# Infrared Sea Surface Effective-Emissivity (IRSSE) Model Upgrade Plans for CRTM

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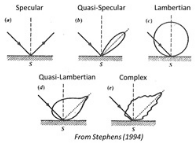
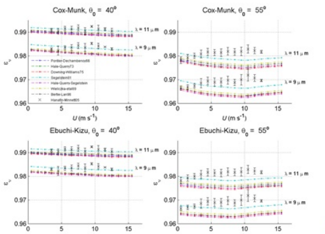
## Background

- For satellite IR remote sensing applications, the **surface emissivity/reflectance** spectrum must be specified with a high degree of absolute accuracy
  - **0.5%** uncertainty results ≈**0.3–0.4 K** systematic error in **LWIR window channels**
- **IR sea-surface emissivity models** have gained widespread acceptance (e.g., *Masuda et al.* 1988; *Watts et al.* 1996; *Wu and Smith* 1997), ***but only after they were validated***
  - **Masuda's model** was published in **1988**, ***but no one used it*** because it was never validated against observations
  - **Marine Atmospheric Emitted Radiance Interferometer (MAERI)** (*Smith et al.* 1996; *Minnett et al.* 2001) led to acceptance and application of emissivity models
  - These models calculated emissivity as the ensemble-mean of 1 − ρ of surface wave facets
  - The models were improved, but **residual systematic discrepancies** (0.1–0.4 K) remained at higher wind speeds and view angles ≥40° (*Nalli et al.* 2001, 2006; *Hanafin and Minnett* 2005) due to incorrect specification of reflected atmospheric radiance



*From Stephens (1994)*



*From Nalli et al. (2008a)*

## JCSDA, STAR and JPSS Support for IRSSE Model Development

- **JSCDA and STAR** supported in-house **FY05-06** research to find a workable solution for application to the CRTM
- This research culminated in the **CRTM IRSSE model** (*Nalli et al.* 2018a,b; *van Delst et al.* 2009)
- Notably, the IRSSE model uses the **effective emissivity principle** to account for quasi-specular reflection in a practical manner
- **JCSDA** has agreed to support (beginning Sep 2019) an **upgrade** to the **CRTM IRSSE model** as part of their **2019 Annual Operating Plan**
  - The plan is to include **surface temperature dependence** along with some other misc upgrades
  - **JPSS will support in-kind work** until Sep 2019

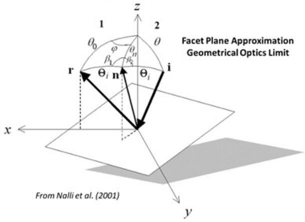
## Radiative Transfer-Based Effective Emissivity (after *Nalli et al.* 2018a,b)

The **directional emissivity** of a terrestrial surface is defined as

$$\epsilon_\nu(\theta_0) \equiv \frac{I_{\nu s}(\theta_0)}{B_\nu(T_s)},$$

where the **surface-emitted radiance** (numerator) is separated from the **surface-leaving radiance** (as measured by a detector) by subtracting the **surface-reflected radiance**

$$I_{\nu s}(\theta_0) = R_{\nu s}(\theta_0,\varphi_0) - \frac{1}{\pi}\int_\theta\int_\varphi r_\nu(\theta,\varphi;\theta_0,\varphi_0)\, I_\nu^{\downarrow}(\theta,\varphi)\cos(\theta)\sin(\theta)\, d\varphi\, d\theta$$



*From Nalli et al. (2001)*

The **conical-directional reflectance for non-isotropic incident radiation** (*Nicodemus et al.* 1977) for the **sea surface reflectance** may be written as

$$\rho_\nu(\theta_0,\sigma_s^2) = \frac{\iint \rho_\nu(\theta_n,\varphi_n;\theta_0)\,P(\theta_n,\theta_0;\sigma_s^2)\left[B_\nu(T_s) - I_\nu^{\downarrow}(\theta)\right] d\varphi_n\, d\mu_n}{\iint P(\theta_n,\theta_0;\sigma_s^2)\left[B_\nu(T_s) - I_\nu^{\downarrow}(\theta)\right] d\varphi_n\, d\mu_n},$$

which, from the mean value theorem is equivalent to

$$\rho_\nu(\theta_0,\sigma_s^2) \equiv \rho_\nu(\overline{\theta}_n,\overline{\varphi}_n;\theta_0;\sigma_s^2) = \rho_\nu[\overline{\Theta}_i(\theta_0),\sigma_s^2]$$

The denominator simplifies as

$$\begin{aligned}\iint P(\theta_n,\theta_0;\sigma_s^2)\left[B_\nu(T_s) - I_\nu^{\downarrow}(\theta)\right] d\varphi_n\, d\mu_n \\ = B_\nu(T_s) - I_\nu^{\downarrow}(\overline{\theta}_\nu)\,,\end{aligned}$$

where $\overline{\theta_\nu} \approx \theta_0$ is a diffusivity angle, thus allowing **simplification of the surface-leaving radiance RTE** as

$$\begin{aligned} R_{\nu s}(\theta_0) &= B_\nu(T_s) - \rho_\nu(\overline{\Theta}_i,N_\nu)\left[B_\nu(T_s) - I_\nu^{\downarrow}(\overline{\theta}_\nu)\right] \\ &\approx B_\nu(T_s) - \rho_\nu(\Theta_e,N_\nu)\left[B_\nu(T_s) - I_\nu^{\downarrow}(\theta_0)\right]\end{aligned}$$

Then, defining an **effective emissivity** as

$$\mathcal{E}_\nu(\theta_0) \equiv 1 - \rho_\nu[\Theta_e(\theta_0)]\,,$$

where the mean incidence angle is the equivalent of an **effective emission angle**, $\overline{\Theta_i} \equiv \Theta_e$, one may arrive at a **simplified RTE for the SLR**

$$R_{\nu s}(\theta_0) = \mathcal{E}_\nu(\theta_0)\,B_\nu(T_s) + [1 - \mathcal{E}_\nu(\theta_0)]\,I_\nu^{\downarrow}(\theta_0)\,.$$

The effective emissivity as defined is thus equivalent to

$$\mathcal{E}_\nu(\theta_0) = \frac{R_{\nu s}(\theta_0) - I_\nu^{\downarrow}(\theta_0)}{B_\nu(T_s) - I_\nu^{\downarrow}(\theta_0)}$$

The effective emission angle $\Theta_e$ is determined iteratively via **least-squares spectral variance minimization**

$$\sigma^2(\Delta\nu) = \frac{1}{n-1}\sum_\nu\left[T_{\nu s}(\Theta_e) - \overline{T}_{\nu s}(\Theta_e)\right]^2\,,$$

where $T_{\nu s}(\Theta_e)$ is the skin temperature given by

$$T_{\nu s}(\Theta_e) = B_\nu^{-1}\left(\frac{R_{\nu s}(\theta_0) - \rho_\nu(\Theta_e,N_\nu)\,I_\nu^{\downarrow}(\theta_0)}{1 - \rho_\nu(\Theta_e,N_\nu)}\right)$$

The retrieved $\Theta_e$ can then be used to derive the entire effective emissivity spectrum.

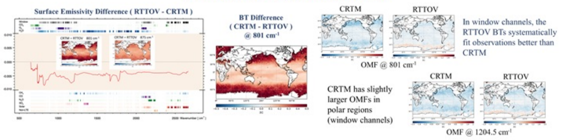
## Need for Upgrades to the IRSSE Model

- **CRTM IR effective-emissivity (IRSSE) model** was derived based on high-accuracy surface-based FTS observations (MAERI), sound theoretical principles, and the need for practical implementation within the CRTM
  - Model was shown to have significantly better agreement with observations over the conventional models (e.g., *Masuda* 2006; *Wu and Smith* 1997)
  - However, small residual deficiencies were still found to exist under certain conditions
    - For example, small residual positive biases were found in the SWIR window, as well as LWIR under dry/cold atmospheric conditions
    - The author was aware of this at the time but ultimately favored simplicity (and was not supported for continued work)
- More importantly, however, was the realization of a **significant temperature dependence**
  - *Nalli et al.* (2008b): "In agreement with other recent work on the subject, we found a significant temperature dependence, which, if unaccounted for, can lead to spectral SLR errors of the same order of magnitude as those we have sought to correct. Therefore, additional work is desirable to derive an optimal seawater refractive index dataset…"
  - Unfortunately, this work was **not** supported at the time
  - However, the recent findings of (e.g., *Liu et al.* 2017) revealed significant **systematic bias** (as much as **1 K**) on a **global scale**, thus bringing this issue back into focus for support

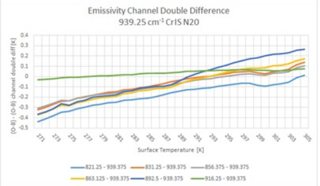
## IRSSE Model Improvement

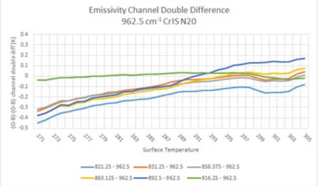
### Temperature Dependence: Observed Global Scale Impact

***From Liu et al., JCSDA Workshop (2017)***



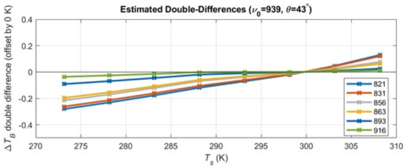
- **Global OBS – CALC double-differences**
  - **2-weeks global NOAA-20 CrIS data (OBS) versus CRTM model calculations (CALC)**
  - Shown are microwindow-channel double-differences of OBS – CALC in regions of varying surface temperature dependence observed in the IR spectrum (e.g., *Pinkley et al.* 1977; see the figures to the right)
  - The **double-differences** serve to place **control** on the unknown atmospheric path uncertainties (e.g., model bias, cloud contamination, water vapor errors, etc.)
- **Significant surface-temperature dependence** is clearly visible **on the order of 1 K**
  - This is of first order significance within the context of the total CRTM forward model uncertainty

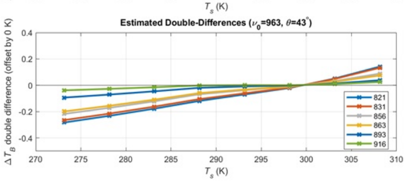




### Planned Work

- **Temperature dependence**
  - **Refractive indices** with temperature dependence are one possibility, **however**
    - *Newman et al.* (2005) is limited to a portion of the LWIR
    - *Hale et al.* (1972) is limited to 2 useful surface temperatures
  - Thus the tentative plan is to use data from *Pinkley et al.* (1977)
  - From the spectral variance minimization of $T_s$, **derive new LUT** to **include** $T_s$, i.e., $\mathcal{E}(\nu,\theta_0,\overline{u},T_s)$
  - **Validate** using global data (e.g., *Liu et al.* 2017) as well as new **MAERI** campaigns-of-opportunity (e.g., *Gero et al.* 2016; *Nalli et al.* 2008b)
    - Collaboration with **UW/CIMSS** and **UM/RSMAS**
- **Improvement to known residual biases in current model (viz., the SWIR window)**
  - Perform separate spectral variance minimizations for the LWIR and SWIR bands (instead of the one-size-fits all approach) and **include $T_s$ parameter** for improved global fitting
  - Use latest version of LBLRTM and use additional atmospheres in the training sample
- **Dovetail efforts with ongoing NUCAPS emissivity retrieval development and SARTA model upgrades**





The next deployment of the M-AERI will be on the Aurora Australis in the Southern Ocean Oct 2017 - May 2018.

**ARM Mobile Facility (AMF2)**
**Marine Atmospheric Emitted Radiance Interferometer (MAERI)**
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- The **STAR NUCAPS Soundings Team** (A. Gambacorta, C. Tan, et al.)

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