DEVELOPMENTS IN OCEAN INFRARED EMISSIVITY/REFLECTION MODELING: COMPARISONS AGAINST OBSERVATIONS

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1. INTRODUCTION

The infrared (IR) spectral emissivity of the earth’s surface is now recognized to be a key factor in radiative transfer forward modeling. The oceans, in particular, cover 70% of the earth’s surface, and a high degree of accuracy is generally necessary for sea surface skin temperature (SST) determination. A mere 0.5% departure from blackbody emission results in significant brightness temperature errors (0.25 K).

Much progress has been made toward modeling the spectral IR emissivity of wind-roughened water surfaces. Existing emissivity models explicitly calculate the ensemble mean emissivity of the wavy surface for a given observer zenith angle and local wind speed (e.g., Masuda et al. 1988; Watts et al. 1996; Wu and Smith 1997; Henderson et al. 2003). For example, the model of Wu and Smith (1997) is now used by both the Global Data Assimilation System (GDAS) at the U.S. National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) (van Delst 2003) as well as by the U.S. National Aeronautics and Space Administration (NASA) Atmospheric Infrared Sounder (AIRS) Science Team. This model improved upon the Masuda et al. (1988) model (used previously by both the GDAS and AIRS) by accounting for surface-emitted-surface-reflected (SESR) emission. However, field observations of emissivity spectra obtained by Hanafin and Minnett (2005) using the Marine Atmospheric Emitted Radiance Interferometer (M-AERI) (Smith et al. 1996; Minnett et al. 2001) suggest that such emissivity models are deficient at larger view angles and wind speeds. We attempt to identify and explain the sources of error in these models using M-AERI data acquired at sea (e.g., during AEROSE 2004). Our preliminary results demonstrate that proper accounting for surface emissivity in window channels must ultimately include appropriate specification of the reflected IR radiation field, especially in window channels.

2. THEORETICAL BASIS

2.1 Surface-Leaving Radiance

In this work, we are concerned with modeling the surface-leaving IR radiance for different quasi-monochromatic spectral channels, ν, observer zenith angles, θ₀, and mean surface wind speeds, U. Assuming a plane-parallel atmosphere with azimuthal symmetry, the IR radiative transfer equation for a downlooking sensor positioned near the surface (viz., M-AERI) includes a bidirectional reflectance integral that renders the exact calculation of reflectance intractable. Because the reflectance from the ocean surface may be described as quasi-specular (i.e., having a significant specular component) (e.g., Nalli et al. 2001), it is common practice to approximate the ocean surface-leaving radiance in the form of (e.g., Závody et al. 1995; Kidder and Vonder Haar 1995; Smith et al. 1996; Watts et al. 1996; Nalli and Smith 1998; Ma et al. 2002)

$$R_\nu(\theta_0) \approx \epsilon_\nu(\theta_0) B_\nu(T_s) + r_\nu(\theta_0) I_{\nu}^\downarrow(\theta_0),$$

(1)

where the atmospheric path attenuation between the observer and the surface is assumed to be negligible in window regions, and $R_\nu$ is the surface-leaving radiance observation (in mW m⁻²sr⁻¹cm⁻¹), $\epsilon_\nu$ is the surface emissivity, $B_\nu$ is the Planck blackbody function, $T_s$ is the skin SST, and $I_{\nu}^\downarrow$ is the downwelling atmospheric emitted radiance (intensity). Conservation of energy at the interface also implies that

$$\epsilon_\nu(\theta_0) = 1 - r_\nu(\theta_0).$$

(2)

Eqs. (1) and (2) suggest that the surface-leaving radiance can be approximated given only the mean reflectivity calculated at the observer angle. For specular surfaces, the reflectivity is known from first
principles in the Fresnel equations. The calculation of 
\( r_v(\theta_0) \), and hence the emissivity \( \epsilon_v(\theta_0) \), has thus been 
the focus of several previous works (e.g., Masuda et al. 
1988; Watts et al. 1996; Wu and Smith 1997; Henderson 
et al. 2003). The basis for calculating sea surface 
emissivity is the facet model which is overviewed below.

### 2.2 Analytical Facet Model

Assuming that the surface curvature due to wave 
slopes is small with respect to IR wavelengths, the 
scattered field at each point on the surface is equivalent 
to that resulting from a plane tangent to the surface at 
that point. Given a statistical description of the wave 
slope distribution, the mean reflectivity of the rough 
surface can, in principle, be defined exactly. Based 
upon aerial photographs, Cox and Munk (1954) de-
scribed the wave slope distribution as approximately 
Gaussian with the variance a linear function of \( \overline{U} \). 
This has led to the derivation of the analytical facet model 
for rough water surfaces (e.g., Masuda et al. 1988; 
Watts et al. 1996; Wu and Smith 1997; Nalli et al. 
2001; Henderson et al. 2003). The form of the equa-
tion, when expressed in local zenith and azimuth angle 
coordinates, and including physics to account for multi-
ple reflections (viz., surface-emitted, surface-reflected 
radiance) and wave shadowing (e.g., Watts et al. 
1996; Wu and Smith 1997; Nalli et al. 2001), is given by

\[
\overline{\epsilon}_v(\theta_0) = 1 - \int_{\mu_{n1}}^{1} \int_{0}^{\varphi_2} \rho^*(\Theta) \ P^*(\mu_n, \mu_0, \Theta, \sigma^2) \ d\varphi \ d\mu_n ,
\]

where \( \rho^* \) is the Fresnel reflectance coefficient (en-
hanced by surface emissions using the same slope PDF). 
\( P^* \) is a normalized probability density function 
(PDF) with variance \( \sigma^2 \), \( \mu_0 = \cos(\theta_0) \), \( \varphi_2 \) is an 
adjusted limit in the integration over azimuth angle, \( \varphi \), 
\( \Theta \) is the facet incidence angle, \( \mu_n = \cos(\theta_n) \), \( \theta_n \) being 
the local zenith angle of the facet normal vector and 
\( \mu_{n1} \) is an adjusted limit for improved quadra-
ture accuracy (Nalli et al. 2001). Eq. (3) explicitly calculates 
the rough surface emissivity as 1 minus the ensemble 
mean reflectivity. While analytical facet models similar 
to (3) have been shown to agree reasonably well with 
a limited dataset using a retrofitted AERI instrument 
et al. 1996; Wu and Smith 1997), there is nonetheless a theoretical limitation in the treatment of multiple reflections in such models (e.g., Henderson 
et al. 2003). However, a more important deficiency is the treatment of the reflected atmospheric emission 
et al. 2001) indicated in the radiative transfer approximation (1), which ignores the diffuse component of quasi-specular reflectance.

Henderson et al. (2003) addressed the multiple re-
fection problem using a Monte Carlo facet model (in-
stead of an analytical one), but they considered only 
emissivity, not the reflected component. Nalli et al. 
et al. 2001, on the other hand, attempted to address this 
latter problem by introducing a reflection-diffusivity an-
gle dependent on column transmittance and applicable 
only to microwindow channels in the LWIR window.

These limitations are only now being revealed with 
the extensive acquisition of M-AERI data in recent 
years (e.g., Hanafin and Minnett 2005). M-AERI 
measures spectra of \( I^p_\nu(\theta) \) at uplooking zenith angles 
\( 0^\circ \) (local zenith) and \( \theta_0 \), as well as the surface-leaving 
radiance, \( R_v(\theta_0) \), at downlooking nadir angle \( \theta_0 \). M-
AERI uses these spectra to retrieve surface emissivity 
based on the premise of finding an effective incidence angle, \( \Theta_{ie} \), that minimizes spectral variance caused by 
absorption features (e.g., Smith et al. 1996; Hanafin 
et al. 2005). Based on M-AERI emissivity 
extractions, Hanafin and Minnett (2005) found that 
emissivity models (viz., Masuda et al. 1988; Watts 
et al. 1996) underestimate emissivity at large \( \theta_0 \) and \( \overline{U} \).

### 2.3 Ensemble Mean Geometry

Hanafin and Minnett (2005) present much of their 
results in terms of \( \Theta_{ie} \). This motivated development 
of a preliminary new approach in this work, namely to 
calculate the effective incidence angle as the ensemble 
mean relative incidence angle, \( \overline{\Theta}_i \), of the surface wave 
facets:

\[
\overline{\Theta}_i = \frac{\int_{\mu_{n1}}^{1} \int_{0}^{\varphi_2} \Theta_i \ P^* \ d\varphi \ d\mu_n}{\int_{\mu_{n1}}^{1} \int_{0}^{\varphi_2} P^* \ d\varphi \ d\mu_n}.
\]

Henderson et al. (2003) wrote a similar formula (based 
on a simplified form of Eq. (3) that excluded the effects 
of wave blocking) to demonstrate the existence of a 
cross-over angle (\( \simeq 68^\circ \)) where increasing \( \overline{\Theta} \) increases 
\( \overline{\epsilon}_v \).

Likewise, the mean local zenith angle of down-
elling radiance is given by

\[
\overline{\theta} = \frac{\int_{\mu_{n1}}^{1} \int_{0}^{\varphi_2} \theta \ P^* \ d\varphi \ d\mu_n}{\int_{\mu_{n1}}^{1} \int_{0}^{\varphi_2} P^* \ d\varphi \ d\mu_n}.
\]

Note that neither of Eqs. (4) or (5) require assump-
tions about multiple reflections since they only predict 
the geometries arising from the mean facet inclination. 
Lookup tables of \( \overline{\Theta}_i(\theta_0, \overline{\Theta}) \) and \( \overline{\theta}(\theta_0, \overline{\Theta}) \) are computed 
for 3 different published mean square slope PDFs (viz.,
Cox and Munk 1954; Su et al. 2002; Ebuchi and Kizu 2002). The results for the mean incidence angle $\Theta_i$ (not shown here) agree roughly with the observations of Hanafin and Minnett (2005) for $\theta_i = 55^\circ$, whereby $\Theta_i$ is seen to decrease with increasing wind speeds, thus increasing the mean emissivity. The cross-over angle actually lies somewhere between $30^\circ$–$40^\circ$, depending on the PDF model. This value is notably smaller than the previous estimates of $68^\circ$ (e.g., Masuda et al. 1988; Watts et al. 1996; Wu and Smith 1997; Henderson et al. 2003).

Based upon the mean geometries given by Eqs. (4) and (5), we propose a preliminary alternative approximation to (1), namely

$$R_\nu(\theta_0) \approx [1 - \rho_\nu(\Theta_i)] B_\nu(T_s) + \rho_\nu(\Theta_i) I_\nu(\theta) ,$$

(6)

where $\rho_\nu$ is the Fresnel reflection coefficient. While this equation also ignores diffuse contributions, it more accurately represents the specular component arising from the specified wave slope geometry.

3. PRELIMINARY RESULTS

To assess the relative accuracies of approximations (1) and (6), we rely on field observations of surface-leaving radiance spectra. The M-AERI is a ship-based Fourier transform IR spectrometer (FTS) that measures calibrated, high-resolution radiance spectra ($\approx 0.5$ cm$^{-1}$ over $\approx 550$–3000 cm$^{-1}$), from both the upwelling and downwelling directions (Minnett et al. 2001). The M-AERI spectral observations used in this preliminary work originate from the 2004 Aerosol and Ocean Science Expedition (AEROSE) in the tropical North Atlantic Ocean. More than 2 weeks of continuous M-AERI data were collected during the AEROSE field experiment; for more details, the reader is referred to Nalli et al. (2006).

The downlooking view at $\theta_0 = 55^\circ$ provides what we consider to be the approximate “true” surface-leaving radiance in window channels (in absorption bands, the atmospheric path between the sensor and the surface obscures the surface signal). We can then use Eqs. (1) and (6) to model the surface-leaving radiance, given the high-accuracy M-AERI retrieval of $T_s$ and the observed downwelling atmospheric radiances, $I_\nu(\theta_0)$, at $\theta_0 = 55^\circ$ and $0^\circ$. We find in our calculations that $\bar{\theta}$ in Eq. (6) is $50^\circ < \bar{\theta} \leq 55^\circ$, so we approximate the radiance at the computed $\bar{\theta}$ from the Beer-Lambert law

$$I_\nu(\bar{\theta}) \approx I_\nu(\theta_0) \exp \left[-\tau_\nu(\sec \theta_0 - \sec \bar{\theta}) \right] .$$

(7)

Because the atmosphere is not isothermal, approximation (7) will underestimate the actual downwelling radiance, but by a factor of 2 less than the overestimation that would occur from using the $55^\circ$ observation itself. Note that the observed downwelling radiance during AEROSE accounts for all atmospheric conditions, including clouds and high levels of dust aerosols.

The mean differences between the modeled and observed surface-leaving brightness temperatures (LWIR window region) for the entire AEROSE cruise using the Cox and Munk (1954) wave slope PDF is shown in Fig. 1. The results for the SWIR window region (daytime only subsample) are shown in Fig. 2. It can be seen that the LWIR calculations based upon Eq. (1) (blue shades) systematically underestimate the observed spectra by 0.1–0.2 K. Because of the reduced atmospheric reflection in the more transparent SWIR window region, the magnitude of bias for the SWIR is somewhat less and spectrally constant at about 0.1 K. The underestimation in the LWIR window is about the same size as the RMS errors for atmospheric transmittance model fitting alone. Calculations based upon Eq. (6), on the other hand, are much closer to the observed spectrum. Note that nearly identical results were obtained using the Su et al. (2002) and Ebuchi and Kizu (2002) wave slope PDFs (not shown here). Thus the potential corrections to be derived from this work amount to a significant improvement in the context of the complete forward radiance model.

![Figure 1: Mean differences between the modeled and observed surface-leaving brightness temperatures (LWIR window region) for the entire AEROSE cruise using the Cox and Munk (1954) wave slope PDF model. The blue and cyan lines are based upon Eq. (1) whereas the red and magenta lines are based upon Eq. (6). Corrections for the mean ship roll angle are applied in the cyan and red curves as indicated in the legend.](image-url)
4. SUMMARY AND FUTURE WORK

This work has presented corroborating evidence that the conventional approach to modeling IR surface-leaving radiance, namely Eqs. (1), (2) and (3), results in a systematic underestimation of radiance in hyperspectral microwindow channels (viz., from M-AERI and presumably AIRS) for non-zero wind speeds and scan angles. While the magnitude of the bias (0.1–0.2 K for $\theta_0 = 55^\circ$) may be negligible for many IR applications, it is significant for high accuracy applications such as skin SST. The angular dependence is particularly important for retrievals from geosynchronous satellites (e.g., GOES and Meteosat), which must observe the earth’s surface at large, constant incidence angles. We propose an alternative approach that correctly treats the specular component of emissivity and reflection from rough water surfaces. Our results thus far show good agreement with M-AERI observed surface-leaving radiance spectra. This new approach to emissivity/reflection modeling will be refined and validated against M-AERI field data from several previous oceanographic cruises from different regions of the globe. This work will be the subject of a future paper.

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REFERENCES


