SECTION 84

MICROWAVE CHARACTERISTICS OF THE OCEAN SURFACE IN THE 1-10 GHz BAND

by

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INTRODUCTION

The objective of this contract study was to investigate, in considerable detail, the microwave characteristics of calm, rough and foam-covered ocean surfaces and to develop a technique for deriving thermodynamic ocean surface temperatures from brightness temperatures measured by an Earth-orbiting radiometer. This investigation encompassed frequencies in the range 1 to 10 GHz (wavelength range of 30 to 3 cm) and was based on the use of a 1-dimensional geometric optics roughness model (1), including shadowing and multiple scattering of radiant electromagnetic energy. Provision is made, in the model, for characterizing surface roughness through the rms slope-versus-wind velocity relations previously established by other researchers (2). Suitable foam and atmospheric models were superimposed on the roughness model.

A wide variety of operating and environmental parameters were brought into the study, including both horizontal and vertical polarizations, an antenna beam zenith angle range of 0 to 60 degrees, wind velocities from 4 to 20 meters/sec., surface temperatures from 276 to 296 Kelvin, salinities of 24 to 37 parts per thousand, and atmospheric conditions ranging from clear sky to heavy rain. Following preliminary studies, concerned with the dielectric properties of model sea water, specular emissivities, and specular brightness temperatures, an initial frequency optimization analysis was performed, involving a total of twelve frequencies in the above range. Based on the response of brightness temperature to changes in surface temperature, and uncertainties introduced by the atmosphere at higher frequencies, the frequency span was compressed to the range 1.4 - 5 GHz. Concurrently, the salinity range was reduced to 31 - 37 parts/thousand, thus eliminating river estuaries from further consideration.

Rough ocean brightness temperatures were generated and a physical foam model was established. This presented some unusual problems, due to the limited amount of information available on the physical structure of a given patch of foam, and the precentage coverage of ocean surfaces by foam as a function of wind velocity. A decision was ultimately, made to represent foam as a porous homogeneous mixture of air and sea water. Comparisons were made between theoretical and experimental (3) brightness temperatures, for identical environmental conditions, at 1.4 and 8.4 GHz. The results were excellent for vertical polarization and moderate for horizontal polarization.

The above information, on the radiative properties of rough, foam-covered ocean surfaces, has been analyzed to show the influence of various operating and environmental parameters on brightness temperatures and to bring out the inherent uncertainties in derived surface temperatures. This has led to the selection of optimum radiometer operating parameters and a particular surface temperature sensing technique (4).

SPECULAR EMISSIVITIES AND BRIGHTNESS TEMPERATURES OF SEA WATER

It was realized at the outset of this study that the development of a surface temperature sensing technique would require a broad range of information, to permit optimization of radiometer operating frequency, polarization and viewing angle. This was made necessary by the basic study objective -- to analyze the accuracy with which influencing microwave characteristics of ocean surfaces and environmental conditions must be known to permit sensing sea surface temperatures to within $\pm 2^{o}C$ of the correct value.

Listed below are the operating and environmental parameters established for the study.

Frequency range:	1 to 10 GHz (wavelength range of 30 to 3 cm.)
Polarizations:	Linear horizontal and vertical.
Antenna beam zenith angles:	0 to 60 degrees.
Surface temperature range:	276 to 296 degrees Kelvin.
Sea water salinities:	24 - 37 parts/thousand. Later reduced to 31 - $37^{o}/oo$.

Ocean roughness model:	1-dimensional geometric optics, taking into account shadowing and multiple scattering.
Wind velocities:	4, 8, 14 and 20 meters/sec.
Foam thickness:	1.7 cm.
Foam coverage:	0.1 - 16% corresponding to wind velocities of 4 - 20 meters/sec.
Atmospheric models:	Clear Sky, Cloud, Moderate Rain (4 mm/hr, Heavy Rain (15 mm/hr).
Stability effects:	Influence of temperature changes, at air-sea interface, on rms wave slope and, hence, brightness temperature.

The Fresnel equations listed below, allow calculation of specular emissivities, for model sea water, utilizing values of dielectric permittivity (see Final Report (1)). Thus, the vertical, ϵ_v, and horizontal, ϵ_h, polarized components are obtained from the following expressions:

$$\epsilon_v = \frac{4(ae' + be'')\cos\varphi}{(e'\cos\varphi + a)^2 + (e''\cos\varphi + b)^2} \qquad (1)$$

$$\epsilon_h = \frac{4a\cos\varphi}{(\cos\varphi + a)^2 + b^2} \qquad (2)$$

where,

$$a = r^{\frac{1}{2}}\cos\gamma$$

$$b = r^{\frac{1}{2}}\sin\gamma$$

$$r = \left[(e' - \sin^2\varphi)^2 + (e'')^2\right]^{\frac{1}{2}}$$

$$\gamma = \frac{1}{2}\tan^{-1}\left(\frac{e''}{e' - \sin^2\varphi}\right)$$

φ is incidence angle, degrees

e' is the real part of the dielectric permittivity

and e'' is the imaginary part of the dielectric permittivity.

Figure 1 presents horizontally and vertically polarized specular emissivities as a function of frequency with temperature and salinity and incidence angle as parameters. The emissivity values show a strong relationship to increasing angle; however, at a given angle and temperature, there is a relatively small reduction as salinity increases from 24 to 37°/oo. At both vertical incidence and an angle of 30 degrees, the emissivities gradually increase with frequency, with a maximum change of approximately 0.06 from 1.4 to 9.3 GHz. The two components of polarization, at $\varphi = 30°$, depart from the vertical incidence values by approximately 0.04. The curves show clearly the effects of changes in salinity; evidently these effects are minor at frequencies above approximately 3 GHz. There is a rather small temperature dependence in the emissivities.

Computation of specular brightness temperatures, for a given homogeneous material, is a relatively straightforward procedure, once the emissivities and influencing atmospheric properties are known. The expression for specular brightness temperature is,

$$T_B = \left[\epsilon T + (1 - \epsilon)\, T_{s,\ down}\right] t_f + T_{s,\ up} \tag{3}$$

ϵ is the emissivity of the surface.

$(1 - \epsilon)$ is the reflectivity of a specular surface, under conditions of thermal equilibrium.

T is the surface temperature, °K.

$T_{s,\ down}$ is the sky brightness temperature, as viewed from the surface, °K.

t_f is the atmospheric transmission factor for that part of the atmosphere lying between the surface and the radiometer.

and $T_{s,\ up}$ is the sky brightness temperature of that part of the atmosphere between the surface and the radiometer (radiating upward to the radiometer), °K.

In the above expression, all terms except the temperature, T, are functions of antenna beam zenith angle. Uniform atmospheric conditions are implied.

BRIGHTNESS TEMPERATURES OF ROUGH OCEAN SURFACES

A naturally occurring ocean surface is characterized primatily by by the salinity and temperature of the sea water, the surface roughness, the foam coverage, and the spray layer. The effect of salinity and temperature on the emission of a specular surface has been discussed (see (4) for more detail), and the effect of a spray layer is outside the scope of this report. Thus, surface roughness and foam coverage remain to be considered.

Figure 2 shows the basic steps in the computation of rough ocean brightness temperatures. The atmospheric radiation and transmission factors generated by the program SKYTEMP are put into the programs ROUGH and FOAM TEMP. The program ROUGH calculates the emissivities and scattering coefficients of an oil-free rough ocean surface and combines them with the atmospheric data to generate brightness temperatures. The program FOAM TEMP has, as input from the FOAM program, the reflectivities of foam-air and foam-water boundaries and the attenuation factor of a foam layer (for further details see (4)). FOAM TEMP then calculates brightness temperatures for a specular layer of foam. The brightness temperatures from FOAM TEMP and ROUGH are then put into ROUGH TEMP which weights them according to the percentage of foam coverage. The output from ROUGH TEMP is the brightness temperature for a rough ocean surface, partially covered with foam.

The thermal emission and reflection characteristics of the ocean depend upon the surface geometry. In the previous section the simplest case of a plane surface was considered. In reality, however, the ocean rarely, if ever, displays a smooth, planar surface. To take into account ocean roughness, a geometrical-optics model of scattering in one dimension, developed by Lynch and Wagner (1), was used. This approach takes into account double-scattering and shadowing effects, unlike the physical-optics model developed by Stogryn (5). At large incidence angles shadowing effects must be taken into account, otherwise significant errors will result.

The Lynch-Wagner approach is essentially a ray-trace analysis which follows a ray from emission through all subsequent intersections with the surface. The infinite set of possible emissions are grouped into subsets according to the number of intersections. In the process, the total emission, visible to the observer, can be represented by the sum of an infinite series in which the first term gives the contribution by direct emission; the second term, the contribution of atmospheric radiation reflecting off the surface once, after emission, and so on. Since shadowing of an emitted ray is equivalent to a surface reflection, the shadowing effects are taken into account in each term. It can be shown that each term in the series is positive; and, therefore, by taking the first and second order terms, one can obtain a lower bound to the emissivity. In similar fashion onc can find a lower bound to the reflectivity which, in turn, gives an upper bound to the emissivity. This is accomplished by expressing the total reflection as a sum of an infinite series, in which the first term gives the contribution of incident radiation reflecting once off the surface; the second term gives the double reflection contribution; and so on. As in the case of emission, only the first two terms are considered.

It is necessary to assign probability densities to the first and second order terms for emission and reflection. If the assumption is is made that the surface is generated by a stationary random process, neglecting correlation between the two surface scattering points, one can express probability densities as known mathematical functions. It turns out that these functions are related to roughness only through the rms slope of the surface. These probability densities, coupled with expressions for the emissivity of a rough ocean surface, as well as values for scattering coefficients are used to determine the reflected atmospheric radiation.

The proper rms slope, denoted by s_o, applicable to the one-dimensional model is given by,

$$s_o^2 = s_u^2 + s_c^2 \qquad (4)$$

where,

s_u = rms slope in the upwind direction,

and s_c = rms slope in the crosswind direction.

According to Cox and Munk (2), the rms slope can be related to wind speed by the following expressions:

$$s_o^2 = \begin{Bmatrix} 5.12 \text{ X } 10^{-3} W + 0.003 \pm 0.004 \text{ Clean Surface} \\ 1.56 \text{ X } 10^{-3} W + 0.008 \pm 0.004 \text{ Oil Slick Surface} \end{Bmatrix} \qquad (5)$$

where, W. is the wind speed measured at 12.5 meters above the surface, in units of meter/sec.

For frequencies above 2 GHz, the oil-free surface rms slope is used. Below 2 GHz, where the wavelength is at least ten times longer than the maximum dimension of capillary waves, thus making these waves non-contributing to the radiation, the oil slick slope is used because it is known that oil suppresses capillary waves.

SURFACE TEMPERATURE UNCERTAINTY DUE TO UNCERTAINTIES IN ENVIRONMENTAL PARAMETERS

In developing a surface temperature sensing technique it is necessary to determine the optimum operating parameters, namely, the frequency, polarization and zenith angle that will minimize surface temperature uncertainties caused by environmental parameters i.e., the atmosphere, wind speed and salinity. To accomplish this, surface temperatures are calculated for various operating and environmental conditions. By noting the change in surface temperature, for specified changes in environmental parameters, the errors caused by environmental uncertainties can be determined.

For clarity, consider the following situation. An observer measures a brightness temperature, T_{Bo}, with a radiometer at a particular frequency, polarization and zenith angle. He then wishes to determine the surface temperature. If he knows the exact wave slope distribution, atmospheric condition and salinity, he may calculate a unique surface t emperature. However, suppose he is only given ranges for the environmental parametes, that is, he only knows the upper and lower bounds on wind speed, atmospheric condition and salinity. He must, then, calculate surface temperature for eight combinations of extreme value corresponding to the three environmental parameters. The temperatures will represent uncertainties due to environmental uncertainties.

In order to perform an analysis on surface temperature uncertainty, it is necessary to generate a brightness temperature represented by T_{Bo}. Thus, it is necessary to assume values for all the operating and environmental parameters as well as a surface temperature. The latter will be called the reference temperature, T_{ref}. Then, using the corresponding generated value for T_{Bo}, and assuming that it is the brightness temperature measured by the radiometer, the procedure for determining the uncertainties described in the preceding paragraph can be performed.

To be specific, let W_o, A_o and S_o be the lower bounds in the ranges of the wind speed, atmospheric condition and salinity; and let W_1, A_1 and S_1 be the upper bounds. In addition, consider three different values of T_{ref}: 276, 284 and 296°K. Using these reference temperatures, three brightness temperatures are generated as follows:

$$\left.\begin{aligned} T_{Bo}^1 &= F(f,\ p,\ \varphi_o,\ W_o,\ A_o,\ S_o,\ 276 \\ T_{Bo}^2 &= F(f,\ p,\ \varphi_o,\ W_o,\ A_o,\ S_o,\ 284) \\ T_{Bo}^3 &= F(f,\ p,\ \varphi_o,\ W_o,\ A_o,\ S_o,\ 296) \end{aligned}\right\} \qquad (6)$$

where: f is frequency and p is polarization.

Note that it was arbitrarily decided to use the lower bounds of the parameters to generate the assumed brightness temperatures; the upper bounds could have been used as well. Let the values of brightness temperatures, to be used for the linear interpolation, be represented by,

$$\left.\begin{aligned}
T_{B1}^{ijk} &= F(f,\ p,\ \varphi_o,\ W_i.\ A_j,\ S_k,\ 276) \\
T_{B2}^{ijk} &= F(f,\ p,\ \varphi_o,\ W_i,\ A_j,\ S_k,\ 284) \\
T_{B3}^{ijk} &= F(f,\ p,\ \varphi_o,\ W_i,\ A_j,\ S_k,\ 291) \\
T_{B4}^{ijk} &= F(f,\ p,\ \varphi_o,\ W_i,\ A_j,\ S_k,\ 296
\end{aligned}\right\} \qquad (7)$$

where, i = 0, 1; j = 0, 1; and k = 0, 1. Thus equation (7) actually represents eight different sets of equations; each set can be substituted into the following equation, to find the corresponding surface temperature:

$$^{m}T_o^{ijk} = \begin{cases} 8(T_{Bo}^{m} - T_{B1}^{ijk}) \,/\, (T_{B2}^{ijk} - T_{B1}^{ijk}) + 276; & T_{Bo}^{m} < T_{B2}^{ijk} \\ 7(T_{Bo}^{m} - T_{B2}^{ijk}) \,/\, (T_{B3}^{ijk} - T_{B2}^{ijk}) + 284; & T_{B2}^{ijk} \leq T_{Bo}^{m} < T_{B3}^{ijk} \\ 5(T_{Bo}^{m} - T_{B3}^{ijk}) \,/\, (T_{B4}^{ijk} - T_{B3}^{ijk}) + 291; & T_{B3}^{ijk} \leq T_{Bo}^{m} \end{cases} \qquad (8)$$

where, m = 1, 2, or 3 and refers to the reference temperature.

The above equation is simply an extension of equation (5). For each reference temperature, there are eight derivable surface temperatures, corresponding to the eight different commbinations of the upper and lower bounds for wind speed, atmospheric condition and salinity. let $^{m}T_o^{max}$ be the highest temperature in the set of eight and $^{m}T_o^{min}$ the lowest. Then, these two values will set an upper and lower bound on surface temperature, for a given reference temperature and set of (W_o, W_1, A_o, A_1, S_o, S_1) for specified operational parameters f, p, and φ_o.

Figure 3 shows graphically the procedure for finding $^{2}T_o^{max}$ and $^{2}T_o^{min}$, for a reference temperature of 284°K. The ranges considered are salinity variations from 31 to 37°/oo, wind variations of 0 to 8 meters/sec., and atmospheric conditions of clear sky to cloud layer. Eight curves are obtained for the various combinations; the curves for the lower bounds of all three environmental parameters are used to generate T_{Bo} from T_{ref}. The vertical dashed line represents T_{Bo}, and every intersection it makes with the family of curves corresponds to a possible surface temperature. $^{2}T_o^{max}$ and $^{2}T_o^{min}$ are the maximum and minimum possible surface temperatures.

SURFACE TEMPERATURE UNCERTAINTY RESULTING FROM COMBINED ENVIRONMENTAL UNCERTAINTIES

Several environmental parameter uncertainties will now be considered. In this analysis, three reference temperatures will be used: $276^{o}K$, $284^{o}K$ and $296^{o}K$. By using three reference temperatures, it is possible to determine the effect of the actual surface temperature on temperature uncertainties.

The information for this section was generated by program OP DEL. the program employs equations (6) through (8) to find a set of surface temperatures for each reference temperature, and for specified environmental conditions. T_o^{max} and T_o^{min} are, then, found for each set and printed out. The surface temperature uncertainty is defined as the difference between T_o^{max} and T_o^{min}. The specified environmental conditions are given by all possible combinations of the following specifications on salinity, atmosphere and wind speed:

S = 31, 33, 37, 31 - 33 and 33 - 37^{o}/oo

A = Clear, Mod. Rain, Heavy Rain, Clear - Mod. Rain, Mod. - Hvy. Rain

W = 0, 4, 8, 14, 20, 0 - 4, 4 - 8, 8 - 14, 14 - 20 meters/sec.

No information is printed out for combinations which do not include at least one uncertainty since, if there are no environmental uncertainties. The operational parameters employed are as follows:

f = 2.5 and 3 GHz

φ_o = 50 and 60 degrees

p = vertical.

The above were chosen as optimum operating parameters in the light of the previous analyses.

Some of the results are shown in Figure 4, for a fixed salinity of 33^{o}/oo. Data at the two frequencies are plotted for two wind ranges, two atmospheric ranges and for $\varphi_o = 60$. For the fixed salinity 2.5 GHz is the preferred frequency showing a lower surface temperature uncertainty for all reference temperatures.

When a range of salinities is considered it is not as easy to select an optimum frequency. It appears that, for low reference temperatures, 2.5 GHz is optimum, whereas for high reference temperatures 3 GHz is preferable. Simply stated, 2.5 GHz appears to be the optimum frequency when there is no salinity uncertainty; however, as the salinity uncertainty increases, a higher frequency is required to minimize the surface termperature uncertainty. The plots also indicate that a greater uncertainty is caused by a 4 - 8 meter/sec., range than a 14 - 20 meter/sec., range in wind velocity, and by a change from moderate to heavy rain. Lastly, the positive slope of most of the plots indicate that surface temperature uncertainty is greater for a warm ocean than a cold one.

OPTIMUM OPERATING PARAMETERS AND SURFACE TEMPERATURE UNCERTAINTY

The study indicates that, to minimize the effects of uncertainties in the environmental parameters, vertical polarization should be used, with a nominal zenith angle of 60 degrees. The choice of frequency depends somewhat on the specified environmental conditions. If there is little uncertainty in slainity, say, one or two parts per thousand, then the operating frequency should be 2.5 GHz. However, if the salinity range is greater, the optimum frequency shifts upward toward 3 GHz. In fact, if the ranges in atmosphere and wind speed were small and the salinity range was relatively large an operating frequency of 4 to 5 GHz would be justified. In addition, the salinity effect is enhanced as sea water temperature increases. Thus, if a sizable salinity range is anticipated, the optimum frequency for a warm ocean should be slightly higher than for a cold ocean, to counteract the increased salinity effect. Considering all factors, however, operation at 2.5 GHz appears to be optimum for surface temperature sensing.

Now that the optimum operating parameters have been set, the magnitude of the surface temperature uncertainty may be determined for a specified environmental situation, by referring to the 2.5 GHz, $\varphi_o = 60^o$ data generated. Considering salinity effects only, the ratio of surface temperature uncertainty to salinity uncertainty varies from 0 to 1 $^oK/^o/oo$, depending on the wind speed and reference temperature. As the reference temperature increases from 276^{o}K, the uncertainty ratio increases by a factor of three to four. In addition, a change in wind speed, from 0 to 20 meters/sec., causes the uncertainty ratio to decrease by approximately a factor of four. The atmosphere appears to have little effect on the value. In the light of this relationship, the following expression has been derived to express the uncertainty ratio as a function of wind speed and reference temperature; the latter can be considered to be surface temperature:

$$R_S = (0.25)\,(1 - 3W/80)\,\left[1 + 3(T - 276)/20\right] \qquad (9)$$

where, W is in meters/sec., and T is in degrees Kelvin. The above equation is a rough approximation and should not be taken as an exact expression.

Turning to wind speed effects, it has been noted that the ratio of surface temperature uncertainty to wind speed uncertainty varies from 0 to 0.9°K/(m/sec.). The ratio is very sensitive to the wind speed range under consideration. For the 0-4 meter/sec., and 4-8 meter/sec., ranges, the ratio has a value of 0.4 to 0.5°K/(m/sec.). The 8-14 meter/sec., range shows the largest ratios, varying from 0.3 to 0.9°K/(m/sec.), and the 14-20 meter/sec., range has the smallest ratios, varying from 0 to 0.2°K/(m/sec.). It would appear that the moderate wind speeds cause a greater uncertainty. The uncertainty ratio increases with reference temperature, approximately doubling as the temperature increases from 276°K to 296°K. The atmosphere and salinity do not have a sizable effect. The following approximate expression shows the uncertainty ratio as a function of wind speed and temperature:

$$R_W = 0.5(1 - |W - 10|/15) \left[1 + (T - 276)/20\right] \tag{10}$$

where, W is the mid-range wind speed.

The uncertainty due to atmospheric uncertainties ranges from 1.6 to 2.9°K for clear sky to moderate rain, and from 0.6 to 1.3°K for moderate to heavy rain. The uncertainty increases only slightly with temperature and salinity and is inversely proportional to wind speed. The uncertainty can be expressed as,

$$\begin{aligned} U_A^1 &= 2.9 - 0.07W, \quad \text{clear to moderate rain} \\ U_A^2 &= 1.3 - 0.035W, \quad \text{moderate to heavy rain} \end{aligned} \tag{11}$$

The temperature uncertainty resulting from a combination of environmental uncertainties may be approximated by the sum of the individual uncertainties. Referring to equation (9) through (11), the total uncertainty is given by,

$$U = R_S \, \Delta S + R_W \, \Delta W + U_A^j \tag{12}$$

in which,

$$j = \begin{cases} 1; & \Delta A = \text{Clear to moderate rain} \\ 2; & \Delta A = \text{Moderate to heavy rain} \end{cases}$$

and,

ΔS = uncertainty in salinity, °/oo

ΔW = uncertainty in wind speed, meters/sec.

and ΔA = uncertainty in atmospheric model.

Thus, the total surface temperature uncertainty, U, depends on both the magnitude of the environmental uncertainties and the mid-range wind speed and surface temperature. In general, high surface temperatures result in high temperature uncertainties.

The determination of surface temperature to within $\pm$ 2°K implies acceptance of a maximum uncertainty of 4°K. Thus, if the difference between the maximum and minimum derived surface temperatures is less than 4°K, a tolerance of $\pm$ 2°K results with respect to a temperature halfway between these values. It is rather difficult to state the conditions under which this tolerance can be satisfied. For instance, if a wind speed range of 0 to 4 meters/sec. is chosen, with an atmosphere range of moderate to heavy rain and salinity range of 31 to 33°/oo, then referring the derived surface temperature uncertainties it is evident that, for reference temperatures of 276°K or 284°K, the $\pm$ 2°K tolerance can be met; however, at 296°K the uncertainty is 4.7°K.

If a $\pm$ 2°K tolerance is to be satisfied under all conditions it will be necessary to reduce the ranges of the environmental parameters. If the salinity is known within 2°/00 and wind speed within 6 meters/sec., and if a somewhat narrower range of atmospheric uncertainty can be achieved, then a $\pm$ 2°K tolerance can be realized for most situations. However, for high surface temperatures in the vicinity of 296°K, these environmental conditions may not be sufficiently narrow. Thus, it appears that supporting sensing or data correlation techniques must be utilized to minimize derived temperature uncertainties under all environmental conditions.

CONCLUSIONS

Several conclusions of importance may be drawn from the results of this study (1). These are as follows:

1. The effects of sea water salinity on emissivities and brightness temperatures become negligible at frequencies above 4 GHz, for maximum salinity uncertainties of 4 parts per thousand.

2. Atmospheric contributions to specular ocean brightness temperatures are considerable, reaching a value of approximately 6°K for vertical polarization, a zenith angle of 45 degrees and clear sky conditions, at all frequencies from 1.4 to 9 GHZ. The contribution is somewhat greater for heavier weather conditions. Thus, atmospheric

effects must be treated with some care, if undue errors are to be avoided in derived surface temperatures.

3. Ocean brightness temperatures show a maximum response to surface temperatures at a frequency of approximately 5 GHz, vertical polarization and zenith angle of 60 degrees. For these conditions, the ratio of the change in brightness temperature to a given change in surface temperature is about 0.6, in the temperature interval 276 - 196°K.

4. At vertical incidence, emissivities decrease slightly with surface roughness, for horizontal polarization, and increase slightly for vertical polarization. The slight reduction in the first-mentioned polarization is probably due to the fact that capillary waves have not been accounted for in the roughness model. Near a zenith angle of 60 degrees, the vertically polarized emissivities cross over and decrease with roughness at angles beyond the cross-over point. A similar cross-over occurs for horizontally polarized emissivities near a zenith angle of 30 degrees.

5. Comparisons between theoretical and experimental rough surface brightness temperatures, without foam, show considerably better agreement for vertical polarization than for horizontal polarization. In the case of vertical polarization, all theoretical values fell within the experimental uncertainty.

6. A foam layer may be realistically modeled as a random porous structure, consisting of 99% air and 1% sea water. The effects of multiple reflections in the foam layer should be taken into account in any future study. In this work, a simplified once-through radiative model, with a single reflection from the underlying water, provided a reasonable basis for determining the brightness temperatures of foam-covered ocean surfaces.

7. Both horizontal and vertically polarized brightness temperatures of rough, foam-covered ocean surfaces are proportional to wind velocity, at frequencies from 1.4 to 5 GHz. In the case of vertical polarization, wind variations have a progressively smaller effect with increasing zenith angle until, in the vicinity of 60 degrees, brightness temperatures are almost independent of wind velocity. At vertical incidence, there is a gradual increase in brightness temperature sensitivity to wind velocity, at both polarizations, as frequency increases from 1.4 to 5 GHz.

8. In a manner similar to the above, the brightness temperatures of rough, foam-covered ocean surfaces are proportional to atmospheric radiation i.e., atmospheric moisture content. The effect is independent of polarization and zenith angle except at angles beyond 40 degrees, for the horizontal component of polarization, where a given increase in

atmospheric moisture causes a somewhat greater increase in over-all brightness temperatures. This is due to relatively higher surface reflectivities in this angular region. A change in atmospheric condition from Clear Sky to Heavy Rain, increases rough ocean brightness temperatures, at vertical incidence, by approximately 0.5^{o}K at 1.4 GHZ; 2^{o}K at 2.5 GHz; 5^{o}K at 4 GHz; and 8^{o}K at 5 GHz.

9. If the effects of atmospheric stability are neglected, an error of 0.8^{o}K or less results in derived surface temperatures, at 2.5 GHz, for the operating and environmental conditions considered in the study.

10. To minimize uncertainties in derived surface temperatures, due to uncertainties in wind speed and atmospheric condition, the optimum operating parameters are: a frequency of 2.5 GHz, vertical polarization and a nominal zenith angle of 60 degrees (slightly smaller errors are expected at an angle of 59 degrees). The derived temperature uncertainties for horizontal polarization are, in general, of such magnitude as to preclude consideration of this polarization for temperature sensing.

11. Surface temperature uncertainties, due solely to salinity uncertainties, can be minimized by operating at a frequency of 4 GHz or above. Thus, the choice of optimum frequency depends on the relative magnitude of the salinity uncertainty compared with other environmental uncertainties. In most cases, involving combined uncertainties, the optimum frequency remains at 2.5 GHz.

12. To satisfy the $\pm 2^{o}$K tolerance on derived surface temperatures, at 2.5GHz, the salinity should be known to within 2 parts/thousand, the wind speed to within 6 meters/sec. (approximately 12 knots) and atmospheric brightness temperature uncertainty to within 1^{o}K, at $_{o} = 60^{o}$, corresponding to approximately the difference between moderate and heavy rain. It would be helpful if the atmospheric uncertainties were reduced to narrower ranges than represented by the difference between clear sky and moderate rain (1.3^{o}K). Thus, a need exists for a supporting technique capable of furnishing some correction for atmospheric effects. Finally, since surface temperature uncertainties increase with absolute temperature, it si important that environmental uncertainties be reduced to a minimum when observing ocean areas at temperatures of 296^{o}K and above.

REFERENCES

1. Lynch, R. J. and R. J. Wagner, "Rough-Surface Scattering: Shadowing, Multiple Scatter, and Energy Conservation: J. Math. Physics, Sept. 1970.

2. Cox, C., and W. Munk, "Statistics of the Sea Surface Derived From Sun Glitter," J. Marine Research, Vol. 13, 1954, pp. 198-227.

3. Hollinger, J. P., "Passive Microwave Measurements of Sea Surface Roughness," IEEE Transactions on Geosciences Electronics, July 1971. Also, private communication on experimental data.

4. Porter, R. A. and F. J. Wentz, "Microwave Radiometric Study of Ocean Surface Characteristics," Final Report, NOAA Contract 1-35140, National Environmental Satellite Service, 1971.

5. Stogryn, A., "The Apparent Temperature of the Sea at Microwave Frequencies," IEEE Transactions on Antennas and Propagation, Vol. AP-15, No. 2, March 1967.

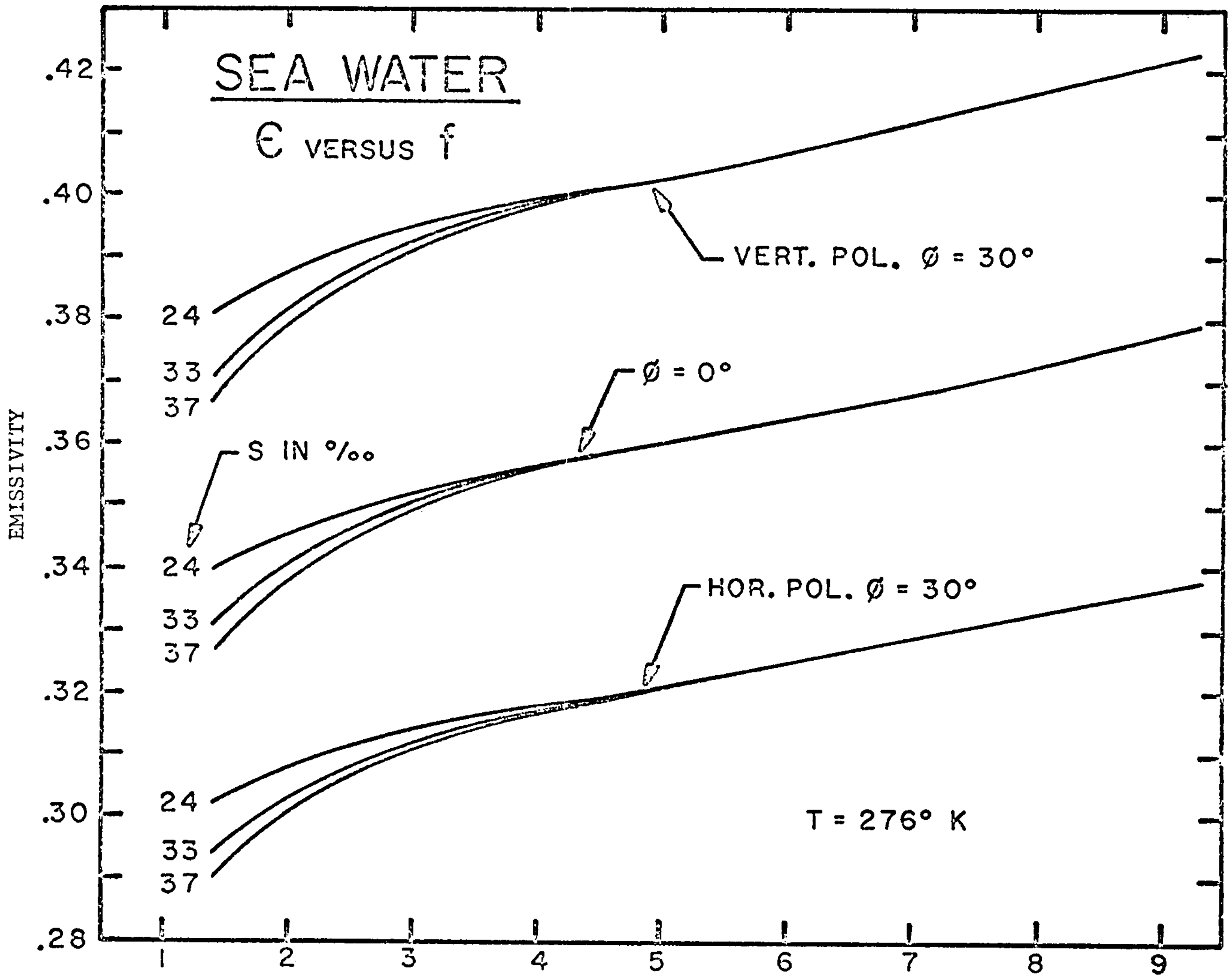

Fig. 1. Specular Emissivity of Model Sea Water versus Frequency for T = 276°K.

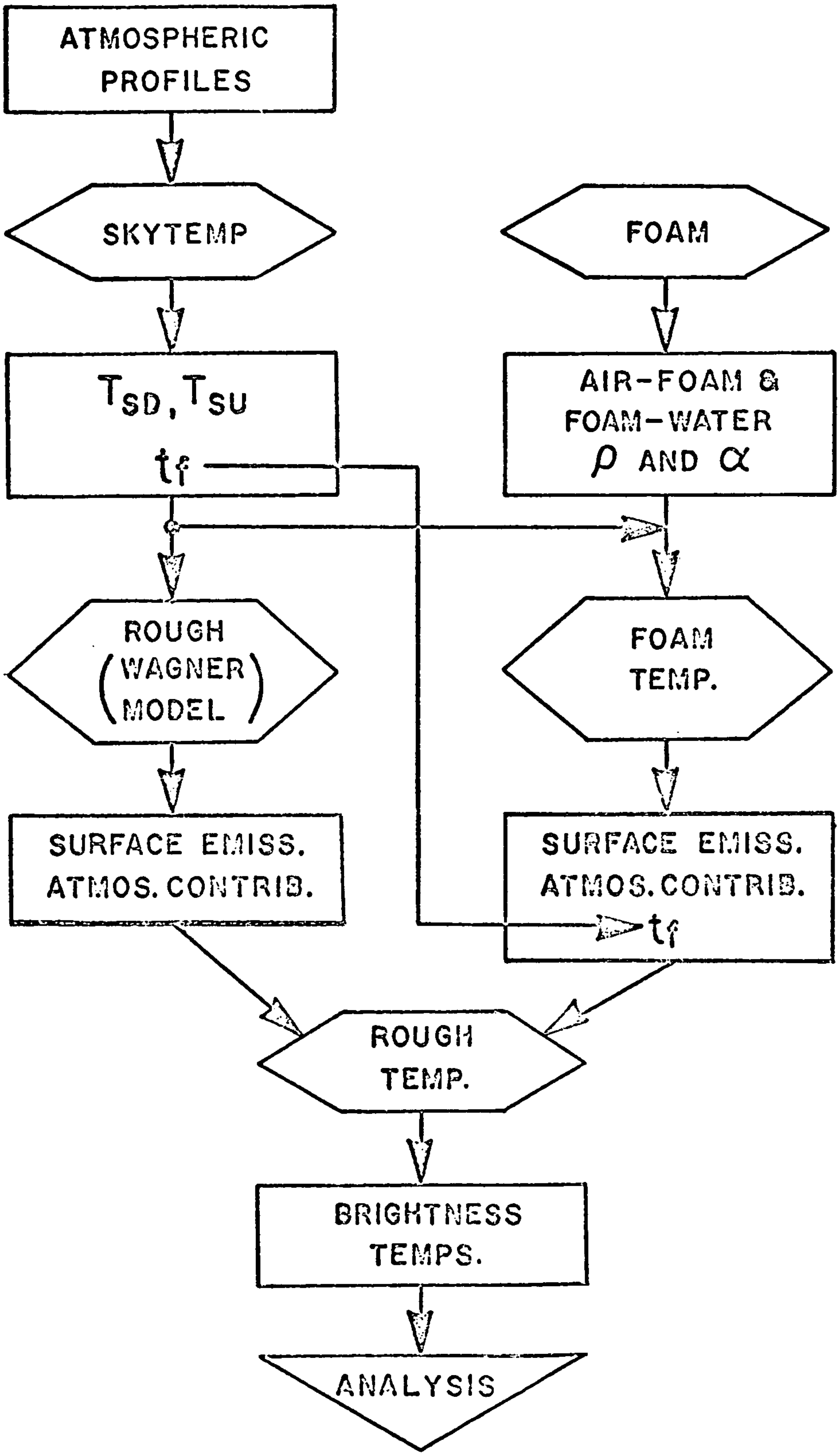

Fig. 2. Flow Chart for Computations of Rough Ocean Brightness Temperatures.

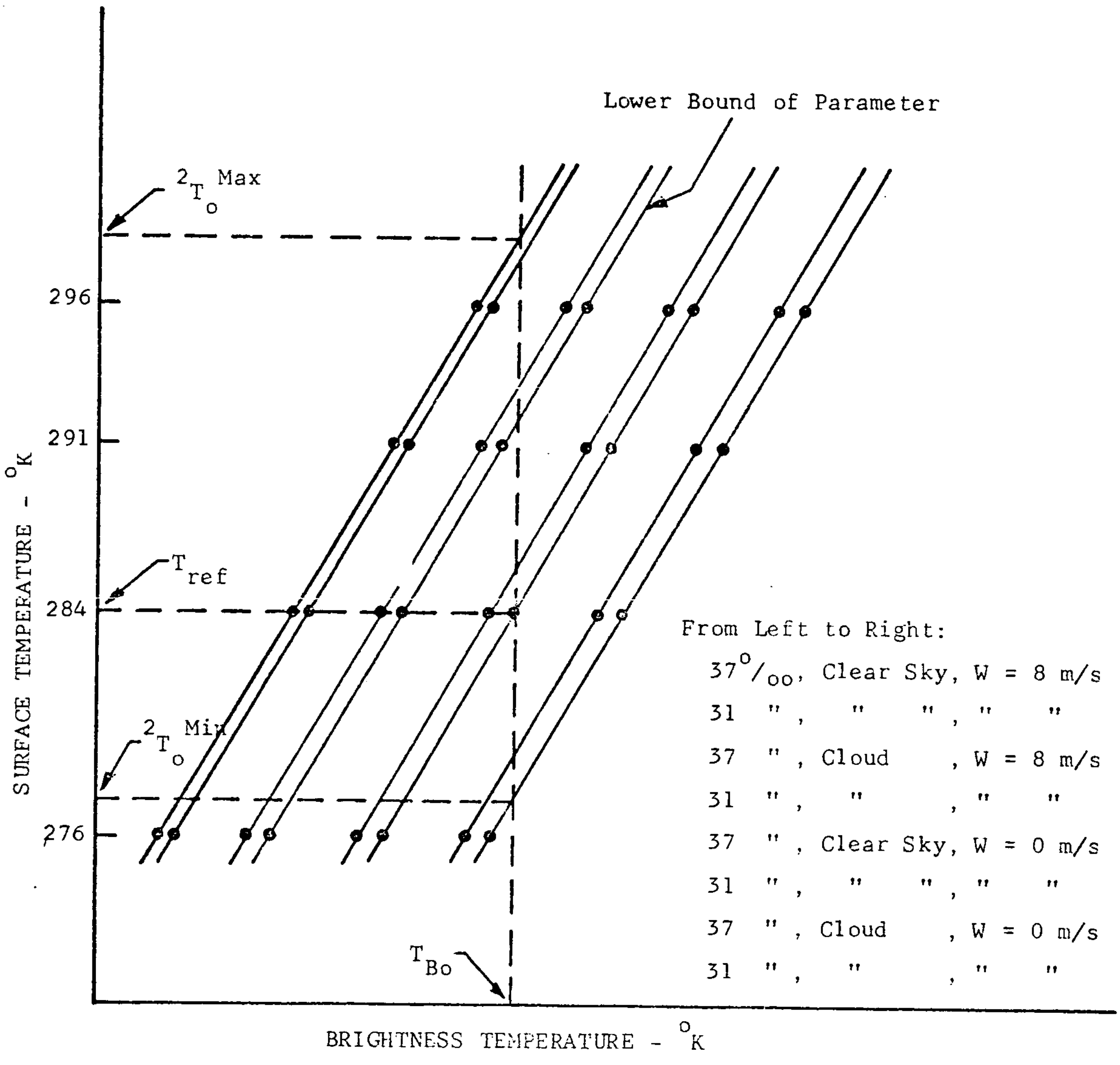

Fig. 3. Derivation of Surface Temperatures from Brightness Temperatures and Determinations of Surface Temperature Uncertainty.

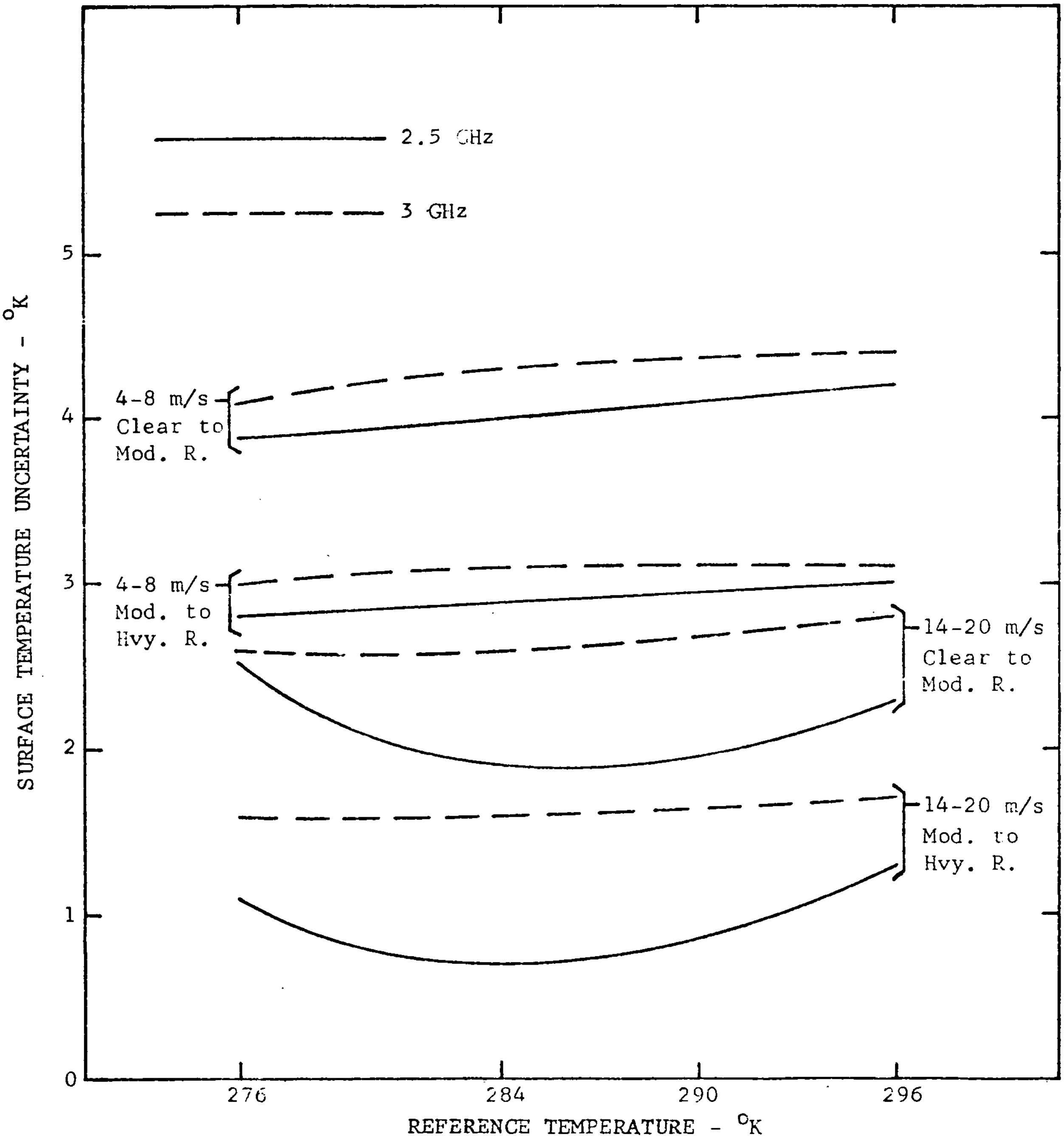

Fig. 4. Surface Temperature Uncertainty versus Reference Temperature for Combined Environmental Uncertainties (ψ_o = 60°, Vert. Pol., S = 33%).