Calibration of the Model for Ocean Surface Emissivity at Microwave Frequencies

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Abstract -- Modifications to the *Klein and Swift* [1] model for specular ocean emissivity have recently been suggested by *Ellison et al.* [2] in order to improve the performance at high microwave frequencies. The work presented here tests both the original and modified models using a set of satellite and ground based observations that is designed to eliminate as much as possible the dependence of the test on parameters other than the surface emission itself. Clear sky, low humidity, and low wind conditions were used exclusively, to reduce the dependence of the test on atmospheric and wind-roughened sea models. Radiosonde observations (RaObs) coincident with TOPEX satellite overpasses were used to reduce errors due to inexact knowledge of the atmosphere. Our tests confirm the superior performance of the Ellison model at higher frequencies. In an effort to remove the residual bias between the models and the observations, we also suggest a parameterized modification to both models that "best fits" the models to the data. In this case, the modified Ellison model maintains its superior performance at high frequencies, suggesting that it has an inherently more accurate frequency dependence. The RMS error in the modified Ellison emissivity model, over the range 18-40 GHz, is found to be 0.0037, which in terms of brightness temperatures translates into a model error of approximately 1K.

INTRODUCTION

The total brightness temperature measured by a downward looking spaceborne microwave radiometer in the zenith direction is given by

$$\begin{aligned} T_a &= T_{UP} + \in_s T_s e^{-\tau(0,H)} \\ &+ (1-\in_s)(T_{DN} + T_C e^{-\tau(0,\infty)})e^{-\tau(0,H)} \end{aligned} \qquad (1)$$

where T_s is the temperature of the surface in Kelvin, $\in_s$ is the emissivity of the surface, $(1-\in_s)$ is the reflectivity of the surface, H is the satellite height in km, T_C is the cosmic radiation, T_{DN} is the upwelling brightness temperature and τ is the opacity of the atmosphere. The total nadir emissivity of the ocean under low wind conditions can be expressed as [3],

$$\in_s = \in_{spec} + 0.0005 * W \qquad \text{for } W < 7 \text{ m/s} \qquad (2)$$

where W is the neutral stability wind speed at 19.5m above the sea surface. The first term in (2) refers to the specular emission of the sea surface and the second term refers to the effect of the wind-induced roughness on the ocean emissivity. The specular emissivity of the ocean is a function of the frequency of operation and the dielectric properties of the sea water. If the ocean surface fills a flat half-space, the emissivity at normal incidence, is given by

$$\in_{spec} = 1 - \left| \frac{1-\sqrt{\varepsilon}}{1+\sqrt{\varepsilon}} \right|^2 \qquad (3)$$

where the second term on the right is the Fresnel reflection coefficient at nadir and ε is the dielectric coefficient of the sea water. The dielectric coefficient of sea water at microwave frequencies below 40 GHz can be represented by a simple Debye relaxation expression, given by

$$\begin{aligned} \varepsilon(f,T,S) &= \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 - j2\pi\tau f} + j\frac{\sigma}{2\pi f \varepsilon_o} \\ &= c_R \varepsilon_R - j c_I \varepsilon_I \end{aligned} \qquad (4)$$

where ε_s and ε_∞ are, respectively, the static and high frequency dielectric coefficients of the sea water, ε_o is the permittivity of free space, τ is relaxation time in seconds, σ is the ionic conductivity of the dissolved salts in mho/m, and f is frequency in Hertz. The parameters ε_s, ε_∞, τ, and σ are all functions of the temperature, T, and salinity, S, of the sea water and are given by *Klein and Swift* [1] and, more recently, by *Ellison et al.* [2] (henceforth referred to as KS77 and E96, respectively). The real and imaginary parts of the permittivity are ε_R and ε_I, respectively.

We introduce two new parameters to (4),namely c_R, and c_I, which are scaling factors to the real and imaginary parts. Retrieval of the adjustable parameters, c_R and c_I, for both the KS77 and E96 ocean models is performed using the Newton-Raphson method to "best fit" the TMR data at 18 and 37 GHz. The performance of each modified model is then evaluated using the RMS, bias and frequency dependence as metrics.

The KS77 model uses a simple Debye expression for the sea water dielectric over a limited frequency range (f < 10 GHz) and polynomial fits for the static dielectric coefficient, the ionic conductivity and the relaxation time as a function of temperature and salinity. This model is still widely used for sea water dielectric coefficient although the authors recommend care when using their model at frequencies above 10 GHz. The E96 model was developed using water samples from the Mediterranean, Polar, Atlantic and Mid-Atlantic Oceans. *Ellison et al.* improved the frequency range over that of KS77 and added a polynomial fit for the high frequency dielectric coefficient.

The atmospheric absorption model described by *Liebe et al.* [4] (henceforth referred to as L93) is dominated in the microwave region by two Van Vleck-Weisskopf broadened water vapor lines, at 22 and 183 GHz, together with an oxygen absorption complex of lines taken from *Rosenkranz* [5], as well as a water vapor continuum term. The atmospheric absorption model described in *Cruz-Pol et al.* [6] (henceforth referred to as ModL) is a modification to L93 that is based on a refined set of observations of atmospheric downwelling brightness temperature by a radiometer/spectrometer operating in the near vicinity of the 22 GHz water vapor line. The modifications consisting of a 1.3% increase in the line strength, together with a 6.6% increase in the line width, of the 22 GHz absorption line are determined to be statistically significant corrections to the L93 model within the range of 18-37 GHz.

DATA SETS

The data used here includes measurements over December 1992 to May 1997, from three different sources. TOPEX altimeter data provides a measurement of the surface wind speed. RaOb profiles from fifteen (15) launch stations around the globe provide atmospheric emission and transmissivity, and near surface air temperature. National Oceanographic Data Center (NODC) data provides sea surface temperature and salinity. These data sets are combined to model the T_B observed by the TOPEX Microwave Radiometer (TMR), and the model is then compared with actual TMR measurements.

Screening of the data is intended to isolate only those cases most amenable to accurate modeling of the T_B. To this end, only low wind, cloud free, and low humidity cases are considered, and only data with near coincident TOPEX overpasses of radiosonde launches. Only TMR brightness temperatures at 18 and 37 GHz are used to test the two emissivity models, since 21GHz is much more sensitive to humidity and introduces significantly larger errors in the estimation of ocean emissivity. After all the data were filtered for the above conditions, we are left with a total of 263 RaOb profiles available with corresponding TOPEX altimeter and radiometer data. The total number of modeled vs. measured T_B data points is then 526, since we are using the two frequency channels; 18 and 37 GHz.

ANALYSIS AND RESULTS

The RMS difference between the modeled and measured T_Bs and the bias were computed for each model. Another metric, the frequency dependence of the bias, is defined as

$$FreqDep = ave\Delta T_{18} - ave\Delta T_{37} \tag{5}$$

where $ave\Delta T_f$ is the error in brightness (TB_{TMR} - TB_{model}) averaged over all 263 data points at the frequency f. This parameter is an indication of the confidence with which the model can be extrapolated to higher frequencies. The obtained values are shown on Table 1 for both ocean emissivity models, E96 and KS77. Both models are shown first with the L93 atmospheric absorption model. The models are also shown using the ModL atmospheric model developed in [6].

As seen in Table 1, the frequency dependence of KS77-L93 is very large, -2.88K. This is not surprising, since this model was meant to be valid only for frequencies less than 10 GHz, although it is commonly used for higher frequencies. The E96-L93 model improves the frequency dependence (down to -2.30K) as well as the RMS and bias.

TABLE 1. COMPARISON AMONG OCEAN EMISSIVITY MODELS.

Model		**Overall RMS**	**Bias [K]**		***FreqDep***
Ocean	**Atm.**	***[K]***	***18GHz***	***37GHz***	***[K]***
KS77	*L93*	**3.55**	-0.16	2.72	-2.88
E96	*L93*	**3.27**	-1.63	0.66	-2.30
KS77	*ModL*	**3.28**	-0.67	1.63	-2.30
E96	*ModL*	**3.45**	-2.14	-0.41	-1.74
ModKS *(c_R=1.12,*	*ModL* *c_I=.961)*	**3.03**	-0.29	0.27	-0.56
ModE *(c_R=1.15,*	*ModL* *c_I=1.001)*	**2.98**	-0.16	0.14	-0.30

The RMS and bias shown in the first two entries of Table 1 agree with results previously presented in [2]. They showed an improvement in the RMS with their E96 ocean model over KS77, as well as a lower bias, when using L93. However, when the new atmospheric model, ModL, is applied (3rd and 4th entries), the RMS and bias for the KS77 model are superior. On the other hand, E96 maintains its superior frequency dependence. This is to be expected since the E96 ocean dielectric model was developed from measurements at frequencies of up to 40 GHz. For both surface models, the frequency dependence with the new atmospheric model shows a small decrease from the one exhibited when using L93 (2.30K and 1.74K), but this dependence is still quite large when one considers the potential error from extrapolating either model to much higher frequencies (e.g. the 85-90 GHz atmospheric window).

Modified Dielectric Model Parameter Estimation

In order to reduce the sensitivity of the error to frequency as well as reduce the RMS difference and bias, both the KS77 and L96 ocean models are parameterized and adjusted to "best fit" the TMR data at 18 and 37 GHz using the Newton-Raphson method. The performance of each modified model is then evaluated using the same metrics described above.

The final estimates of the parameters are c_R = 1.12 and c_I = 0.961 for KS77 and c_R = 1.15and c_I = 1.001 for E96. These modified versions of KS77 and E96 will be referred to as ModKS and ModE in the remainder of this work. Fig. 1 depicts the emissivity as given by the two ocean models and the two modified models. The average error in the modified emissivity models, over the range 18-40 GHz, is found to be 0.0037 and 0.0035, for ModE and ModKS, respectively. In terms of brightness temperature, this error translates into approximately, 0.0037 × 290K, or 1.07 K.

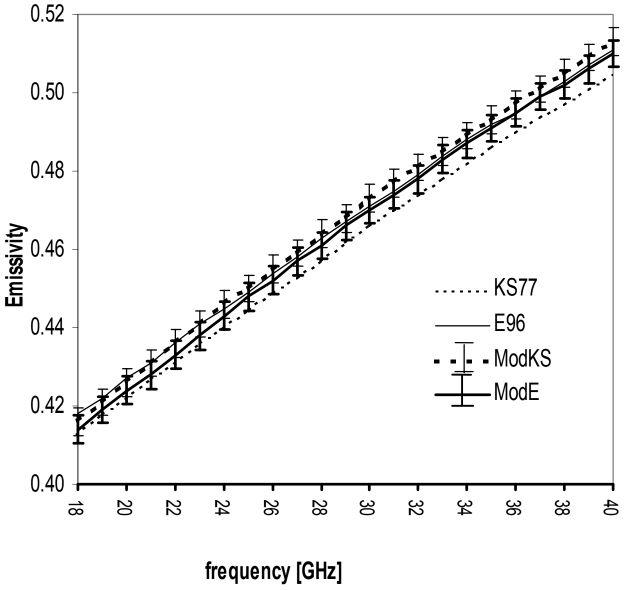

Fig. 1. The nominal and modified ocean emissivity models, KS77 and Mod KS (dash lines) and E96 and ModE (solid lines) versus frequency. The error bars denote the standard deviations in the modified models. Plot is for T_{sea}=280K and S=35‰.

The resulting RMS difference, bias and frequency dependence for the nominal and modified models are presented in Table 1. The bias in the modified models is significantly decreased, to about –0.16K for ModE and to about –0.3K for ModKS at both frequencies (see Table 1, 5th and 6th entries). The frequency dependence is also lowered, to –0.56K and –0.30K for ModKS and ModE, respectively. The overall RMS difference for both modified ocean models decreases, to 3.03K and 2.98K, respectively.

A comparison between the two modified models suggests that ModE has a superior overall performance to that of ModKS. It has the lowest bias. Its frequency dependence is half of that exhibited by ModKS, which will allow for more reliable extrapolation to higher frequencies. For these reasons, ModE is the model that we would recommend for future remote sensing applications involving microwave emissions from the ocean.

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