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

Team led by S. English (UK) & C. Prigent (FR)
Sponsor: ISSI (International Space Science Institute)

Sea foam modeling from L band to millimeter wave frequencies
Progress report

Magdalena D. Anguelova

maggie.anguelova@nrl.navy.mil

SCIENCE TEAM MEETING 4

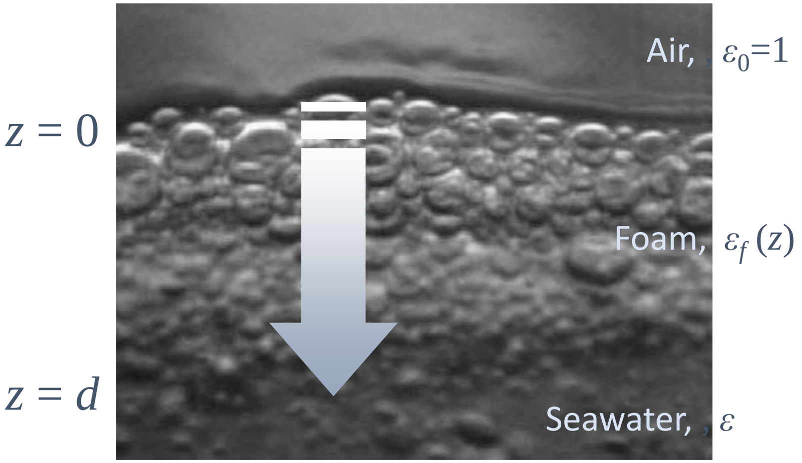
Topics related to modeling foam emissivity

$$e = W e_f + (1 - W)(e_0 + e_r) \qquad W(U) = aU^b$$

- Foam emissivity (e_f) model
  - Foam component (L to W bands)
  - Foam for L-W bands in full RTM
  - Foam for higher freqs (up to 180 GHz)
- Whitecap fraction parameterization $W(U)$ and $W(U, T)$
  - Cubic wind exponent
  - Parameterization based on satellite W retrievals
  - Test in full RTM
- Uncertainties of e_f and W assessment
  - Conventional statistics
  - Uncertainty quantification

Foam component (L to W bands)

- LOCEAN (F90) and NRL (IDL) implementations (Dec 2019)
- Code differences understood and reconciled (Apr 2020)
- Detailed model and code description written (ver. 1)
- General and closed form approaches compared
  - With all other elements the same
  - Dec 2020 and May 2021
  - Since Dec 2020
- Sensitivity analysis to environmental conditions done
- Sensitivity analysis to foam properties done
- Frequency-specific foam properties proposed
- Model and code description updated with new results
  - To be shared with the team after NRL pub release approval



Foam void fraction $f_a(z)$		
Variable	Value	Units
Layer thickness (t)	2	cm
Upper profile limit (v_{af})	0.95	
Lower profile limit (v_{fw})	0.01	
Profile shape (m)	1	
Integration data points	20	

Observation conditions		
Variable	Value	Units
Sea surface temperature (SST)	293 19.85	K °C
Sea surface Salinity (SSS)	34	psu
Incidence angle (θ)	55	°

Implementation differences reconciled

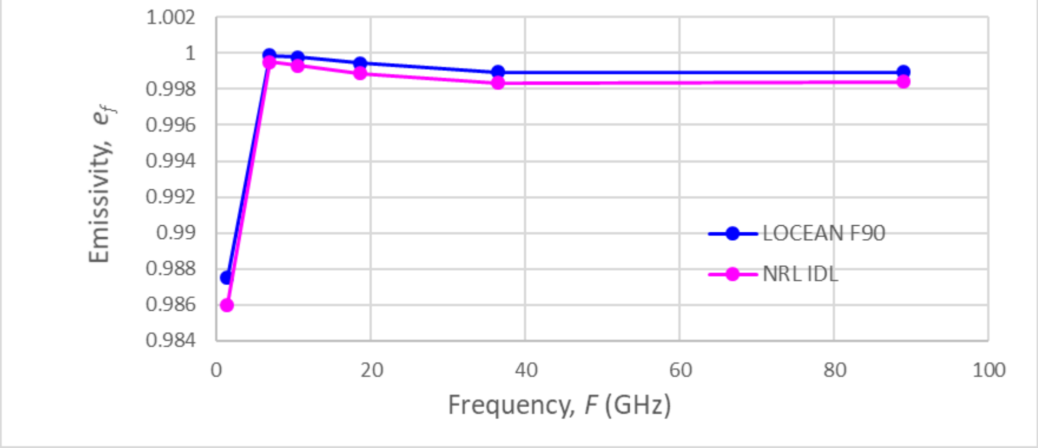


Figure 1a: Original codes, V pol

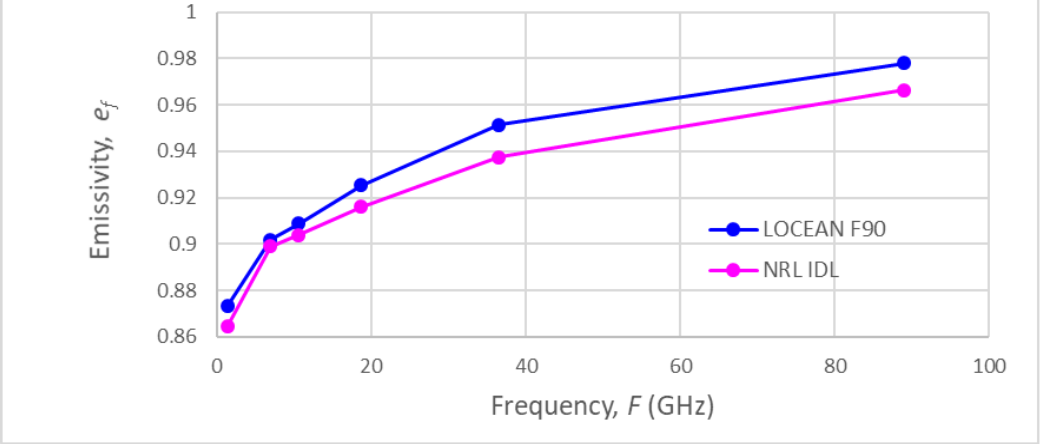


Figure 1b: Original codes, H pol

Table 2: Elements comprising the code implementations (LOCEAN F90 and NRL IDL) and their modifications in steps.

Step #	Code	Foam emiss e_f	Integration	Coding Γ_2	Permittivity	PD (%)[1]
1	F90	Closed form	Simpson	Input err	KS77	0.067 (V)
Orig	IDL	General form	Trapezoid	Formula err	S97	0.921 (H)

$$PD = |(a-b)|/[(a+b)/2] *100$$

Implementation differences reconciled

Figure 2a: Differences for each code modification, V pol

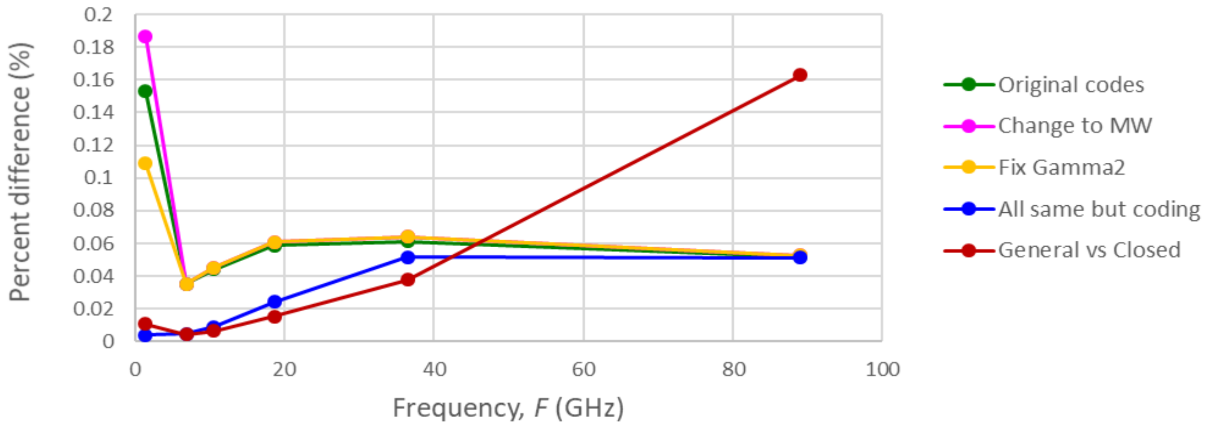


Figure 2b: Differences for each code modification, H pol

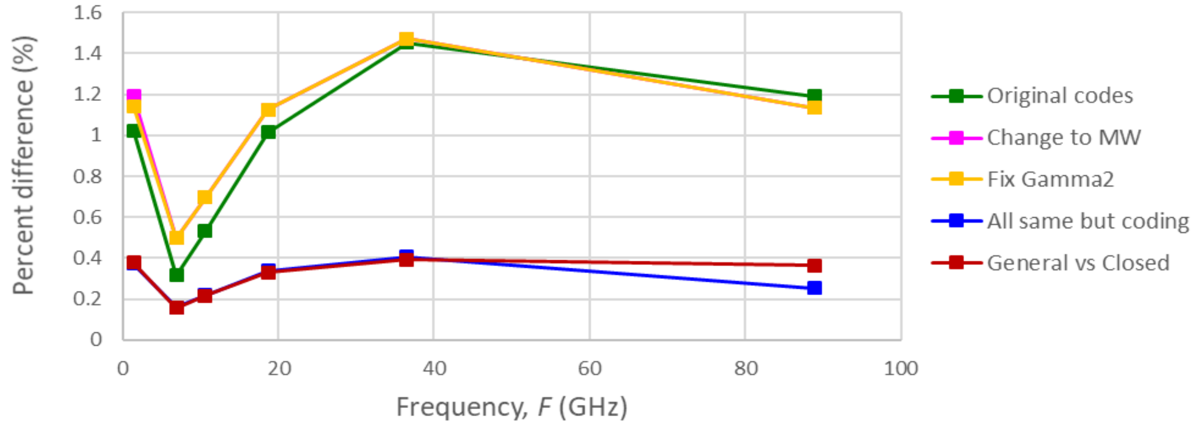


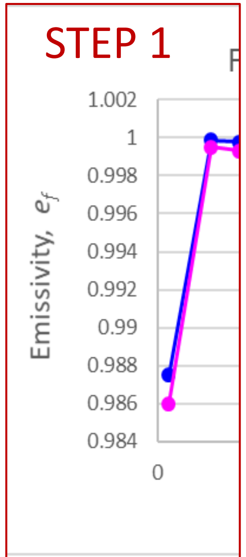
Table 2: Elements comprising the code implementations (LOCEAN F90 and NRL IDL) and their modifications in steps.

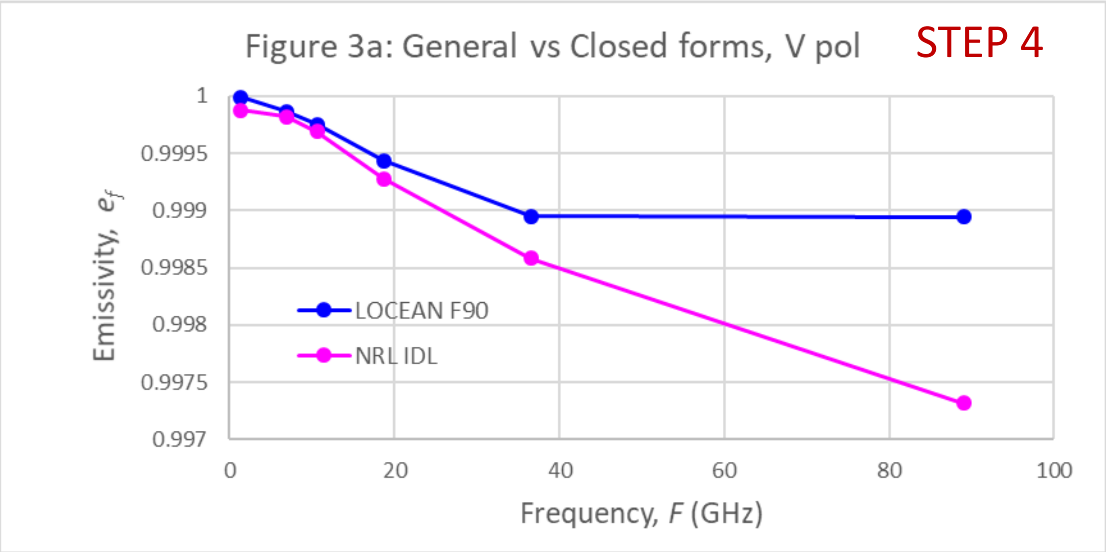
Step #	Code	Foam emiss e_f	Integration	Coding Γ_2	Permittivity	PD (%)[1]
1	F90	Closed form	Simpson	Input err	KS77	0.067 (V)
Orig	IDL	General form	Trapezoid	Formula err	S97	0.921 (H)
2	F90	Closed form	Simpson	Input err	MW	0.074 (V)
Perm	IDL	General form	Trapezoid	Formula err	MW	1.019 (H)
3	F90	Closed form	Simpson	Input Fix	MW	0.061(V)
Fix Γ_2	IDL	General form	Trapezoid	Formula Fix	MW	1.011(H)
4	F90	Closed form	Simpson	Input Fix	MW	0.040 (V)
Int rule	IDL	General form	Simpson	Formula Fix	MW	0.307 (H)
5	F90	Closed form	Simpson	Input Fix	MW	0.024 (V)
e_f form	IDL	Closed form	Simpson	Formula Fix	MW	0.291 (H)

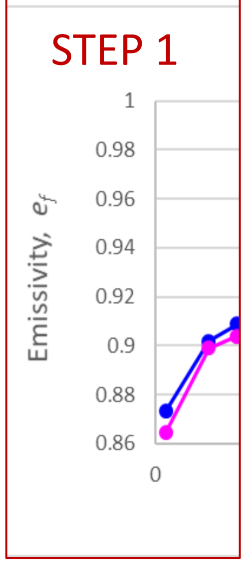
[1]The color for each step matches the color of the respective line in Figure 2.

$$PD = |(a-b)|/[(a+b)/2] *100$$

Implementation differences reconciled







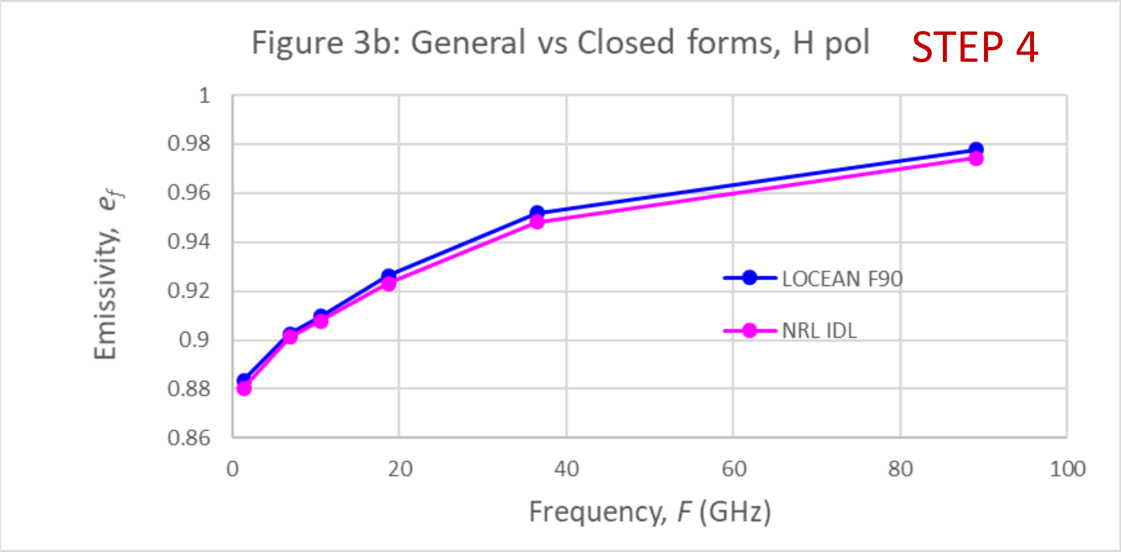


Table 2: Elements comprising the code implementations (LOCEAN F90 and NRL IDL) and their modifications in steps.

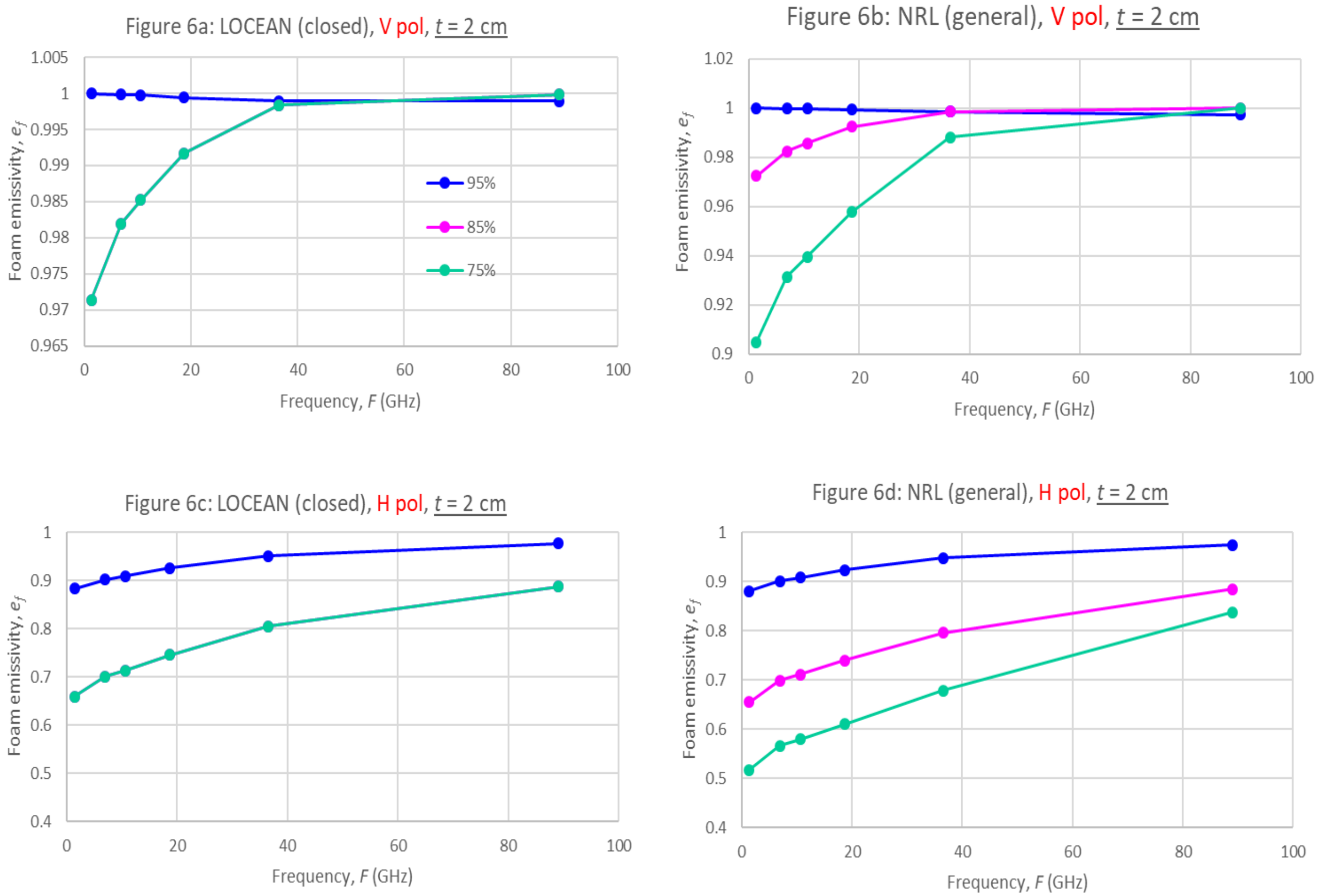
Step #	Code	Foam emiss e_f	Integration	Coding Γ_2	Permittivity	PD (%)[1]
1	F90	Closed form	Simpson	Input err	KS77	0.067 (V)
Orig	IDL	General form	Trapezoid	Formula err	S97	0.921 (H)
2	F90	Closed form	Simpson	Input err	MW	0.074 (V)
Perm	IDL	General form	Trapezoid	Formula err	MW	1.019 (H)
3	F90	Closed form	Simpson	Input Fix	MW	0.061(V)
Fix Γ_2	IDL	General form	Trapezoid	Formula Fix	MW	1.011(H)
4	F90	Closed form	Simpson	Input Fix	MW	0.040 (V)
Int rule	IDL	General form	Simpson	Formula Fix	MW	0.307 (H)
5	F90	Closed form	Simpson	Input Fix	MW	0.024 (V)
e_f form	IDL	Closed form	Simpson	Formula Fix	MW	0.291 (H)

[1]The color for each step matches the color of the respective line in Figure 2.

$$PD = |(a-b)|/[(a+b)/2] *100$$

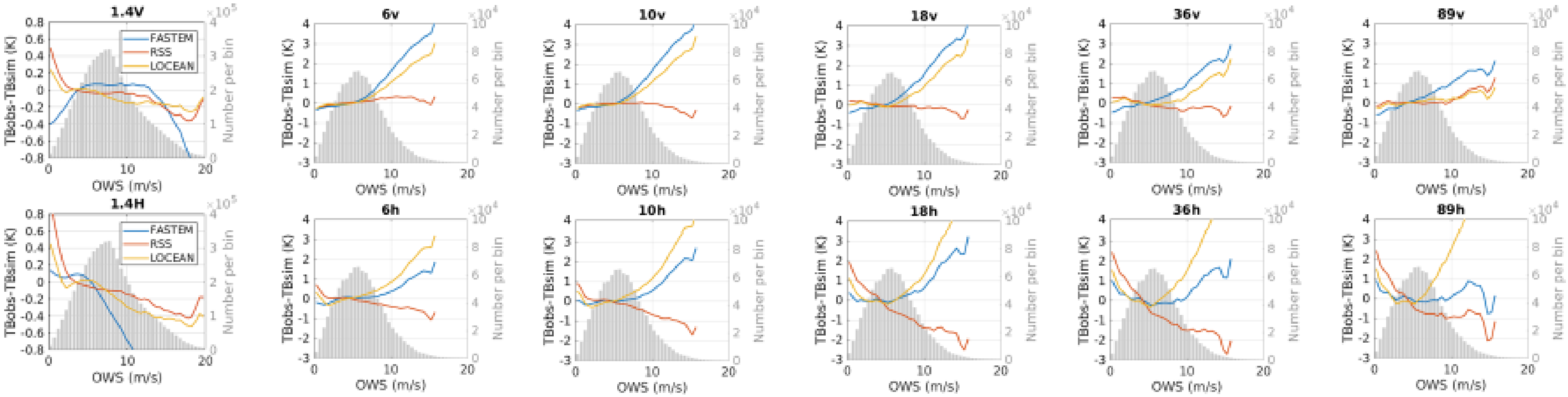
Sensitivity analysis to foam properties

- Emissivity decreases for lower void fraction
- General form more sensitive to void fraction variations compared to closed form
- Emissivity at H pol changes more with void fraction variations than V pol



Frequency-specific foam properties

Kilic et al. (2019)



<u>As in LOCEAN & GitHub:</u>

t = 2 cm

v_{af} = 95%

<u>As in GitHub (not in LOCEAN):</u>

W MOM86 with

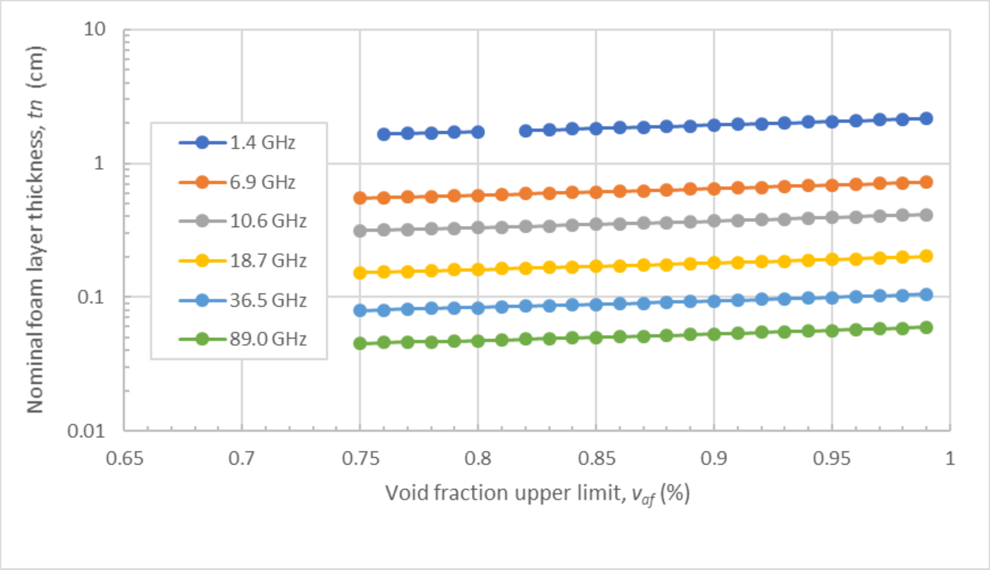
b = 2.55

$\varDelta T$ = 0

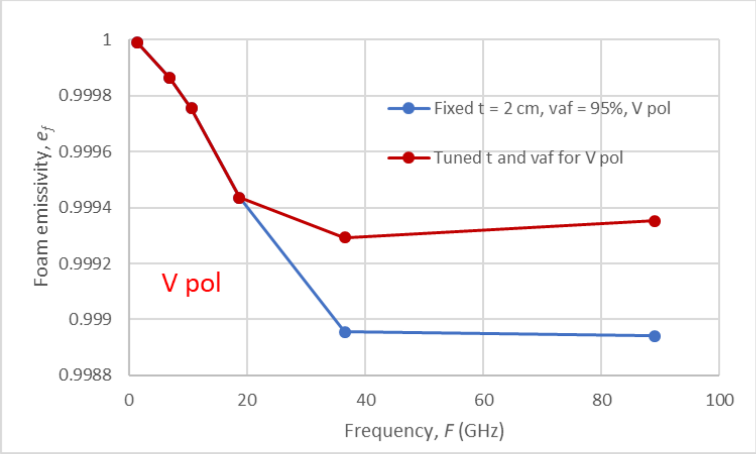
- Use Kilic et al (2019) results as a reference
- Shown is $\Delta T_B = T_{B\,\mathrm{obs}} - T_{B\,\mathrm{sim}}$ as a function of wind speed
- LOCEAN (F90 implementation, yellow) is well tuned for L band ($\Delta T_B < \pm 0.5$ K)
- For higher freqs and H & V pols, increasing +ΔT_B, thus model underestimates T_B

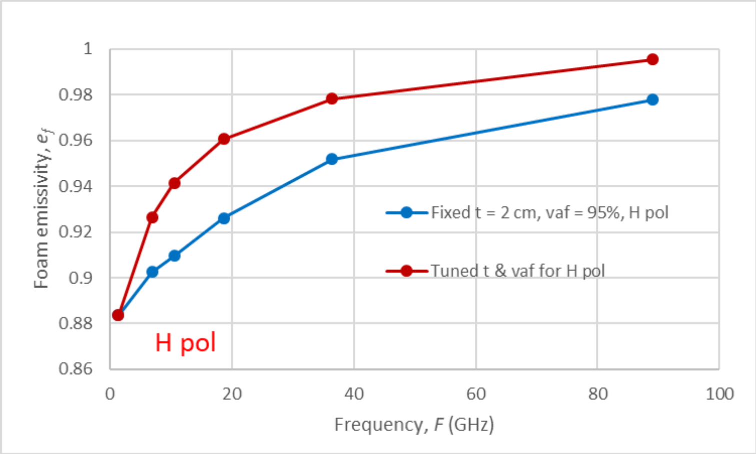
Frequency-specific foam properties

- Effective foam thickness (Yin et al., 2016)
- Use nominal foam thickness (contains the same water content as skin depth)
- Changes little with void fraction
- Use the average



- Increase v_{af} so that e_f increases





Fixed values

t = 2 cm

v_{af} = 95%

Tuned values

F (GHz)	t_n (cm)	v_{af} for V	v_{af} for H
1.4	2	0.95	0.95
6.9	0.6	0.95	0.96
10.6	0.4	0.95	0.964
18.7	0.2	0.95	0.968
36.5	0.1	0.98	0.97
89	0.1	0.97	0.98

Foam fraction parameterization

- Cubic dependence of *W* on *U* from physics

Wu, 1988, JPO

Waves break when there is excessive energy supplied by the wind, while the viscous dissipation is generally insignificant. In an equilibrium state, the energy lost through wave breaking must be balanced by the energy gained from the wind. Consequently, the percentage of sea surface covered by breaking waves under the equilibrium state can be related to the energy flux from the wind (Wu 1979),

$$W \sim \dot{E} \tag{1}$$

Foam fraction parameterization

Wu, 1988, JPO

Waves break when there is excessive energy supplied by the wind, while the viscous dissipation is generally insignificant. In an equilibrium state, the energy lost through wave breaking must be balanced by the energy gained from the wind. Consequently, the percentage of sea surface covered by breaking waves under the equilibrium state can be related to the energy flux from the wind (Wu 1979),

$$W \sim \dot{E} \qquad (1)$$

- Cubic dependence of *W* on *U* from physics

$$W \sim \dot{E} \sim \tau V \sim (\rho u_*^2) u_* \sim u_*^3 \quad \Rightarrow \quad W(U) \Rightarrow U^3$$

Foam fraction parameterization

Wu, 1988, JPO

Waves break when there is excessive energy supplied by the wind, while the viscous dissipation is generally insignificant. In an equilibrium state, the energy lost through wave breaking must be balanced by the energy gained from the wind. Consequently, the percentage of sea surface covered by breaking waves under the equilibrium state can be related to the energy flux from the wind (Wu 1979),

$$W \sim \dot{E} \quad (1)$$

- Cubic dependence of *W* on *U* from physics

$$W \sim \dot{E} \sim \tau V \sim (\rho u_*^2) u_* \sim u_*^3 \quad \Rightarrow \quad W(U) \Rightarrow U^3$$

- $W(U)$ not exactly cubic
  - Cubic if $u_* \sim U$, e.g., $u_* = \sqrt{C_D} U$
  - But
    - C_D is not constant, often $C_D(U)$

Foam fraction parameterization

- Cubic dependence of W on U from physics

$$W \sim \dot{E} \sim \tau V \sim (\rho u_*^2) u_* \sim u_*^3 \Rightarrow W(U) \Rightarrow U^3$$

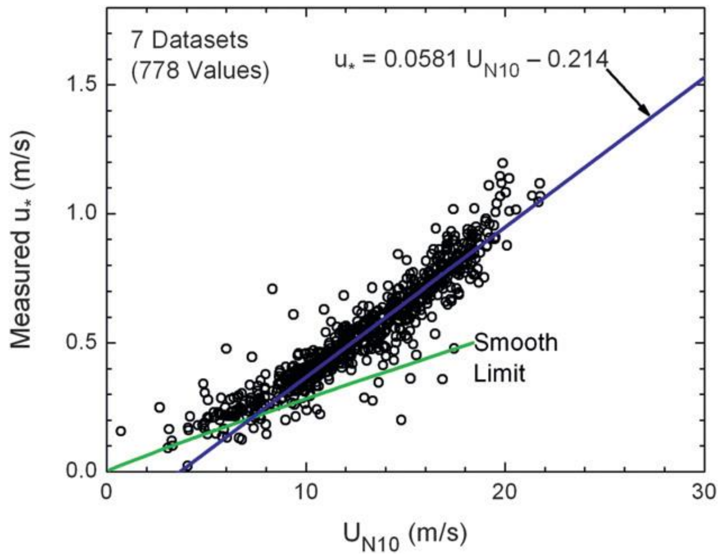
- $W(U)$ not exactly cubic
  - Cubic if $u_* \sim U$, e.g., $u_* = \sqrt{C_D} U$
  - But
    - C_D is not constant, often $C_D(U)$
    - Measurements show linear, but not proportional $u_* = aU$+b

Wu, 1988, JPO

Waves break when there is excessive energy supplied by the wind, while the viscous dissipation is generally insignificant. In an equilibrium state, the energy lost through wave breaking must be balanced by the energy gained from the wind. Consequently, the percentage of sea surface covered by breaking waves under the equilibrium state can be related to the energy flux from the wind (Wu 1979),

$$W \sim \dot{E} \qquad (1)$$

Andreas et al., 2012, JAS



Foam fraction parameterization

- Cubic dependence of *W* on *U* from physics

$$W \sim \dot{E} \sim \tau V \sim (\rho u_*^2) u_* \sim u_*^3 \quad \Rightarrow \quad W(U) \Rightarrow U^3$$

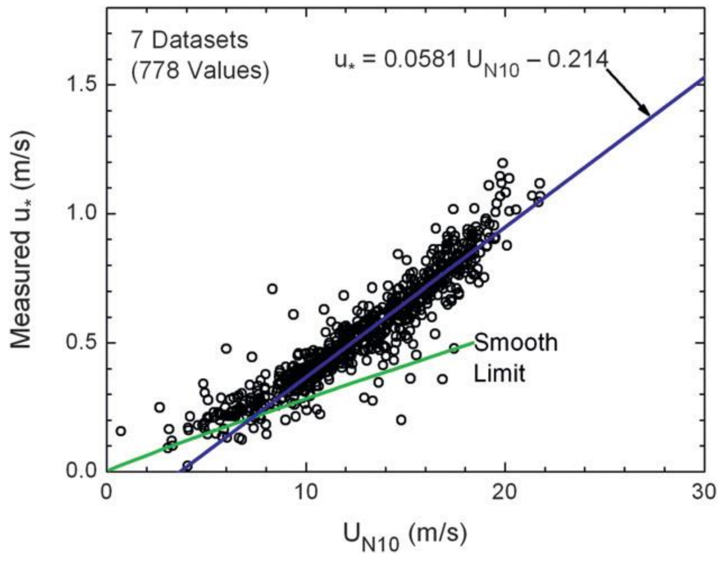
- $W(U)$ not exactly cubic
  - Cubic if $u_* \sim U$, e.g., $u_* = \sqrt{C_D} U$
  - But
    - C_D is not constant, often $C_D(U)$
    - Measurements show linear, but not proportional $u_* = aU$+b
- So: Is $W(U) = a(U - b)^3$ really cubic?
  - If using U^3, then must have a = const and $b(U)$
  - Coefficient b also would include other variables

Wu, 1988, JPO

Waves break when there is excessive energy supplied by the wind, while the viscous dissipation is generally insignificant. In an equilibrium state, the energy lost through wave breaking must be balanced by the energy gained from the wind. Consequently, the percentage of sea surface covered by breaking waves under the equilibrium state can be related to the energy flux from the wind (Wu 1979),

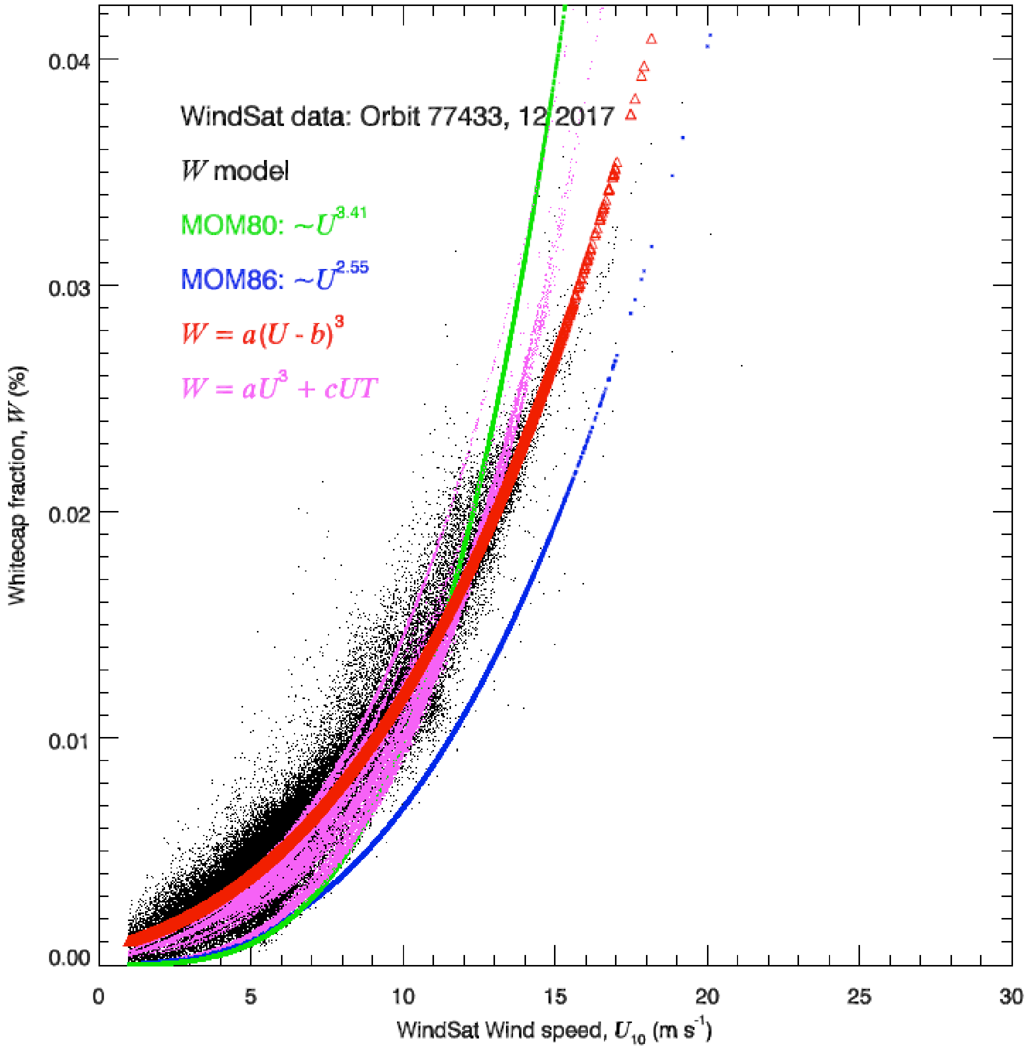
$$W \sim \dot{E} \qquad (1)$$

Andreas et al., 2012, JAS



Foam fraction from satellite *W*

- WindSat retrievals of *W*
- Non-linear least square fit
- Only wind speed dependence
  - $W(U) = a(U - b)^3$
  - $W(U) = aUn$
- Multi-variable fit to data: wind and SST
  - $W(U,T) = aU^3 + cUT$
- Multi-variable fit other approaches



Foam components (e_f and W) in full RTM

- Emmanuel's code at GitHub
- Input from ERA-Interim (U10, SST, SSS, Stab)
  - Data from Lise Kilic (987,235 data points)
  - Matched with AMSR2
  - Used 9873 data points
    - every 100, for calc time
  - Modified main code and config file Tb.p

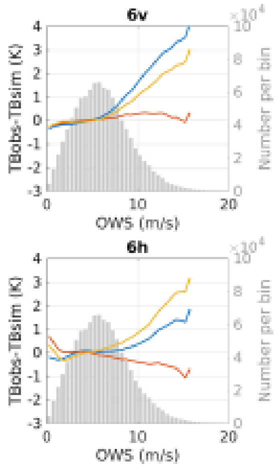
Foam components (e_f and W) in full RTM

- Emmanuel’s code at GitHub
- Input from ERA-Interim (U10, SST, SSS, Stab)
  - Data from Lise Kilic (987,235 data points)
  - Matched with AMSR2
  - Used 9873 data points
    - every 100, for calc time
  - Modified main code and config file Tb.p
- $T_{B\,\mathrm{sim}}$ at TOA for 4 cases of foam properties

- Atm and roughness the same
- Foam properties
  - ✓ Control
    - t = 2 cm; v_{af} = 95% (LOCEAN)
    - W MOM86 with $\Delta T \neq 0$
  - ✓ Tuned 1
    - t and v_{af} freq-specific
    - W MOM86 with $\Delta T \neq 0$
  - ✓ Tuned 2
    - t and v_{af} freq-specific
    - W MOM86 with $\Delta T = 0$
  - ✓ Tuned 3
    - t and v_{af} freq-specific
    - $W(U, T)$ from WindSat

Foam components (e_f and W) in full RTM

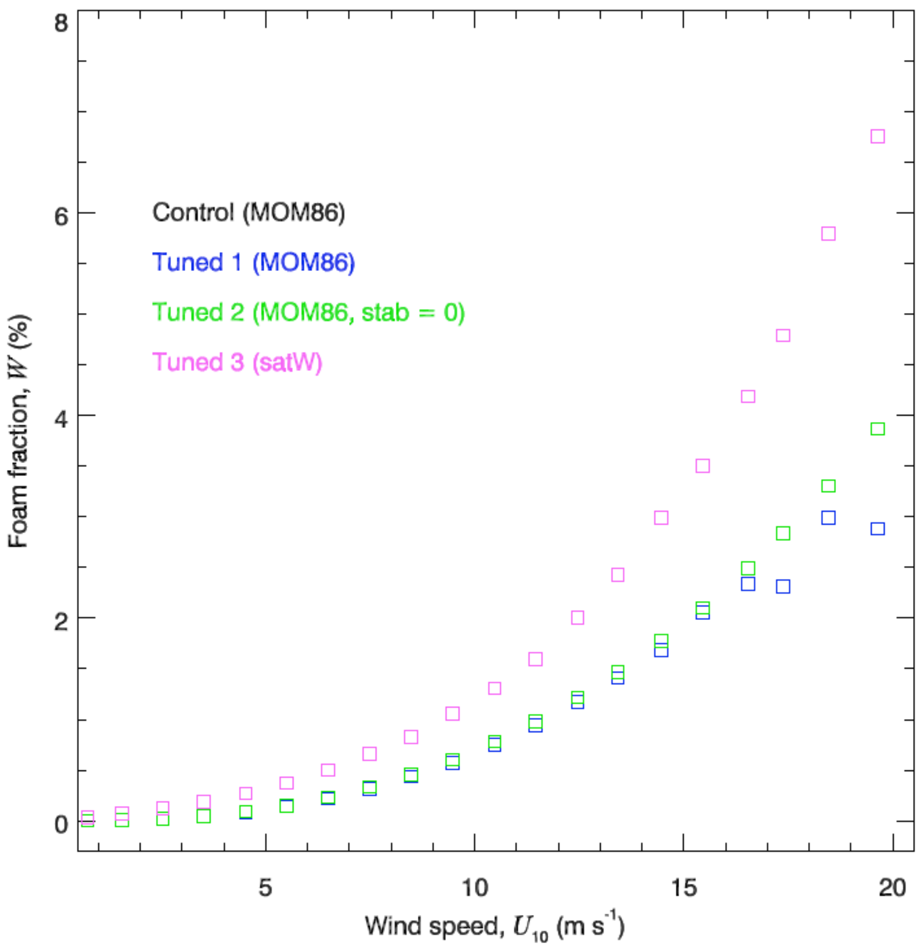
- Emmanuel's code at GitHub
- Input from ERA-Interim (U10, SST, SSS, Stab)
  - Data from Lise Kilic (987,235 data points)
  - Matched with AMSR2
  - Used 9873 data points
    - every 100, for calc time
  - Modified main code and config file Tb.p
- $T_{B\,\mathrm{sim}}$ at TOA for 4 cases of foam properties
- Compare $T_{B\,\mathrm{sim}}$ to AMSR2 $T_{B\,\mathrm{obs}}$
- Analyze ΔT_B in view of Kilic et al. (2019)



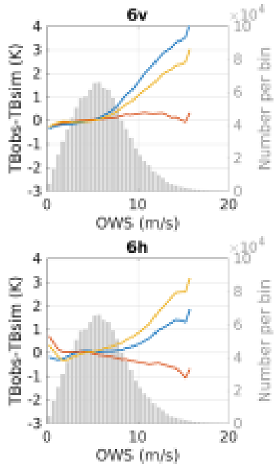
- Atm and roughness the same
- Foam properties
  - ✓ Control
    - t = 2 cm; v_{af} = 95% (LOCEAN)
    - W MOM86 with $\Delta T \neq 0$
  - ✓ Tuned 1
    - t and v_{af} freq-specific
    - W MOM86 with $\Delta T \neq 0$
  - ✓ Tuned 2
    - t and v_{af} freq-specific
    - W MOM86 with $\Delta T = 0$
  - ✓ Tuned 3
    - t and v_{af} freq-specific
    - $W(U,T)$ from WindSat

Foam components (e_f and W) in full RTM: RESULTS

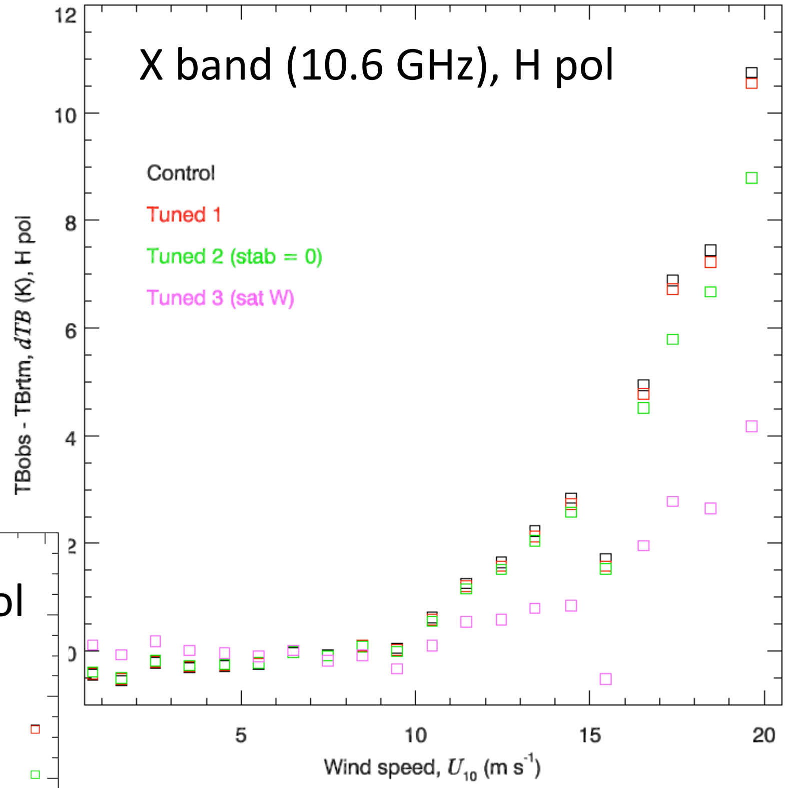
Results for 9873 data points, binned by wind speed

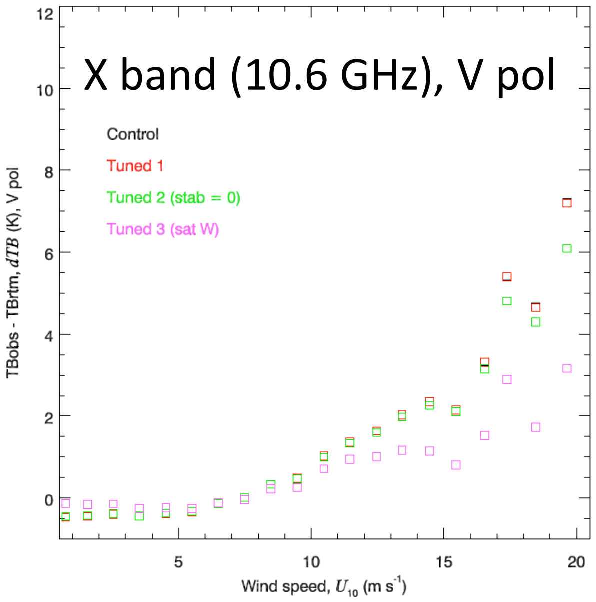


- Atm and roughness the same
- Foam properties
  - ✓ Control
    - t = 2 cm; v_{af} = 95% (LOCEAN)
    - **W MOM86 with $\Delta T \neq 0$**
  - ✓ Tuned 1
    - t and v_{af} freq-specific
    - W MOM86 with $\Delta T \neq 0$
  - ✓ Tuned 2
    - t and v_{af} freq-specific
    - W MOM86 with $\Delta T = 0$
  - ✓ Tuned 3
    - t and v_{af} freq-specific
    - $W(U, T)$ from WindSat

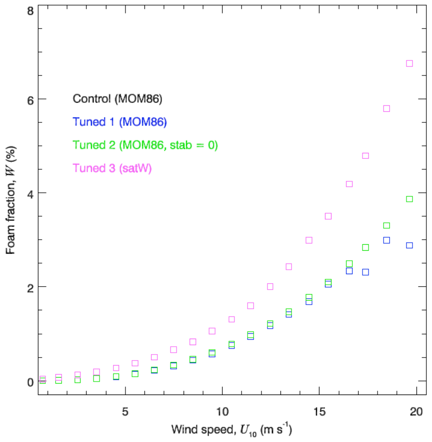


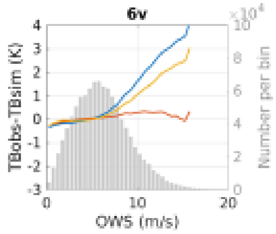
Foam components (e_f and W) in full RTM: RESULTS

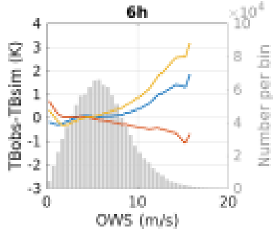




Results for 9873 data points, binned by wind speed

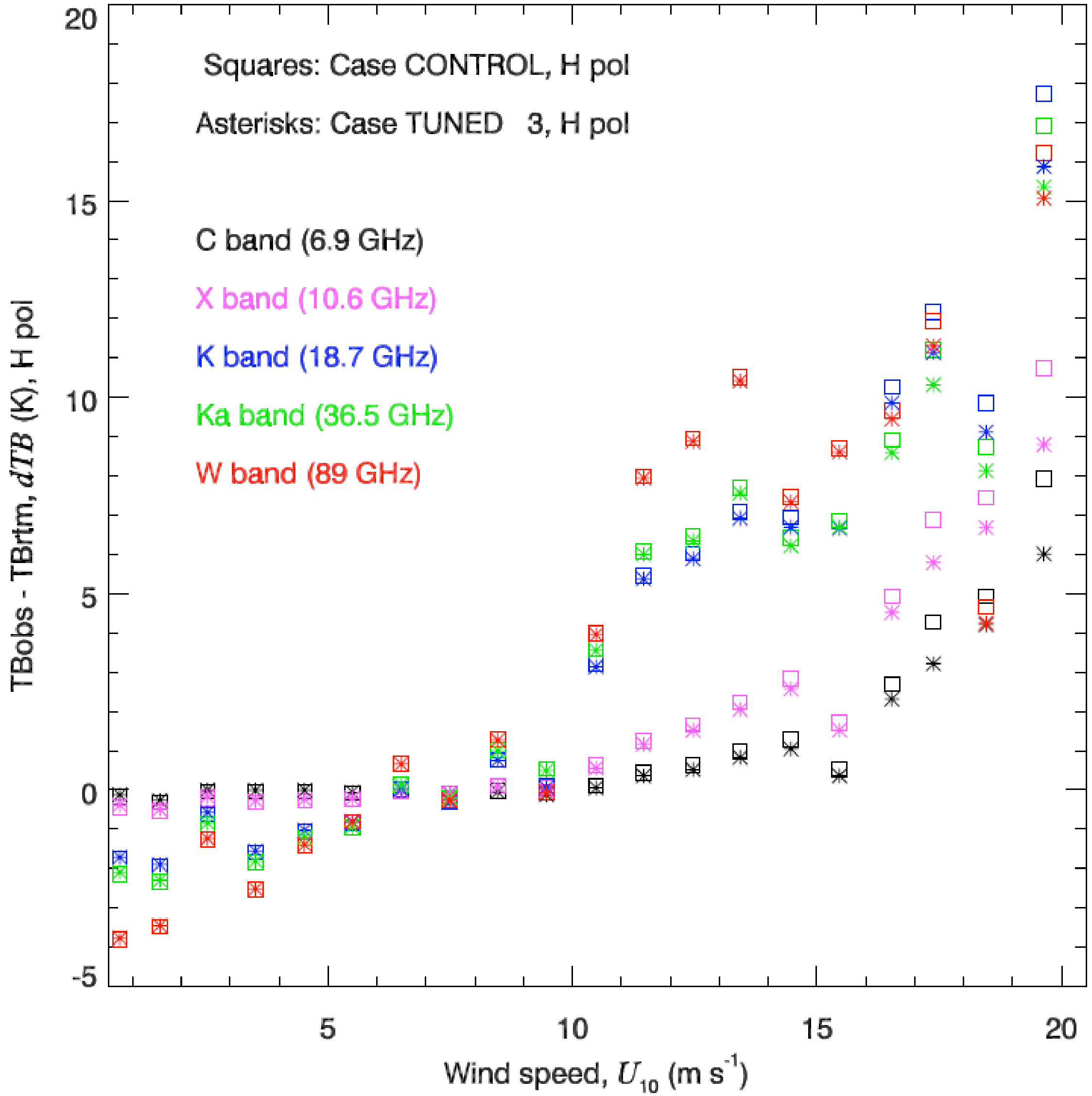




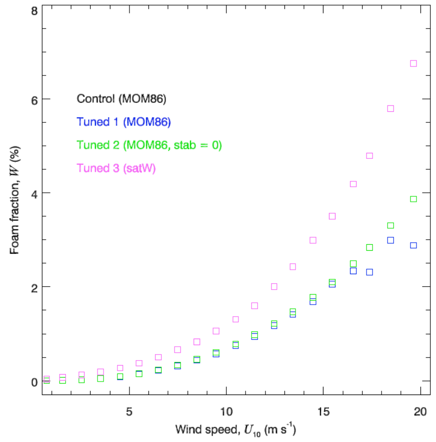


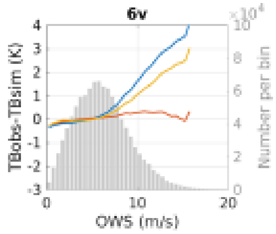
- Atm and roughness the same
- Foam properties
  - ✓ **Control**
    - t = 2 cm; v_{af} = 95% (LOCEAN)
    - W MOM86 with $\Delta T \neq 0$
  - ✓ Tuned 1
    - t and v_{af} freq-specific
    - W MOM86 with $\Delta T \neq 0$
  - ✓ Tuned 2
    - t and v_{af} freq-specific
    - W MOM86 with $\Delta T = 0$
  - ✓ Tuned 3
    - t and v_{af} freq-specific
    - $W(U, T)$ from WindSat

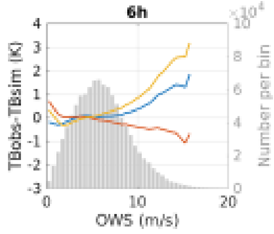
Foam components (e_f and W) in full RTM: RESULTS



Results for 9873 data points, binned by wind speed







- Atm and roughness the same
- Foam properties
  - ✓ Control
    - t = 2 cm; v_{af} = 95% (LOCEAN)
    - W MOM86 with $\Delta T \neq 0$
  - ✓ Tuned 1
    - t and v_{af} freq-specific
    - W MOM86 with $\Delta T \neq 0$
  - ✓ Tuned 2
    - t and v_{af} freq-specific
    - W MOM86 with $\Delta T = 0$
  - ✓ Tuned 3
    - t and v_{af} freq-specific
    - $W(U, T)$ from WindSat

To do

- Pub release of foam component report and sent to everyone
- Report on tuning and validation of foam in full RTM
- Prepare closed form F90 code for GitHub
- Present results on
  - Results on high freqs
  - Results on *W* parameterizations
  - Results on *W* uncertainty

Reminder: Closed and general formulations of e_f

$$T_{Bf}(\theta,p) = T_{B\,foam}(\theta,p) + T_{B\,water}(\theta,p) = T_{fU}(\theta,p) + T_{fD}(\theta,p) + T_{Bw}(\theta,p)$$

- Ulaby et al. (1986): Closed form using homogeneous layer (e.g., foam with constant f_a)

$$e_i(\theta_1,p) = \frac{1-\Gamma_1}{1-\Gamma_1\Gamma_2/L_2^2}\left[\left(1+\frac{\Gamma_2}{L_2}\right)\left(1-\frac{1}{L_2}\right)(1-a_2)+\frac{1-\Gamma_2}{L_2}\right]$$

- LOCEAN (F90): Closed form (above), but use f_a profile for L_2 (quasi-closed)

$$T_{fU}(\theta,p) = \frac{1-\Gamma_1}{1-\Gamma_1\Gamma_2/L_2^2}\; T_{sU}(\theta_f,0)$$

$$T_{fD}(\theta,p) = \frac{\Gamma_2(1-\Gamma_1)}{L_2(1-\Gamma_1\Gamma_2/L_2^2)}\, T_{sD}(\theta_f,t)$$

- NRL (IDL): General form, use profile f_a for L_2 and separate terms

$$T_{Bw}(\theta,p) = \frac{(1-\Gamma_1)(1-\Gamma_2)}{L_2(1-\Gamma_1\Gamma_2/L_2^2)}\, T_{sw}(\theta_w,t)$$