A Reference Quality Model for Ocean Surface Emissivity and Backscatter from the Microwave to the Infrared

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Sponsor: ISSI  (International Space Science Institute)

SEA FOAM MODELS FROM L BAND TO MILLIMETER WAVE FREQUENCIES

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SCIENCE TEAM MEETING
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OUTLINE

• SEA FOAM AND ITS HIGH EMISSIVITY
• REQUIREMENTS FOR A FOAM EMISSIVITY MODEL
• FOAM EMISSIVITY AT WINDSAT FREQUENCIES (6 – 37 GHZ)
• FOAM EMISSIVITY AT L BAND (1 – 2 GHZ)
• FOAM EMISSIVITY AT MILLIMETER-WAVE (mmW) FREQUENCIES (37 – 150 GHZ)
• WHITECAP FRACTION
• WHAT NEEDS TO BE DONE?
SEA FOAM

WHITECAPS
SEA FOAM FLOATING ON THE SURFACE

BUBBLE PLUMES
THE BUBBLE BELOW THE SURFACE

SEA SPRAY
SOME INCLUDE THE SPRAY DROPLETS
SEA FOAM CHARACTERISTICS

- FOAM LAYERS ON THE SURFACE

ARTIFICIAL FOAM

- BUBBLE SIZE DISTRIBUTION (MICRO)
  - MIN BUBBLE RADIUS $a = 50 \, \mu m$
  - MAX BUBBLE RADIUS $a = 1 \, cm$

- VOID FRACTION (MACRO)

$$f_a = \frac{\text{Volume of air}}{\text{Volume of mixture}}$$

- VOID FRACTION PROFILE
  - STRATIFICATION OF BUBBLES BY SIZE
  - VERTICAL AIR-SEAWATER CONTENT CHANGES

FOAM FROM BREAKING WAVES
FOAM MECHANICAL STRUCTURE AND EMISSIVITY

• FOAM ITSELF HAS LOW EMISSIVITY
  • WILLIAMS (1971)
    • FOAM + METAL PLATE: LOW EMISSIVITY
    • FOAM + SEAWATER: HIGH EMISSIVITY

• HIGH EMISSIVITY OF THE FOAM-SEAWATER SYSTEM COMES FROM 2 MAIN FEATURES
  • MEDIUM WITH HIGH ATTENUATION (= EMISSION) OF EM RADIATION
    • RADIATIVE PROCESSES IN FOAM-SEAWATER SYSTEM
  • AVAILABILITY OF EM RADIATION
    • IMPEDANCE MATCHING BY FOAM
ATTENUATION IN THE FOAM-SEAWATER SYSTEM

• ABSORPTION
  • BY SEAWATER (LOSSY MEDIUM)
  • GRADUAL INCREASE OF SEAWATER WITH $f_a$ PROFILE IN DEPTH
  • SMALL IN BUBBLE WALLS AT THE TOP OF THE LAYER
  • MAX AT THE BOTTOM OF THE LAYER
    • NEED 1 M THICK FOAM WITH HIGH VOID FRACTION TO ABSORB
    • WHATEVER 1 MM SEAWATER CAN ABSORB

• SCATTERING
  • $\lambda$-DEPENDENT
  • SIZE PARAMETER $x$ DETERMINES THE SCATTERING REGIME
  • VOLUME AND SURFACE SCATTERING

• ABSORPTION VS SCATTERING
  • LITERATURE REVIEW: $\leq 15\%$ SCATTER @ 37 GHz
  • RIGOROUS SCATTERING CALCULATIONS: SIMILAR

$$x = \frac{2\pi a}{\lambda}$$

\[\begin{align*}
\nu > 40 \text{ GHz} & \quad x \geq 1 \\
\nu \leq 40 \text{ GHz} & \quad x < 1
\end{align*}\]

Scattering increases

Scattering negligible
SCATTERING IN FOAM

- **GMM THEORY (GENERALIZED MULTI-PARTICLE MIE)**
  - Scattering from bubble aggregates
  - Interaction and interference between bubbles
  - Well validated experimentally

- **GMM IMPLEMENTATION (COMMUNITY CODE)**
  - Homogeneous spheres (spray)
  - Shell & core particles (bubbles)
  - Monodisperse and polydisperse

- **GMM CALCULATIONS**
  - Foam streaks: 2 mm to 10 m (observed)
    - Laboratory and field experiments
    - Empirical relationship to wind speed
  - Monodisperse cluster of bubbles
  - At several bubble radii: 50 μm to 10 mm (observed)
  - Different bubble wall thicknesses (observed)

**Foam attenuation via the efficiency factors**

\[
Q_{\text{ext}} = Q_{\text{sca}} + Q_{\text{abs}}
\]
FOAM SCATTERING AT DIFFERENT FREQUENCIES

- NEGLECT SCATTERING
  - FOR L BAND AND WINDSAT
  - SCATTERING < 18% @ 37 GHZ

- ACCOUNT FOR SCATTERING
  - FOR mmW FREQUENCIES
  - CONTRIBUTES > 25% TO $Q_{ext}$

- FOAM IS EMISSIVE AT mmW FREQS
  - ABSORPTION DOMINATES ATTENUATION
  - REFLECTION/SCATTERING DOMINATES IN VIS
  - SCATTERING STARTS TO DOMINATE IN IR

- EFFICIENCY FACTORS $Q_{ext} = Q_{sca} + Q_{abs}$

- FREQUENCY DEPENDENCE
  - FIXED BUBBLE DIMENSIONS TYPICAL
  - FIXED FOAM STREAK TYPICAL FOR 12 M/S WIND
\[ \eta = \frac{1}{\sqrt{\varepsilon}} \]
\[ \eta = \frac{1}{\sqrt{\varepsilon}} \]

- Foam layer at the surface is a necessity.

\[ r \propto \Delta \eta \]

- Visual representation of impedance matching.

Graph showing impedance vs. void fraction for different frequencies (6.8 GHz, 18.7 GHz, 37.0 GHz).
HIGH FOAM EMISSIVITY

- Emergent behavior of foam-seawater system: The whole is greater than its parts

- Seawater is the major attenuating agent
  - Strong attenuation of EM radiation
  - Strong emission

- Foam impedance matching
  - Delivers radiation to the attenuating agent
  - Most effective when the void fraction is over the full range
1) VARIABLES
   ▪ INSTRUMENTAL (frequency, polarization, incidence angle)
   ▪ FOAM VARIABLES
     ▪ MICROSCOPIC FOR BUBBLES (e.g., radius, wall thickness, size distribution) OR
     ▪ MACROSCOPIC FOR FOAM LAYERS (void fraction $f_a$ and layer thickness $t$)

2) NON-UNIFORM PROFILE OF FOAM DIELECTRIC PROPERTIES IN FOAM LAYER DEPTH
   ▪ VERTICAL PROFILE OF FOAM MECHANICAL STRUCTURE
     ▪ BUBBLE PROPERTIES [e.g., $n(z)$] OR
     ▪ FOAM LAYER CHARACTERISTICS [e.g., $f_a(z)$]
   ▪ VERTICAL PROFILE OF FOAM THERMODYNAMIC TEMPERATURE $T_f(z)$ (STOGRYN, 1970)
   ▪ VERTICAL PROFILES OF BOTH FOAM TEMPERATURE AND STRUCTURE [e.g., $T_f(z)$ AND $f_a(z)$]

3) RADIATIVE PROCESSES FOR ATTENUATION
   ▪ ABSORPTION AND VOLUME SCATTERING
   ▪ SURFACE SCATTERING AT IRREGULAR AIR-FOAM AND FOAM-WATER BOUNDARIES
   ▪ MULTIPLE REFLECTIONS AND TRANSMISSIONS AT THE BOUNDARIES OF THE FOAM LAYER

4) A DISTRIBUTION OF FOAM CHARACTERISTICS DUE TO GEOGRAPHIC AND METEOROLOGICAL VARIABILITY
   ▪ BUBBLE DIMENSIONS OR
   ▪ FOAM LAYER THICKNESSES
PREVIOUS FOAM EMISSIVITY MODELS

• STOGRYN (1972): ONLY INSTRUMENTAL VARIABLES, NO FOAM CHARACTERISTICS

• DROPPLEMAN (1970)
  • INCLUDES VOID FRACTION, BUT NO VERTICAL VARIATIONS
  • COHERENT SCATTERING LEADS TO BOGUS OSCILLATIONS

• ROSENKRANZ AND STAELIN (1972)
  • LAYERS OF EQUAL THICKNESS
    • BOGUS OSCILATIONS
    • LAYERS WITH VARYING THICKNESSES

• RAIZER AND COLLEAGUES (1981)
  • VERTICAL PROFILE VIA BUBBLES
  • SPRAY LAYER INCLUDED

• TSANG AND COLLEAGUES
  • SCATTERING (DENSE MEDIA RT)
  • NO VERTICAL VARIATIONS
MODEL PHYSICAL FEATURES FOR APPLICATION

• NO NEED TO FOLLOW ALL REQUIREMENTS

• FREQUENCY RANGE DETERMINES THE NEEDED FEATURES
  • SCATTERING (VOLUME AND SURFACE) WHEN NEEDED
  • MODELING APPROACH
    • EFFECTIVE MEDIUM THEORY FOR FREQS BELOW 37 GHz
    • MIE SCATTERING THEORY FOR FREQS ABOVE 37 GHz

• VERTICAL VARIATIONS MOST IMPORTANT
  • BREAKING WAVE MIXING ALLOWS \( T_f(z) = \text{CONST} = T_s \)
  • REQUIRE VOID FRACTION PROFILE

\[
\begin{align*}
\text{Size parameter} & \quad x = 2\pi a/\lambda \\
\nu > 40 \text{ GHz} & \quad x \geq 1 \quad \text{Scattering increases} \\
\nu \leq 40 \text{ GHz} & \quad x < 1 \quad \text{Scattering negligible}
\end{align*}
\]
MODEL FEATURES FOR WINDSAT FREQUENCIES

- MACRO CHARACTERISTICS (LAYER, NOT BUBBLES)
- VERTICALLY HOMOGENOUS FOAM TEMPERATURE
- VERTICALLY INHOMOGENEOUS (DEPTH PROFILE)
- INCOHERENT APPROACH
  - APPLICABLE FOR WEAK SCATTERING
  - IGNORE EXPLICIT SCATTERING TERM
  - EXTINCTION = ABSORPTION
- FLAT FOAM LAYER BOUNDARIES
  - NO SURFACE SCATTERING
  - SPECULAR REFLECTIONS
- MULTIPLE REFLECTIONS AT THE FOAM LAYER BOUNDARIES
- DISTRIBUTION OF FOAM LAYER THICKNESSES

WindSat is the first spaceborne polarimetric microwave radiometer
Launched on 06 January 2003

<table>
<thead>
<tr>
<th>Freq (GHz)</th>
<th>Polarization</th>
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<tbody>
<tr>
<td>6.8</td>
<td>h, v</td>
</tr>
<tr>
<td>10.7</td>
<td>h, v, +/- 45,</td>
</tr>
<tr>
<td>18.7</td>
<td>h, v, +/- 45,</td>
</tr>
<tr>
<td>23.8</td>
<td>h, v</td>
</tr>
<tr>
<td>37.0</td>
<td>h, v, +/- 45,</td>
</tr>
</tbody>
</table>

Gaiser et al., 2004

Demonstrated the capability of polarimetric microwave radiometry to measuring the ocean surface wind vector from space
VOID FRACTION PROFILE

\[ f_a = a - me^{bz} \]
\[ a = v_{af} + m \]
\[ v_{af} = 99\% \quad @ \quad z = 0 \]
\[ v_{fw} = 1\% \quad @ \quad z = t \]
\[ b = \frac{1}{t} \ln\left(\frac{a - v_{fw}}{m}\right) \]

- FOAM PERMITTIVITY FROM \( f_a(z) \)
- REFRACTIVE MIXING RULE

\[ \varepsilon_f = \left[ f_a + (1 - f_a)\varepsilon^{1/2}\right]^2 \]

- FOAM ATTENUATION FROM \( \varepsilon_f(z) \)

\[ \alpha_f(z) = k_0|\text{Im}\sqrt{\varepsilon_f(z)}| \]
\[ k_{extf}(z) = 2\alpha_f(z) = k_{absf}(z) + k_{scaf}(z) \approx k_{absf}(z) \]
CONTRIBUTIONS TO THE SIGNAL FROM FOAM

- REFLECTION TERM: FRESNEL FORMULA
- EMISSION TERMS
  - NO SCATTERING
  - UPWEELING
  - DOWNWEELING
  - TRANSMISSION TO/FROM SEAWATER
- MULTIPLE REFLECTIONS

\[ T_{Bf\, obs} = T_{Bfr}(\theta, p) + T_{Bsc}(\theta, p) + T_{BUf}(\theta, p) + T_{BDf}(\theta, p) + T_{Bfw}(\theta, p) \]
DISTRIBUTION OF FOAM LAYER THICKNESS

\[ T_{Bf_{\text{obs}}} = T_{Br} + T_{BLU} + T_{BLD} + T_{Bw} \]

\[ T_{Bf} = \int_{t_{\text{min}}}^{t_{\text{max}}} T_{Bf_{\text{obs}}}(t) p(t) dt \]

\[ t_{\text{min}} = 0.04 \text{ cm} \approx \lambda_{0@37 \text{GHz}} / 20 \]

\[ t_{\text{max}} \leq 25 \text{ cm} \approx 5\lambda_{0@6.8 \text{GHz}} \]

\[ p(t) = \frac{1}{t\sqrt{2\pi \gamma^2}} \exp \left[ -\frac{(\ln t - \zeta)^2}{2\gamma^2} \right] \]

\[ \zeta = \ln \left( \frac{\mu^2}{\sqrt{\sigma^2 + \mu^2}} \right) \]

\[ \gamma = \sqrt{\ln \left( \frac{\sqrt{\sigma^2 + \mu^2}}{\mu^2} \right)} \]

Use \( t \) statistics:
\[ \mu = 1.9 \text{ cm (mean)} \]
\[ \sigma = 0.806 \text{ cm (std. dev.)} \]

Obtain lognormal peak @ \( t = 3.53 \text{ cm} \)

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Reising et al., 2002
FOAM EMISSIVITY

Exponential $f_a$ profile, 99% to 1%
Refractive mixing rule

$T_s = 20 \, ^\circ C$
$S = 34 \, \text{psu}$
UPPER LIMIT OF VOID FRACTION

Exp \( f_a, v_{fw} = 1\% \)

\( v_a f (\%) \)

- 99
- 95
- 85
- 75

Refractive mixing rule

\( T_s = 20 \, ^\circ C \)

\( S = 34 \, \text{psu} \)
COMPARISON TO OTHER MODELS

\[ \text{Incidence angle, } \theta (\text{deg}) \]

- **10.8 GHz**
  - NRL foam RTM, Void fraction UPPER limit = 93%
  - Experiment, Rose et al. (2002)

- **35 GHz**
  - NRL foam RTM, Void fraction UPPER limit = 86%
  - Experiment, Raizer & Sharkov (1982)
WINDSAT FOAM RTM @ 1.4 GHZ

\[ F = 1.4 \text{ GHz} \]

H pol, rmse = 0.016
V pol, rmse = 0.016

- - - This study, \( v_{\text{sh}} = 44\% \)
- - - Camps et al. (2005)

Experiment, Camps et al. (2005)
WINDSAT FOAM RTM @ L1 (CYGNSS)

$F = 1.57542 \text{ GHz}$

- **V pol**
- **H pol**

Foam: Refractive mixing rule

Exponential $f_a$ profile, 99% to 1%

**Seawater**

$T_s = 28^\circ\text{C}$

$S = 34 \text{ psu}$
FOAM STREAKS AT MILLIMETER-WAVE FREQS

\[ k_{\text{ext}}(z) = k_{\text{abs}}(z) + k_{\text{sca}}(z) \]

- Bubble radius: 500 \( \mu \text{m} \)
- Bubble wall: 20 \( \mu \text{m} \)
- Frequency: 89 GHz

Efficiency factor, \( Q \) vs. Streak length, \( L \) (m)

Extinction
Absorption
Scattering

Wind > 10 m/s
WHITECAP FRACTION AND FOAM EMISSIVITY

\[ e = e_W + e_r = W E_f + (1 - W) E_r \]

- FROM EARLY PHOTOGRAPHIC DATA
  - CURRENTLY USED
- NEW, IMPROVED PHOTOGRAPHIC DATA
- FROM SATELLITE (WINDSAT) OBSERVATIONS
DISCUSSION QUESTIONS

FUTURE WORK

• VOID FRACTION PROFILE: VARIATIONS IN THE UPPER LIMIT
  • WIND SPEED
  • FREQUENCY

• THICKNESS DISTRIBUTION: VARIATIONS OF
  • PEAK PLACE
    • CONTROL WITH THE WIND SPEED?
  • DISTRIBUTION WIDTH

• MILLIMETER-WAVE FREQS
  • GMM CALCULATIONS FOR ATTENUATION IN
    • FOAM PATCHES
    • 3-D FOAM LAYERS
  • FOAM EMISSIVITY MODEL

• WHITECAP FRACTION: \( W(U, H_{SW}, \Delta T, T) \)

ADDITIONAL FEATURES?

• DO WE NEED TO WORK ON SPRAY?
  • INITIAL RESULTS FOR L BAND
  • PLANNED SPRAY EFFECT AT 89-94 GHZ
  • HIGHER?