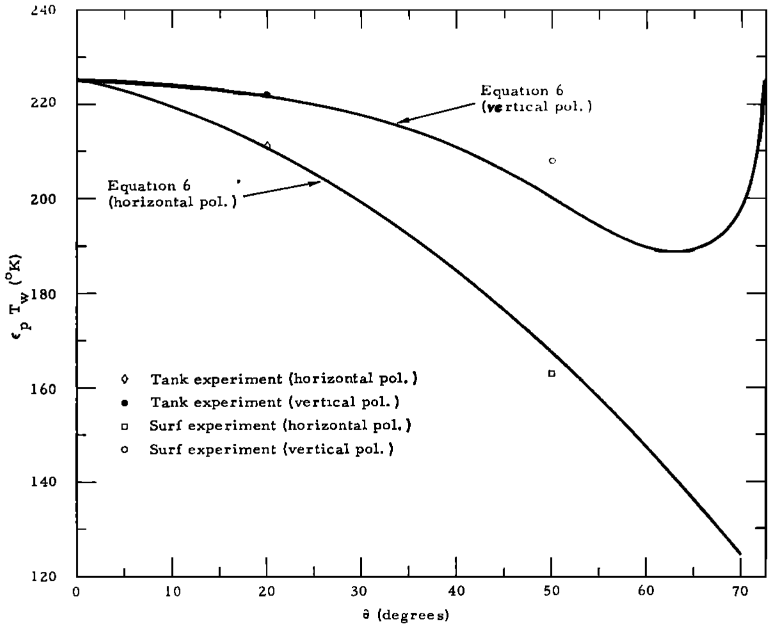

Fig. 4. Emitted temperature of foam at 13.4 GHz

of 103°K for a 100% foam-covered surface. This estimate falls precisely on the dotted curve shown in Figure 5 by Nordberg et al. and, of course, is not compatible with the possible alternate curve discussed in the reference. The assumption that the brightness temperature at $\theta = 0$ is the same as that for a smooth sea surface for case B and for the nonfoam part of

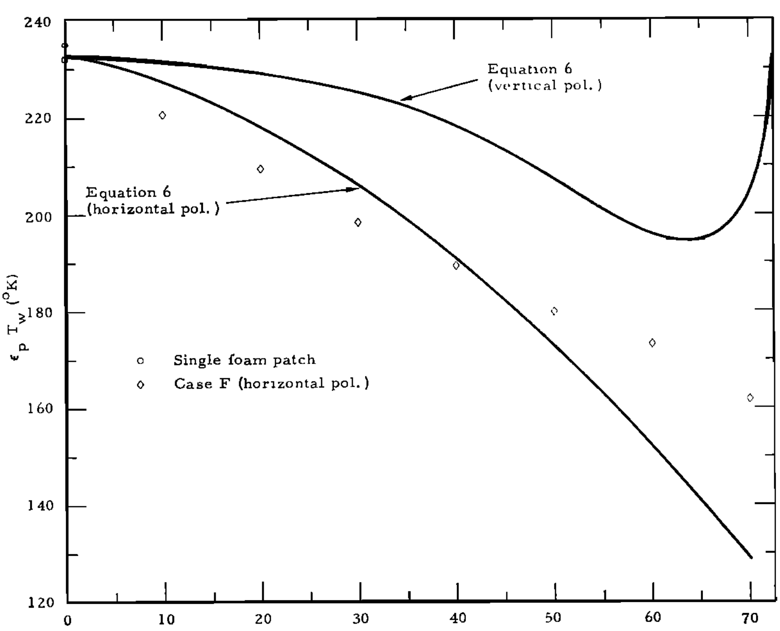

Fig. 5. Emitted temperature of foam at 19.4 GHz.

the temperature contribution to case F is consistent with both the theoretical results of *Stogryn* [1967] and the observation of *Nordberg et al.* [1971] that at $\theta = 0$ and wind speeds less than 7 m/sec (in which case foam coverage is nil) no brightness temperature increase over that of a specular surface occurs.

At angles of incidence other than $\theta = 0°$, an allowance for wave effects must be made in interpreting the data of case F. The measurements of *Hollinger* [1971] show that the product $\epsilon_h T_w$ at 19.4 GHz increases at approximately the rate $0.05 + 0.0175\ \theta$°K per m/sec wind speed for $30 < \theta < 70°$. Although the maximum wind speed on which this rate was based was 15 m/sec, an extrapolation to the 25 m/sec speed applicable to case F was made. Hence, the product $\epsilon_h T_w$ for the foam-free contribution to the brightness temperature was calculated on the basis of the specular surface result plus an additional term equal to $1.25 + 0.4375\ \theta$ °K. Although there is some deviation from Hollinger's data for angles less than 30°, the linear dependence of the additional term with θ was assumed to hold for all angles. Such an approach leads to only a small wind-speed dependence at $\theta = 0$ and is consistent with the assumptions made in the previous paragraph.

Figure 5 shows the resultant product $\epsilon_h T_w$ for a 100% foam-covered surface at 19.4 GHz when the data from Nordberg et al. is analyzed in the manner discussed above. It is important to note that $\epsilon_h T_w$ decreases with increasing angle in a manner similar to that observed at 13.4 and 37 GHz. If the effects of waves had not been extracted from the measured data, a substantial increase in $\epsilon_h T_w$ would have been obtained with increasing angle (approximately 18°K between $\theta = 0$ and 60°), thus, the implication is of an anomalous behavior at 19.4 GHz. This indirect evidence, together with the direct evidence of *Hollinger* [1970, 1971] on the temperature effects of waves, demonstrates the untennability of the contention of Nordberg et al. that the effect of wave-slope geometry is negligible when foam cover is not total. At sufficiently large angles, wave structure cannot be ignored. For θ near zero, of course, wave-geometry effects are considerably reduced in magnitude, and foam that exists on the water surface may easily produce the dominant effect.

To correlate the data shown in Figures 3–5 and to provide a means for extrapolating to other frequencies, it is desirable to fit the data with a simple analytic expression. The functional form

$$\epsilon_p(\nu, \theta)T_w = \epsilon(\nu, 0)T_w F_p(\theta) \quad (p = h \text{ or } v) \tag{6a}$$

was chosen in analogy with the known behavior of the emissivity of a smooth water surface. That is, to within an accuracy of a few per cent in the range $5 < \nu < 50$ GHz, computations show that ϵ_h and ϵ_v for the specular case may be approximated as functions of angle only times a function of frequency only. In fitting the form (6*a*) to the data, the constraint $\epsilon_h T_w = \epsilon_v T_w$ at $\theta = 0$ was imposed because of the isotropy of the foam. It was found that

$$\epsilon(\nu, 0)T_w = 208 + 1.29\nu\ °\text{K} \tag{6b}$$

$$F_h(\theta) = 1 - 1.748 \times 10^{-3}\theta - 7.336 \times 10^{-5}\theta^2 + 1.044 \times 10^{-7}\theta^3 \tag{6c}$$

$$F_v(\theta) = 1 - 9.946 \times 10^{-4}\theta + 3.218 \times 10^{-5}\theta^2 - 1.187 \times 10^{-6}\theta^3 + 7 \times 10^{-20}\theta^{10} \tag{6d}$$

where ν is expressed in GHz and θ in degrees. The curve fits were performed in the angular range $0 \leq \theta \leq 70°$. Computations based on (6) are shown in Figures 3, 4, and 5. It is believed that the analytical results fall within the uncertainties in the experimental data. The largest deviations between the analytic results and various data points occur at large angles. However, it is precisely in this region that the possibility of cumulative errors in the treatment of the data was greatest. The advantage of working primarily with data obtained from 100% foam-covered surfaces is apparent at this point. If the analytical results are applied to partially foam-covered surfaces, absolute errors are reduced by a factor f.

It is interesting to observe that the frequency dependent part of (6) is well represented by a linear function in the range $13.4 < \nu < 37$ GHz. Exact calculations for a smooth water surface also show an almost linear dependence of the emissivity on frequency in this range but with a rate of increase approximately 29% smaller than that given by (6*b*) for foam. In particular, these results imply that the increase in the brightness temperature of foam over that of a specular surface is roughly 3°K greater at 19.34 GHz than at 8.36 GHz for $\theta = 0°$ (less at higher angles). This observation is in accord with that of *Hollinger* [1970] who found the same increase at 8.36 and 19.34 GHz within his measurement error of about 20%.

ACTIVE MEASUREMENTS

No measurements of the scattering coefficients of naturally occurring foam appear to have been made. Information based on active measurements is limited to that obtained from small-scale laboratory simulation experiments and, to date, is very restricted in scope.

Two types of experiments have been reported by *Rooth and Williams* [1970] at a frequency of 9.8 GHz. One consisted of measuring the reflection coefficient of foam produced from soapy water in a small (2.5 ft. diameter) wading pool. The transmitting and receiving horns each had a half-power beam width of 17° and measurements were conducted slightly beyond the near fields of the horns. Only results for vertical polarization were obtained and these primarily for the case in which both the angle of incidence and reflection were 7°. Several different bubble sizes were investigated as well as the effect of varying the foam thickness. Upon identifying the integral term of (3) with the measured reflection coefficient, emissivities varying from 0.44 (single layer of 0.5-mm diameter bubbles) to nearly 1 (1-cm-thick foam layer) were found. Attempts to measure radiation scattered at angles that differed from the incidence angle were unsuccessful. Similar results were obtained at an angle of incidence of 45°. The second type of experiment discussed by Rooth and Williams consisted of a reflection measurement that used a slotted wave guide terminated with a 2-mm layer of foam on water. A reflection coefficient of 0.027 that, with the same assumption as above, yields an emissivity of 0.973 was found. This value agrees poorly with the passive emissivity measurements discussed in the previous section.

The only other known active measurements relating to foam were kindly performed by Mr. G. Poe for the author. Measurements of the reflection coefficient were performed with the Aerojet-General ellipsometer at a frequency of 37 GHz using a small tray of water at a temperature of 295°K. The water surface was covered by 5 mm of foam consisting of soap bubbles ranging from 0.1 to 2 mm in diameter with an average size estimated to be 0.5 mm. Measurements were made at angles of 30°, 40°, and 50° keeping the angle of incidence equal to the angle of reflection. Horizontal or vertical polarization could be chosen independently for both the transmitted and received wave. The magnitude of the cross-polarized received power from foam was found to be more than 50 db below that received with uncrossed polarization from a reference metal plate. Hence, at least for $\theta \approx \theta'$ and $\varphi \approx 0$, one can conclude that the scattering coefficients γ_{hv} and γ_{vh} are extremely small. For uncrossed polarizations, the reflection coefficients were found to be 0.130, 0.163, and 0.203 for horizontal polarization and 0.065, 0.040, and 0.010 for vertical polarization at angles of 30°, 40°, and 50°, respectively. Neither of these sets of numbers yield emissivities (assumed approximately equal to one minus the reflectivity) in quantitative agreement with the passive measurements. Several explanations are possible. The first is that the foam made from soap has different properties from natural sea foam (e.g., bubble size distribution, thickness) so that only qualitative comparisons should be made. A second possibility is that a significant amount of energy was scattered away from the specular direction (the half-power-antenna beam widths were approximately 5°), thus invalidating the assumed relation between the emissivity and the reflection coefficient. In fact, if it is assumed that the integral term in (3) has a value 50% greater than the measured reflectivities, the horizontally polarized data yields values of $\epsilon_h T_w$ of 234°, 218°, and 199°K at angles 30°, 40°, and 50°, respectively. This is in agreement with the passive emissivity data. A 50% correction does not result in adequate agreement with the passive measurements when applied to the vertically polarized data. However, the angular range over which γ_{vv} has significant values does not necessarily coincide with that of γ_{hh}. A further discrepancy arising with the vertically polarized data is that the reflectivity is monotonely decreasing with increasing angle, which implies a monotone increase in the emissivity. The increase is consistent with the increase observed with the passively obtained data at large angles but contradicts the behavior observed with this data for smaller angles at both 37 and 13.4 GHz.

Since it is possible to choose the angle of the receiving antenna to be different than that of the transmitting antenna in the ellipsometer, an attempt was made to obtain information for vertical polarization when the angles of incidence and scattering differed. Although a slight difference in the form of the scattering curve for foam compared to that of a reference metal plate was obtained, the difference was not great enough to allow a quantitative distinction to be made between possible nonspecular scattering and the effects of the finite-antenna beam widths.

Because of the limited data and gross nature of the hypotheses required to convert the reflection measurements to emissivities and because of possible structural differences between natural foam and foam made from soapy water, the scattering measurements that have been discussed do not appear to be as reliable quantitative guides to the emissivity of sea foam as the passive measurements. However, they do indicate some qualitative features that can be extrapolated validly to natural foam. In particular, it is probably correct to assume that the scattering coefficients have substantial values only for θ' differing from θ by less than 10° and that the cross terms γ_{hv} and γ_{vh} are small compared to γ_{hh} and γ_{vv} in this angular region.

CONCLUSIONS

A consistent picture of the emissivity characteristics of sea foam at microwave frequencies, which is summarized by the set of equations 6, has resulted from the analysis of available radiometric data. Although based on data obtained in the frequency range $13.4 \leq \nu \leq 37$ GHz, it is believed that an extrapolation to the range $3 \lesssim \nu \lesssim 50$ GHz is valid. The considerable scatter in the experimental data, which is evident in the figures, will hopefully, be reduced in future studies.

Presently available information on the scattering properties of foam is far less extensive than desirable for quantitative applications to radiometric problems. While it is in partial qualitative agreement with the radiometric data, quantitative agreement is lacking. Considerably more confidence is placed in the radiometric data than in the deductions based on the presently available scattering measurements.

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