Ocean Surface IR Emissivity and Reflectance

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Introduction

- The IR spectral radiative properties of the earth's surface (viz., emissivity and reflectance) are recognized to be key factors in most satellite remote sensing applications

- Although the surface emissivity is often close to unity, the current accuracy requirements for parameter retrievals have invalidated the "classical" (e.g., Twomey, 1977) assumption of a blackbody surface (e.g, Kornfield and Susskind, 1977)

- Therefore, most statistical and physical retrieval algorithms must account somehow for non-unity emissivity

IR Radiative Transfer 101

Definitions

(assuming azimuthal symmetry)

- **Emissivity:**

$$\varepsilon_\nu(\theta_0) = \frac{R_\nu(\theta_0)}{B_\nu(T_s)}$$

- **Absorptivity:**

$$a_\nu(\theta_0) = \frac{I_{\nu a}^{\downarrow}(\theta_0)}{I_\nu^{\downarrow}(\theta_0)}$$

- **Bidirectional reflectance (BRDF):**

$$r_\nu(\theta,\theta_0) = \frac{I_{\nu r}^{\uparrow}(\theta_0)}{I_\nu^{\downarrow}(\theta)\cos(\theta)}$$

Conservation of Energy and Kirchhoff's Law for Surfaces

Conservation of Energy implies that for radiance incident upon a layer interface

$$a_\nu I_\nu + r_\nu I_\nu + \tau_\nu I_\nu = I_\nu$$
$$\Rightarrow a_\nu + r_\nu + \tau_\nu = 1.$$

For an opaque surface,

$$\tau_\nu = 0$$
$$\Rightarrow r_\nu = 1 - a_\nu.$$

For a layer in thermodynamic equilibrium, **Kirchhoff's Law** states that

$$\varepsilon_\nu(\theta_0) = a_\nu(\theta_0)$$
$$\Rightarrow \varepsilon_\nu(\theta_0) = 1 - r_\nu(\theta_0)$$

IR Radiative Transfer Equation (RTE)

(assuming azimuthal symmetry)

$$R_\nu(\theta_0) = \underbrace{\left[\varepsilon_\nu(\theta_0) B_\nu(T_S) + \underbrace{\int_0^{\pi/2} r_\nu(\theta,\theta_0) I_\nu^{\downarrow}(\theta) \cos\theta \sin\theta \, d\theta}_{I_{\nu r}(\theta_0)} \right]}_{R_{\nu s}(\theta_0) \equiv \text{Surface Leaving Radiance}} \tau_{\nu s}(\theta_0) + I_\nu^{\uparrow}(\theta_0),$$

$R_\nu(\theta_0) \equiv$ observation

$I_{\nu r}(\theta_0) \equiv$ surface reflected radiance

$\varepsilon_\nu(\theta_0) \equiv$ surface emissivity

$\tau_{\nu s}(\theta_0) \equiv$ path transmittance

$r_\nu(\theta,\theta_0) \equiv$ bidirectional reflectance

$I_\nu^{\downarrow}(\theta) \equiv$ downwelling radiance

$I_\nu^{\uparrow}(\theta_0) \equiv$ upwelling radiance

$B_\nu(T_S) \equiv$ blackbody surface emission

$\theta \equiv$ local zenith angle

$\theta_0 \equiv$ observer local zenith angle

Optics 101

Air-Water Interface Plane

- **Complex index of refraction:** $N_\nu = n(\nu) + i\,k(\nu)$
- **Snell's Law:** $n(\nu) = \dfrac{\sin(\Theta_i)}{\sin(\Theta_t)}$
- **IR Reflectivity:** $\rho(N_\nu, \Theta_i) = \dfrac{1}{2}\left(|\rho_{\|}|^2 + |\rho_{\perp}|^2\right)$
- **Fresnel Equations:**

$$\rho_{\|}(N_\nu, \Theta_i) \equiv \left(\frac{E_{0r}}{E_{0i}}\right)_{\|} = \frac{N_\nu \cos\Theta_i - \cos\Theta_t}{N_\nu \cos\Theta_i + \cos\Theta_t}$$

$$\rho_{\perp}(N_\nu, \Theta_i) \equiv \left(\frac{E_{0r}}{E_{0i}}\right)_{\perp} = \frac{\cos\Theta_i - N_\nu \cos\Theta_t}{\cos\Theta_i + N_\nu \cos\Theta_t}$$

- Such reflection is defined as **specular**.

Optical Constants of Water

- The **extinction coefficient** $k(\nu)$ has been obtained in the laboratory by applying the Beer-Lambert Law for the attenuation of radiant flux through a cell wedge of pure water.
- The refractive index $n(\nu)$ can then be obtained from *k* via Kramers-Kronig analysis (a Fourier transform technique).
- Friedman (1969) obtained corrections for the effects of dissolved ions present in sea water.

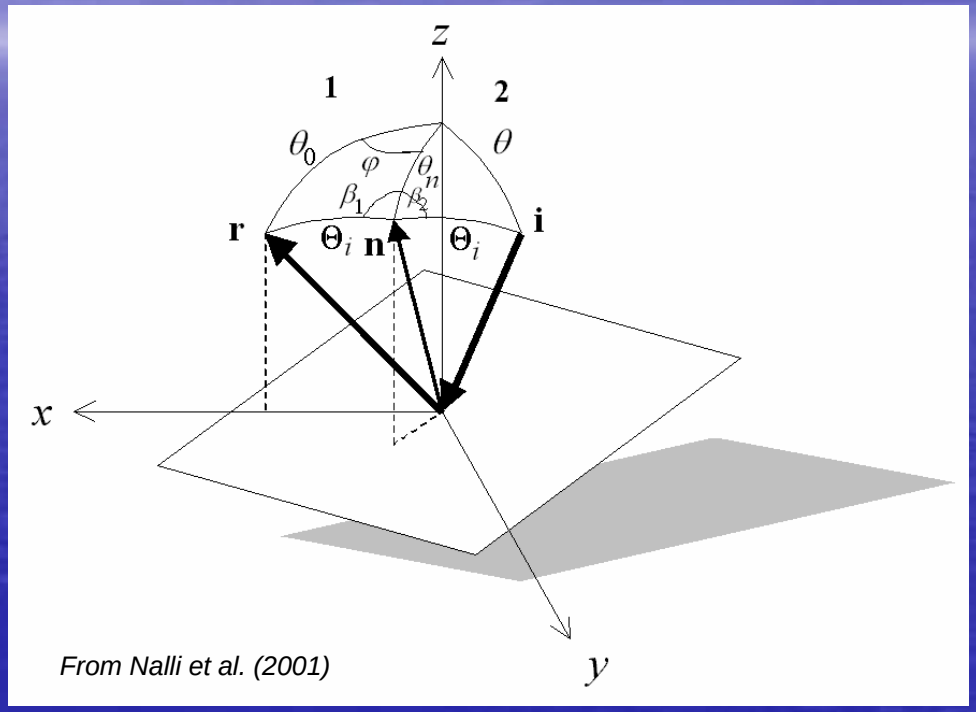
Analytical Facet Model

Wind Roughened Water Surfaces

- Winds perturb the surface creating capillary waves, which, depending on speed and fetch, generate “gravity” waves.
- This roughness scatters incident radiation in directions other than the specular direction.
- Because surface curvature is large compared to IR (and visible) wavelengths, the geometrical optics limit applies.

Wave-Facet Tangent Plane

- The reflected field at each point on the surface is then equivalent to that from a plane tangent to the surface at that point.
- Waves can thus be modeled as facet planes.
- IR (and visible) reflection from water surfaces is considered **quasi-specular**, because the specular component is still significant.



Cartesian coordinate system for a wave facet

Wave Slope Probability Distribution

- Cox and Munk (1954) (and others) have found that the ocean surface slope distribution to be approximately Gaussian and isotropic

$$P(z_x, z_y) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{z_x^2 + z_y^2}{2\sigma^2} \right)$$

- Cox and Munk also found the mean-square slope σ^2 to vary directly and linearly with wind speed.
- The ensemble mean emissivity is written as

$$\bar{\varepsilon}_\nu(\theta_0) = 1 - \frac{1}{\mu_0} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho_\nu(\Theta_i) P(z_x, z_y) \frac{\cos(\Theta_i)}{\mu_n} dz_x dz_y$$

Coordinate Transformation and Accounting for Wave Blocking

- The slope components (z_x, z_y) are expressed in terms of local zenith cosine and azimuth angle

$$P(z_x, z_y) = P(\mu_n, \sigma^2) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{1-\mu_n^2}{2\mu_n^2\sigma^2} \right)$$

- Wave blocking is accounted for by adjusting the limit on the azimuth integration and using a normalized PDF, P^*. The facet model is then expressed as

$$\overline{\varepsilon}_\nu(\theta_0) = 1 - \int_0^1 \int_0^{\varphi_2} \rho_\nu(\Theta_i) P^*(\mu_n, \sigma^2)\, d\varphi\, d\mu_n$$

- This essentially is the famous Masuda et al. (1988) model. Among other things, Masuda et al. published convenient lookup tables of model emissivity

$$\overline{\varepsilon}_\nu \equiv 1 - \overline{\rho}_\nu = f(\nu, \theta_0, \overline{V})$$

Observations of Ocean Surface Emissivity

Field Observations

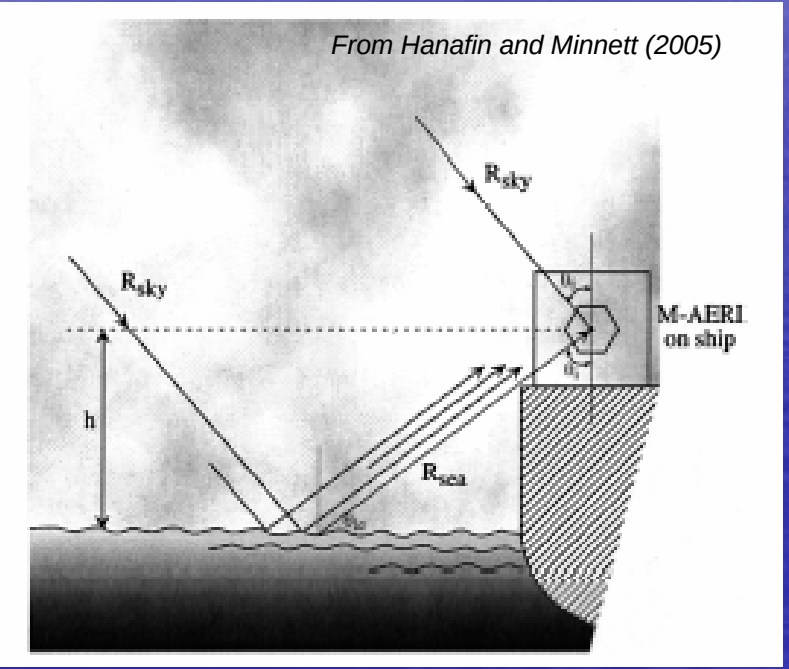
- Despite the convenience of the Masuda et al. (1988) model, it was not widely used. This was probably because of the lack of any means to "validate" the model against independent field data.

- In 1995, a retrofitted UW-Madison Atmospheric Emitted Radiance Interferometer (AERI) was deployed at sea for a 4-day field experiment in the Gulf of Mexico (Smith et al., 1996). For the first time, IR spectra of the ocean surface were obtained.

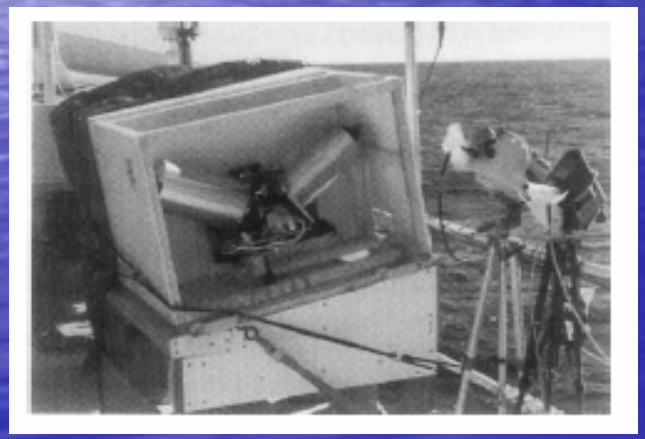
- The algorithm for retrieving spectral emissivity from the AERI (and today's M-AERI) uplooking (atmospheric) and downlooking (ocean) radiances is based upon

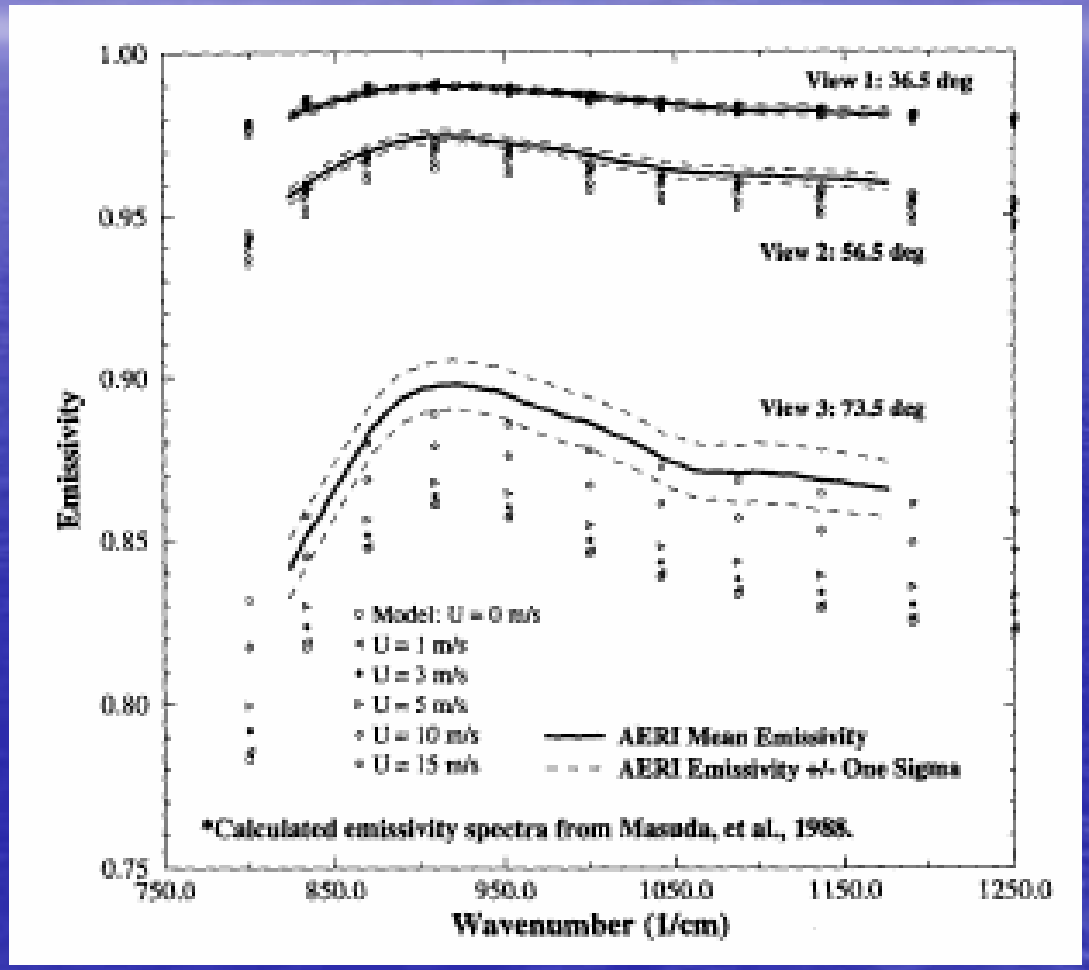
$$T_B(\nu,\theta) = B_\nu^{-1}\left(\frac{R_\nu^{\uparrow}(\theta_{sea}) - [1-\varepsilon_\nu(\Theta_{ie})]R_\nu^{\downarrow}(\theta_{sky})}{\varepsilon_\nu(\Theta_{ie})}\right)$$

The effective incidence angle of the emissivity is iterated until the T_B spectral variance is minimized.



First Comparison of Masuda Model Against AERI Field Observations (Smith et al., 1996)





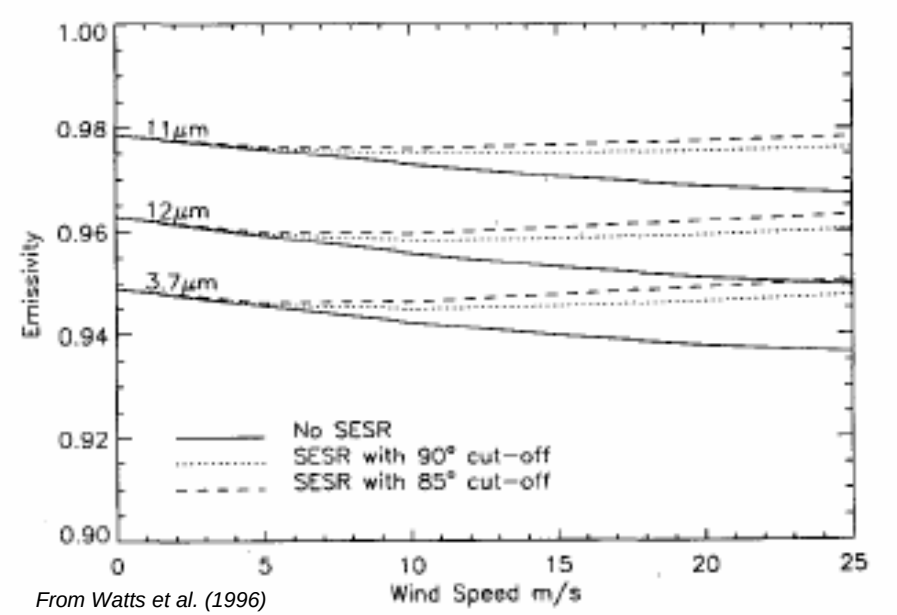
Figures from Smith et al. (1996)

Enhancements

- Comparisons against observed emissivity from AERI during the 4-day Gulf of Mexico cruise suggested a significant deficiency in the Masuda model at larger view angles.
- This has led to a number of recent enhancements in the basic emissivity facet models.
- Watts et al. (1996) and Wu and Smith (1997) both include physics to account for multiple reflections.
  - Surface-emitted, surface-reflected (SESR) radiation was determined to be significant
  - SESR was accounted for by first computing an enhanced Fresnel reflectivity using the same PDF
- More recently, Henderson et al. (2003) used a Monte Carlo facet model to account for this effect in a more rigorous manner.

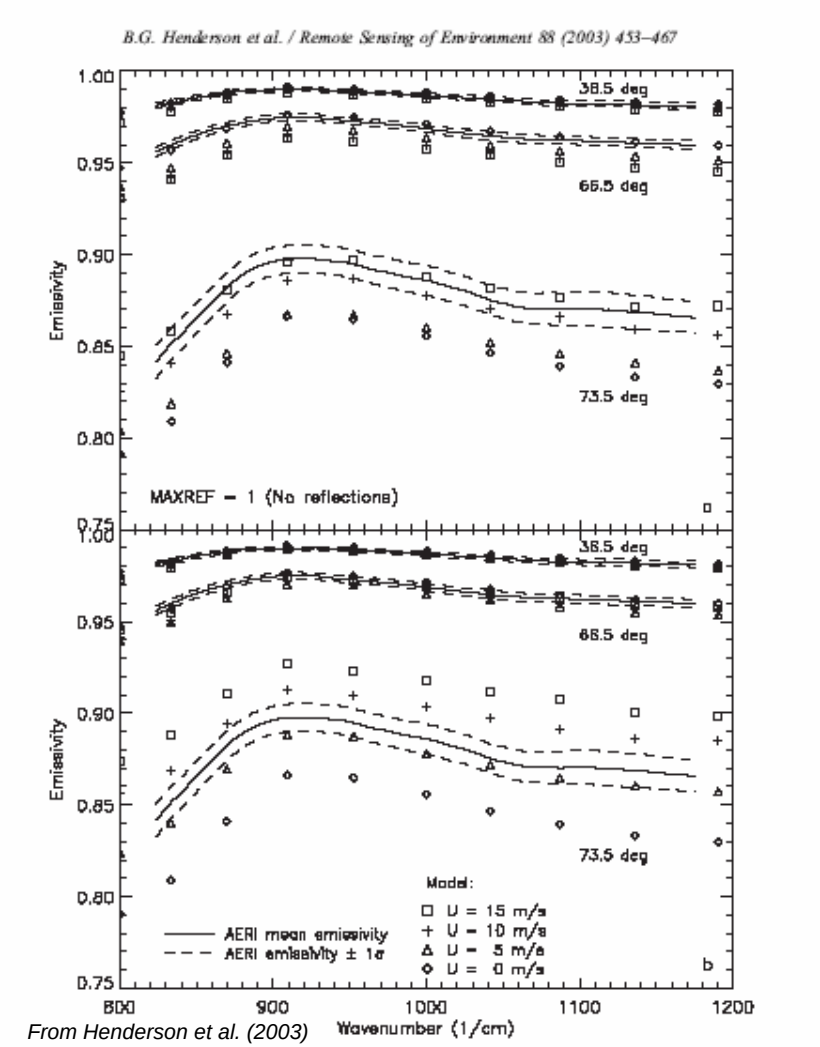
Enhanced Emissivity Models

Watts et al. (1996)



From Watts et al. (1996)

Henderson et al. (2003)



From Henderson et al. (2003)

- Among other things, note that the enhanced emissivity models predict a higher emissivity with increasing surface roughness.
- It should also be noted that these models have not attempted to model the reflected component of radiance.

Summary

- Over oceans, spectral emissivity can be predicted as a function of local surface windspeed, based upon classical interface optics and the wave facet model.
- Land surfaces are another story…
- Published ocean emissivity models compare reasonably well against observations (viz., AERI).
- However, more recent results from M-AERI (Hanafin and Minnett, 2005) are showing even these “enhanced” models to be somewhat deficient at larger angles and windspeeds.
- To be continued…