Ocean Surface Reflection / Emissivity Model

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Radiative Transfer Equation (RTE)

Cloud free, non-scattering, azimuthal symmetry

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

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

$R_{\nu s}(\theta_0) \equiv$ 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

$\theta_0 \equiv$ local satellite zenith angle

Ocean Surface IR Emissivity and Reflectance

- Radiance emissivity models (e.g., Masuda et al., 1988; Watts et al., 1996; Wu and Smith, 1997) have been derived from Cox-Munk wave slope statistics.
- Lookup tables (LUT) of model emissivity are used in radiative transfer modeling:

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

- Reflectance of atmospheric radiance is a more challenging problem:
  - Surface is neither specular nor Lambertian, but **quasi-specular**
  - Depends upon the hemispherical radiance distribution
  - Using 1 – ϵ may lead to systematic errors of forward radiance in window channels
  - These errors may be significant for applications requiring high accuracy (e.g., SST)

Marine Atmospheric Emitted Radiance Interferometer (M-AERI)

- **Ship-based FTS** designed to sample downwelling and upwelling calibrated IR spectra near the surface (Minnett et al., 2001)
- High accuracy calibration is achieved using 2 **NIST-traceable** blackbodies
- **Derived products** include
  - High accuracy radiometric skin SST derived from semi-opaque spectral region (~7.7 μm) (Smith et al., 1996)
    - Essential for accurate cal/val of advanced instruments and algorithms
    - 0.1 K absolute accuracy– this simply is the “gold-standard” for satellite “ground truth”
  - Continuous retrievals of lower tropospheric profiles at turbulent time scales (e.g., Feltz et al., 1998)
  - Retrieval of ocean surface spectral emissivity

M-AERI Field Campaigns

1996 Combined Sensor Program (CSP)

NOAA Ship *Discoverer*
Pago Pago, March 96

UW-Madison M-AERI Prototype
Onboard NOAAS *Discoverer*

CSP Photo credits: B. Osborne

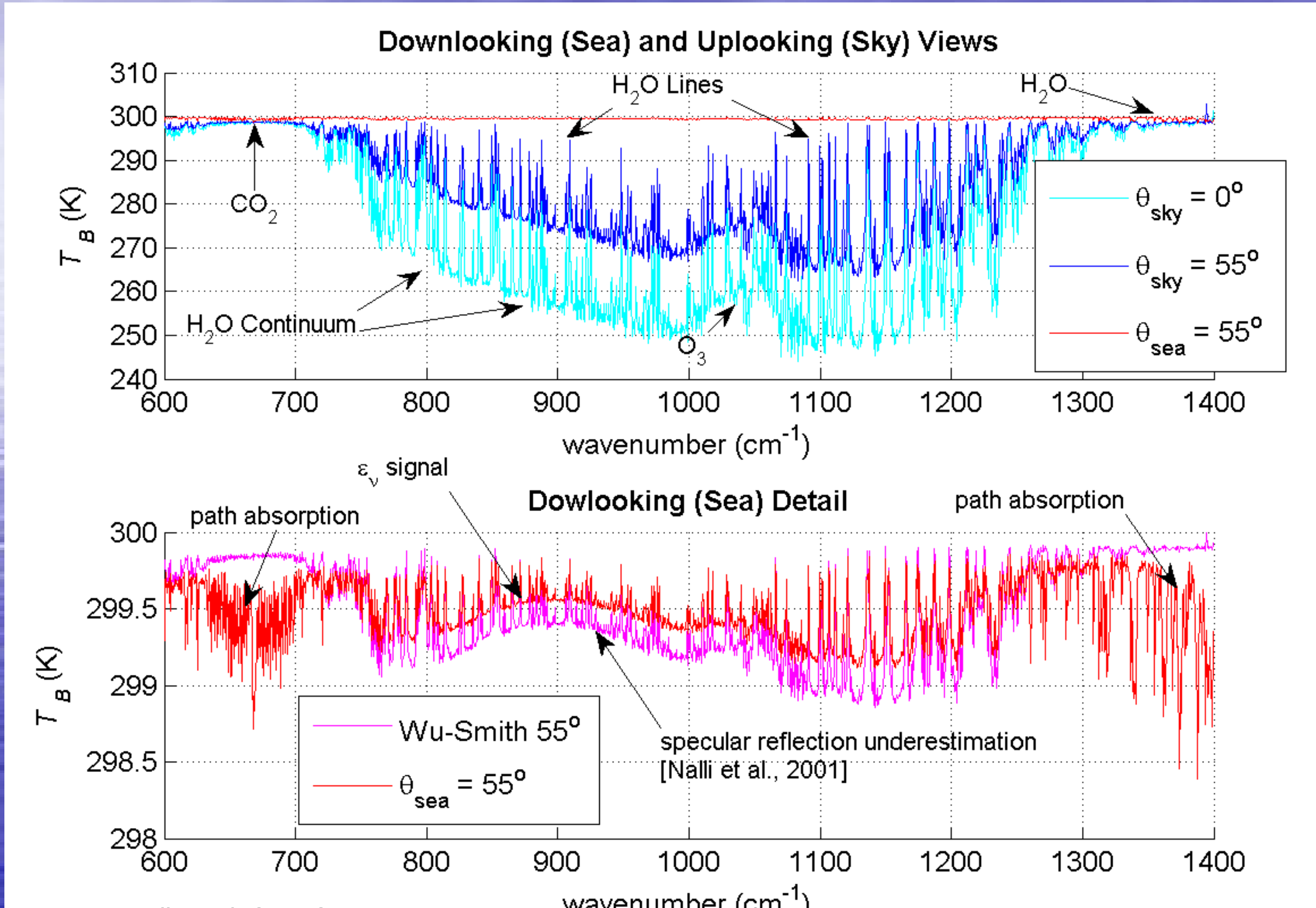
2004 Aerosol and Ocean Science Expedition (AEROSE)

U. Miami M-AERI &
UW/APL CIRIMS

NOAA Ship *Ronald H. Brown*
Bridgetown, Feb 04

M-AERI High Resolution Spectra

M-AERI Brightness Temperatures, AEROSE 06-Mar-04

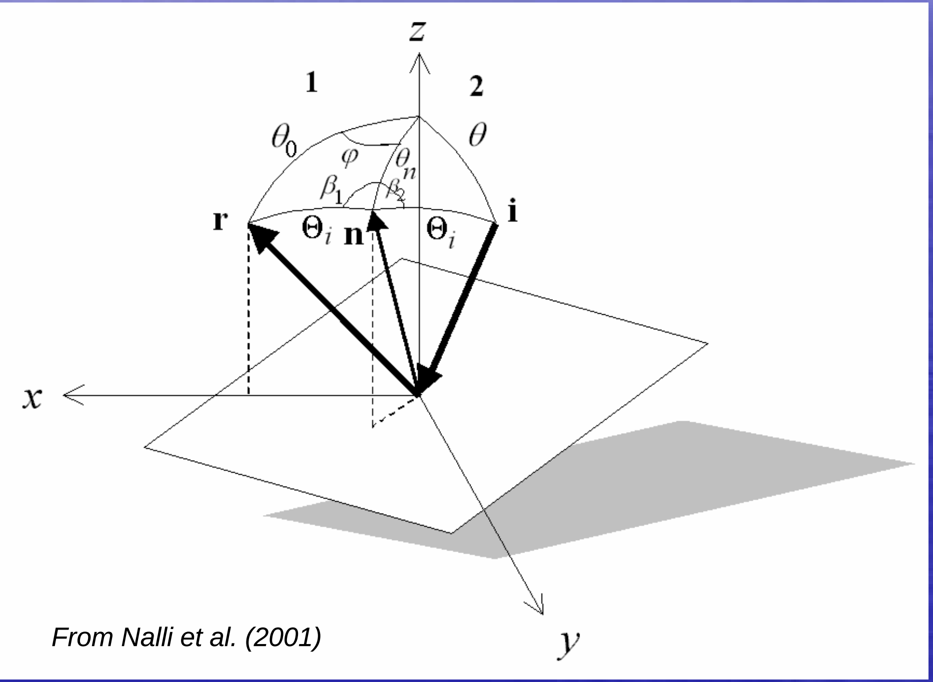


From Nalli et al. (2005)

- M-AERI provides field observations of atmospheric and oceanic emitted IR radiance spectra
- M-AERI spectral observations have led to validation and enhancement of
  - Surface emissivity/reflection models (Wu and Smith, 1997; Nalli et al., 2001)
  - Line-by-line and fast transmittance models (e.g., Han et al., 1997)

Quasi-Specular Reflection Model

- Kirchhoff Approximation: Surface waves have dimensions large compared to IR λ (geometrical optics limit)
- Fresnel Reflectivity: Known from observed refractive indices
- Facet Model: Cox-Munk mean square slope statistics dependent upon local surface wind speed
- Coordinate transformation: Transform slope coordinates to local zenith and azimuth angle
- Account for wave blocking and reflected emission consistent with the emissivity model



Cartesian coordinate system for a wave facet under the Kirchhoff approximation

Reflected Radiance

The reflected IR radiance from the atmosphere is then given by

$$R_{\nu s}(\theta_0) = \int_0^1 \int_0^{\varphi_2} \rho_\nu(\varphi, \mu_n)\, I_\nu^{\downarrow}[\theta(\varphi, \mu_n, \mu_0)]\, P(\varphi, \mu_n, \mu_0)\, d\varphi\, d\mu_n,$$

θ, φ are the zenith and azimuth angles

φ_2 is the azimuth upper limit that elimates self-blocking

$\mu_0 = \cos\theta_0, \quad \mu_n = \cos\theta_n$

θ_n is the facet normal zenith angle

ρ_ν is the Fresnel reflection coefficient

P is a normalized Cox-Munk wave slope PDF

This equation essentially describes the reflected radiance as the ensemble effect of rays reflected from all possible slopes into the field of view of the observer.

Reflection Diffusivity-Angle

For convenience in retrievals, computation is greatly reduced by introducing a reflection diffusivity-angle $\overline{\theta}_\nu$ (Nalli et al., 2001)

$$I_\nu^{\downarrow}(\overline{\theta_\nu}) \equiv \frac{\int_0^1 \int_0^{\varphi_2} \rho_\nu I_\nu^{\downarrow}(\theta)\, P\, d\varphi\, d\mu_n}{\int_0^1 \int_0^{\varphi_2} \rho_\nu P\, d\varphi\, d\mu_n},$$

which leads to

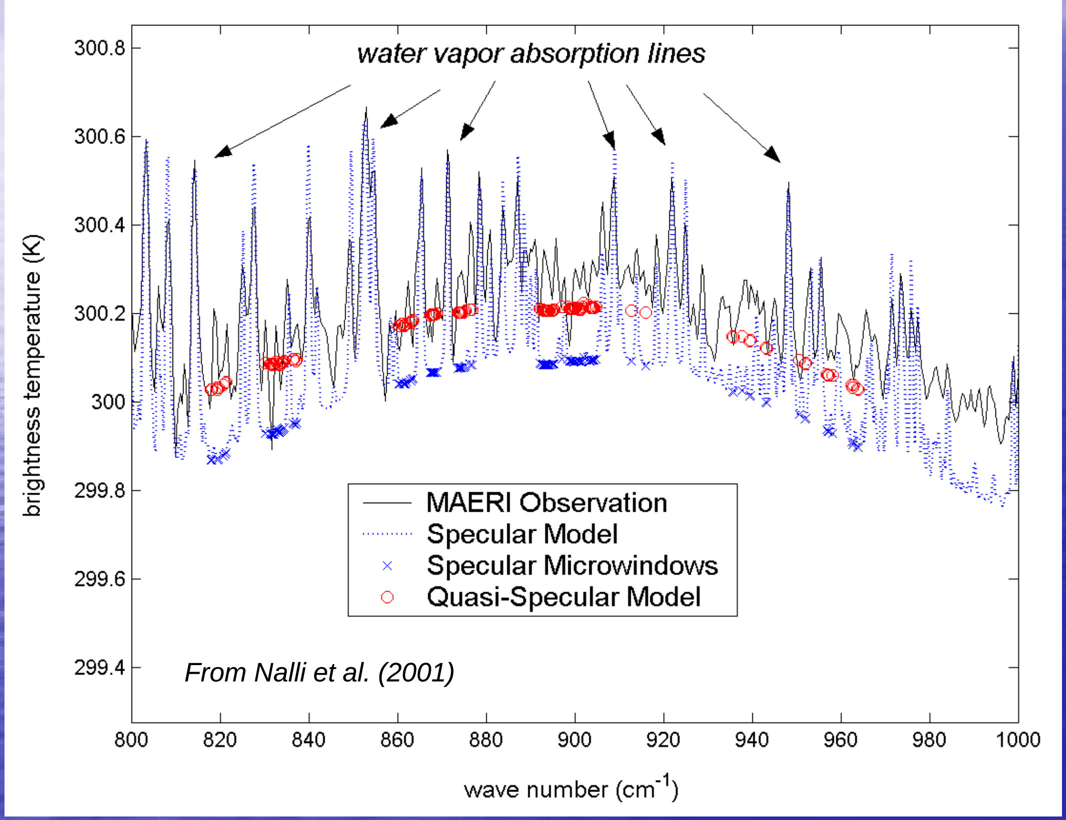
$$R_{\nu s}(\theta_0) = I_\nu^{\downarrow}(\overline{\theta_\nu})\, \overline{r_\nu}(\theta_0, \overline{V}),$$

from which $\overline{\theta}_\nu$ can be determined by finding the zeros of the equation.

A fast transmittance model can be used to calculate LUT for a range of wavenumbers, wind speeds and atmospheric opacities, i.e.,

$$\overline{\theta}_\nu = f\left(\nu, \theta_0, \overline{V}, \tau_{\nu 0}(\theta_0)\right).$$

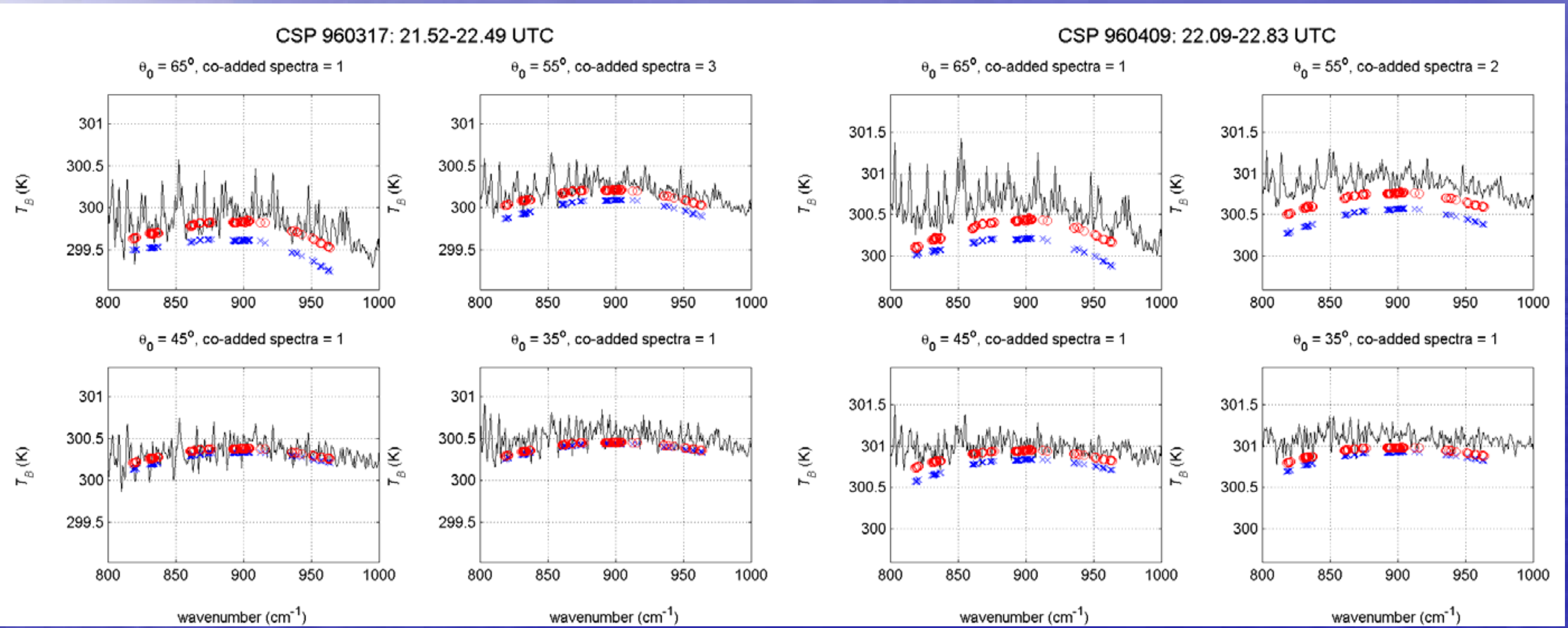
M-AERI Ocean Surface Spectra



- Non-unity emissivity signal is apparent
- Water vapor absorption lines appear as "spikes"
- The specular model underestimates the observation in microwindows by ~0.2 K

Model calculations versus M-AERI observation for 55^0 view angle at 22:18 UTC, 17-Mar-96.

Model versus M-AERI



17-Mar-96, 22:18 UTC (2.1 S, 179.9 W)
V = 4.9 m/s; roll = −1.08^0

09-Apr-96, 22:28 UTC (7.3 N, 172.6W)
V = 13.7 m/s; roll = −0.45^0

Work Plan

- Research and Development
  - Install uplooking and downlooking forward radiance models (e.g., kCARTA) on research workstation. (in progress)
  - Conduct statistical analyses of M-AERI field data to verify/quantify model error.
  - Characterize window channel spectral response functions and centroid Planck approximations.
  - Run forward radiance calculations for window channels over range of wind speeds, zenith angles and atmospheric conditions.
  - Derive lookup tables and/or parametric fit of reflection diffusivity angle designed to be used in conjunction with the Wu-Smith emissivity model currently implemented by NCEP/EMC.
- Implementation and Dissemination
  - Validate model calculations against M-AERI spectra acquired during oceanographic field campaigns, including AEROSE 2004.
  - Tech transfer to NCEP/EMC for operational implementation into CRTM.
  - Implementation within AIRS forward model.
  - Document work in peer-reviewed journal publication.
  - Document and present work at 2 scientific conferences (1 domestic and 1 international).