Dielectric Models of Sea-Water Comparison + Uncertainties

Thomas Meissner + Frank Wentz + Andrew Manaster
Remote Sensing Systems (RSS), Santa Rosa, USA
meissner@remss.com

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Outline

1. Introduction and Recap:
    - Overview of Models
    - Meissner-Wentz Model
    - Validation Techniques
2. L-band
    - Update: Measurements of Zhou et al. (GWU 2020)
    - Somaraju-Trumpf (SOM) and Boutin-Vergely (BV) models
3. Comparison at Higher Frequencies (L – W Bands)
    - Comparison with FASTEM5
4. Uncertainty Assessment
5. Summary + Conclusions

Introduction and Recap

Dielectric Constant of (Sea-) Water

- Complex dielectric constant (permittivity).
  - **Central input of all MW radiometric modeling**
- Based on electromagnetic theory.
  - Measures response of medium to applied electric field.
  - Determines emissivity of specular (flat) ocean surface (Fresnel).

$$E_{0p} = 1 - \left| r_p \right|^2, \quad p = V, H$$

$$r_V = \frac{\varepsilon \cos(\theta_i) - \sqrt{\varepsilon - \sin^2(\theta_i)}}{\varepsilon \cos(\theta_i) + \sqrt{\varepsilon - \sin^2(\theta_i)}} \qquad r_H = \frac{\cos(\theta_i) - \sqrt{\varepsilon - \sin^2(\theta_i)}}{\cos(\theta_i) + \sqrt{\varepsilon - \sin^2(\theta_i)}}$$

  - Determines optical index of refraction -> cloud water absorption (Rayleigh).

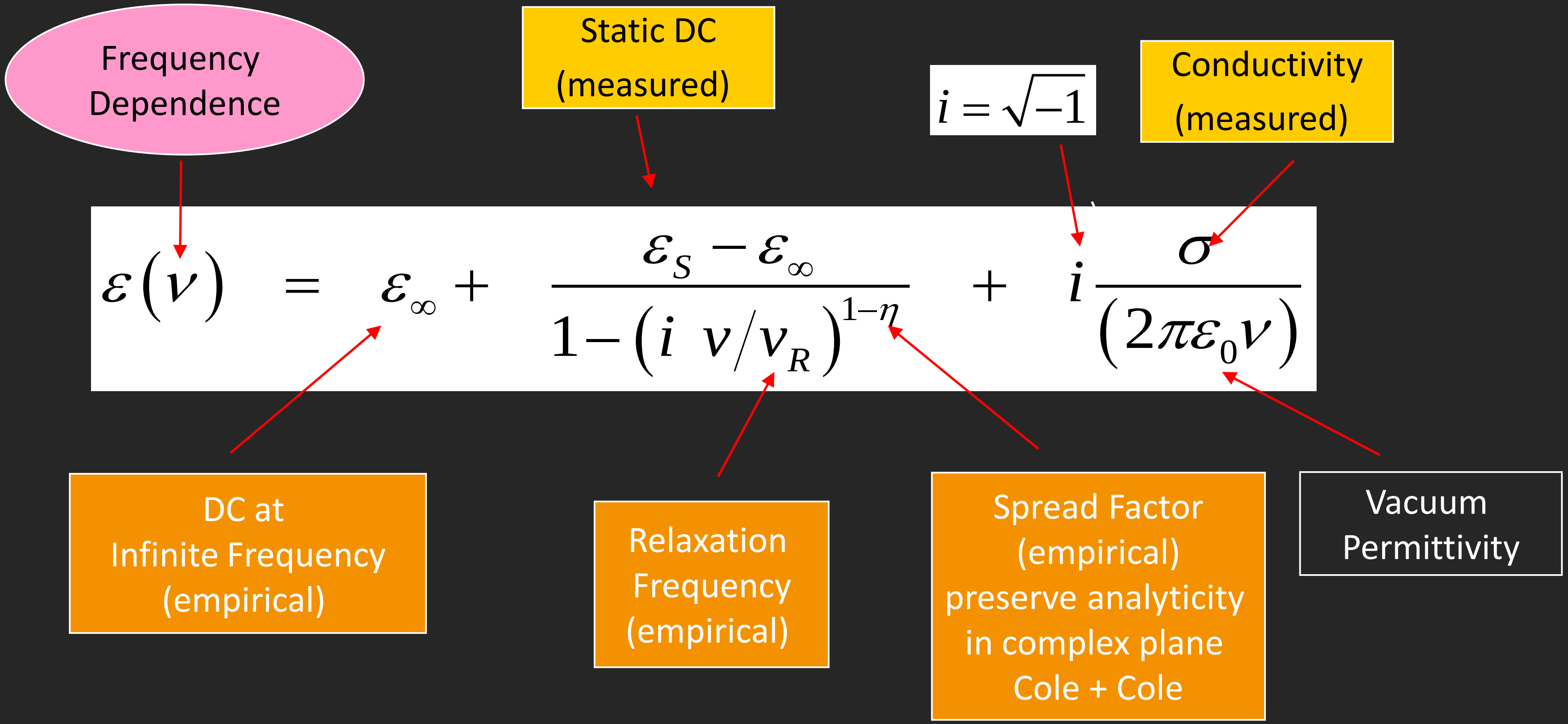
$$\alpha_L \approx \frac{6\pi \cdot \rho_L}{\lambda \cdot \rho_0} \cdot \mathrm{Im}\left(\frac{1 - \varepsilon_L}{2 + \varepsilon_L} \right)$$

Dielectric Constant of (Sea-) Water

- Basis for measurement of:
  - SST (C-band, X-band).
  - Salinity (L-band).
  - Enters also in retrieval of wind speed, vapor and cloud water.

Single Debye Relaxation

Physical mechanism based on orienting polar molecules in electric field + restoring force (viscous medium). Connects different frequencies.



Frequency Dependence

Static DC (measured)

$i = \sqrt{-1}$

Conductivity (measured)

$$\varepsilon(\nu) = \varepsilon_\infty + \frac{\varepsilon_S - \varepsilon_\infty}{1-\left(i\ \nu/\nu_R\right)^{1-\eta}} + i\frac{\sigma}{\left(2\pi\varepsilon_0\nu\right)}$$

DC at Infinite Frequency (empirical)

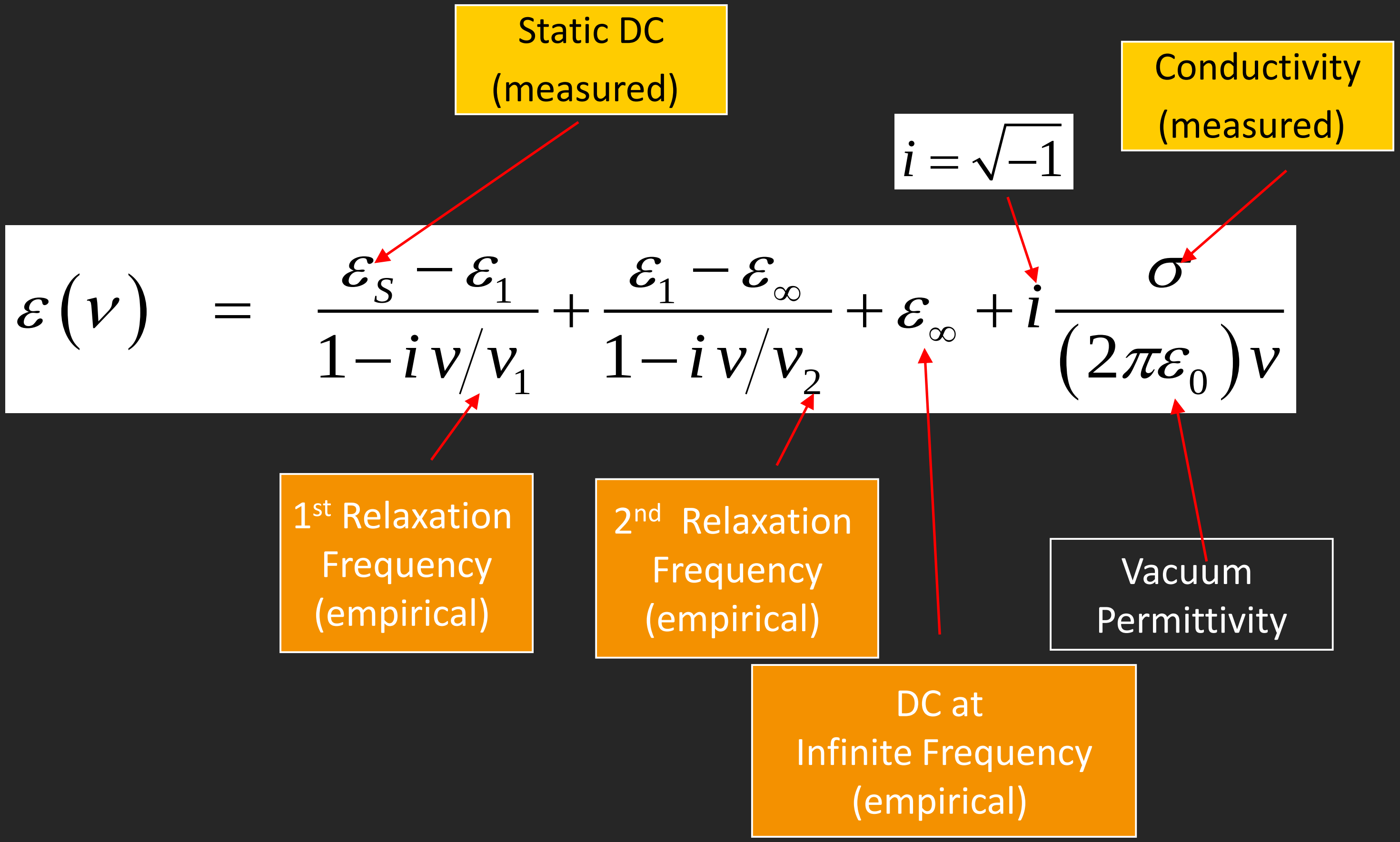
Relaxation Frequency (empirical)

Spread Factor (empirical) preserve analyticity in complex plane Cole + Cole

Vacuum Permittivity

- Accurate below 18 GHz.
- Parameters depend on Temperature and Salinity.

Double Debye Relaxation



Static DC (measured)

$i = \sqrt{-1}$

Conductivity (measured)

$$\varepsilon(\nu) = \frac{\varepsilon_S - \varepsilon_1}{1 - i\,\nu/\nu_1} + \frac{\varepsilon_1 - \varepsilon_\infty}{1 - i\,\nu/\nu_2} + \varepsilon_\infty + i\frac{\sigma}{(2\pi\varepsilon_0)\,\nu}$$

1st Relaxation Frequency (empirical)

2nd Relaxation Frequency (empirical)

Vacuum Permittivity

DC at Infinite Frequency (empirical)

- Necessary above 18 GHz.
- Comprises single Debye law.

Low and High Frequency Limits

$$\lim_{\nu \to 0} \varepsilon(\nu) \quad = \quad \varepsilon_S + \left(\varepsilon_1 - \varepsilon_S\right) \cdot \frac{\nu^2}{\nu_1^{\,2}} + i \frac{\sigma}{\left(2\pi\varepsilon_0\right)\nu}$$

- L-band and lower: Dominated by values ε_S and σ

$$\varepsilon\left(\nu \gg \nu_1\right) \quad \approx \quad \varepsilon_\infty + \left(\varepsilon_1 - \varepsilon_\infty\right) \cdot \frac{\nu_2^{\,2}}{\nu^2} + i \cdot \left(\varepsilon_1 - \varepsilon_\infty\right) \cdot \frac{\nu_2}{\nu}$$

- Sensitive to 2nd Debye relaxation and ε_1, ε_∞

Models and Measurements of Dielectric Constant (1)

- **Klein – Swift (1977)**
  - Fit to laboratory measurements at low frequency.
  - Did not include very low SST.
  - Widely used in microwave applications.
  - Single Debye relaxation.
  - Accurate at low frequencies (below 18 GHz).
  - Decreasing accuracy at higher frequencies and in cold water.
  - Bias at 0°C: 2 K (37 GHz) – 5 K (85 GHz).
- **Wentz (1997)**
  - Inconsistencies retrieving SSM/I EDRs over cold water (negative cloud water retrievals, SST dependent biases in wind speed) when using KS.
  - Re-fitted and adjusted model parameters.
  - Single Debye relaxation.
- **Guillou et al. (1998), Ellison et al. (2002)**
  - Laboratory measurements up to W-band (85 GHz).
  - W-band measurements reliable: comparison with SSM/I
  - We do not use their lower frequency data.

Meissner – Wentz (MW) Dielectric Constant

2004, 2012 IEEE TGRS papers

- Double Debye relaxation law.
- Uses laboratory measurements to pure water (1- 400 GHz).
  - Smooth transition from saline to pure water.
- The conductivity σ is taken from **Stogryn et al.1995** laboratory measurements.
- Static dielectric constant ε_S is taken from laboratory measurements.
- Fit to **Wentz 1997** up to 37 GHz and **Guillou et al. 1998** at 85 GHz.
- Fine-tuned and tested with satellite observations (SSM/I, WindSat).
  - V-pol, wind < 5 m/s: Emissivity does not change with wind speed.
- Does not use L-band satellite measurements.
- The **MW model** is used in all RSS passive microwave ocean retrievals (L – Ka band).

Models and Measurements of Dielectric Constant (2)

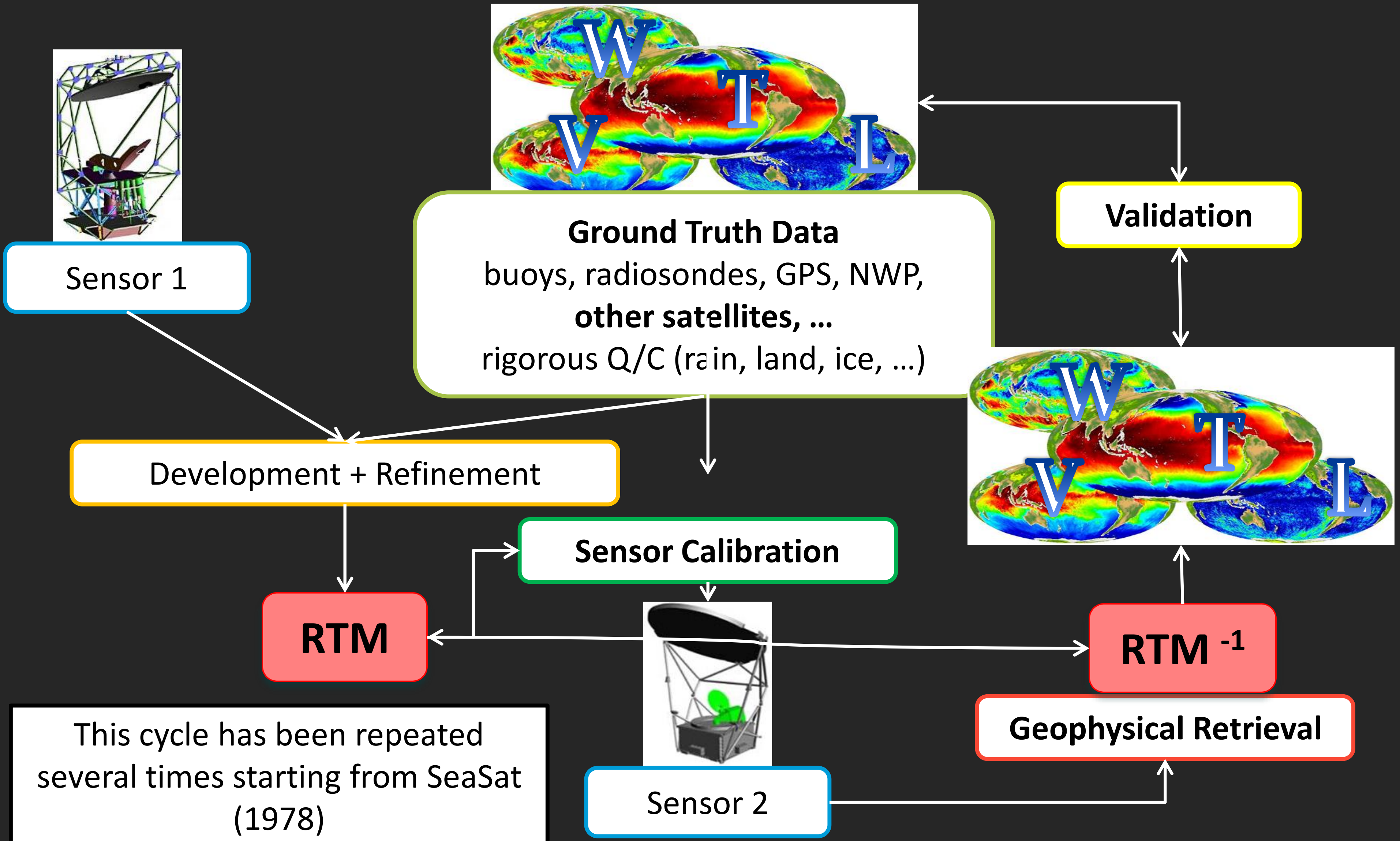
- **FASTEM 2011.**
  - 2 typos in printed version. FORTRAN code OK.
- **GWU 2020 (Zhou et al.): L-band**
  - Laboratory measurements at 1.41 GHz.
  - Updated in 2020: Better fit.
  - Older version had unrealistic dependence on salinity.
  - Single Debye relaxation fit.
  - Fit is good and valid at L-band.
- **Somaraju – Trumpf (2006)**
  - Double Debye relaxation.
  - Pure-water measurements of Stogryn et al.
  - Simple physical inspired model for salinity dependence, similar to ionic plasmas.
  - Only the static term ε_s depends on salinity.
  - Decreases linearly: $\varepsilon_s \cdot (1 - SSS \cdot \alpha(T))$
  - Assume constant α(T): no SST dependence.
- **Boutin - Vergely (2020)**
  - Same as Somaraju – Trumpf.
  - Fit SST dependence of α(T) based on SMOS observations.

General Remark

(Non-) Sense of Dielectric Model Use and Misuse

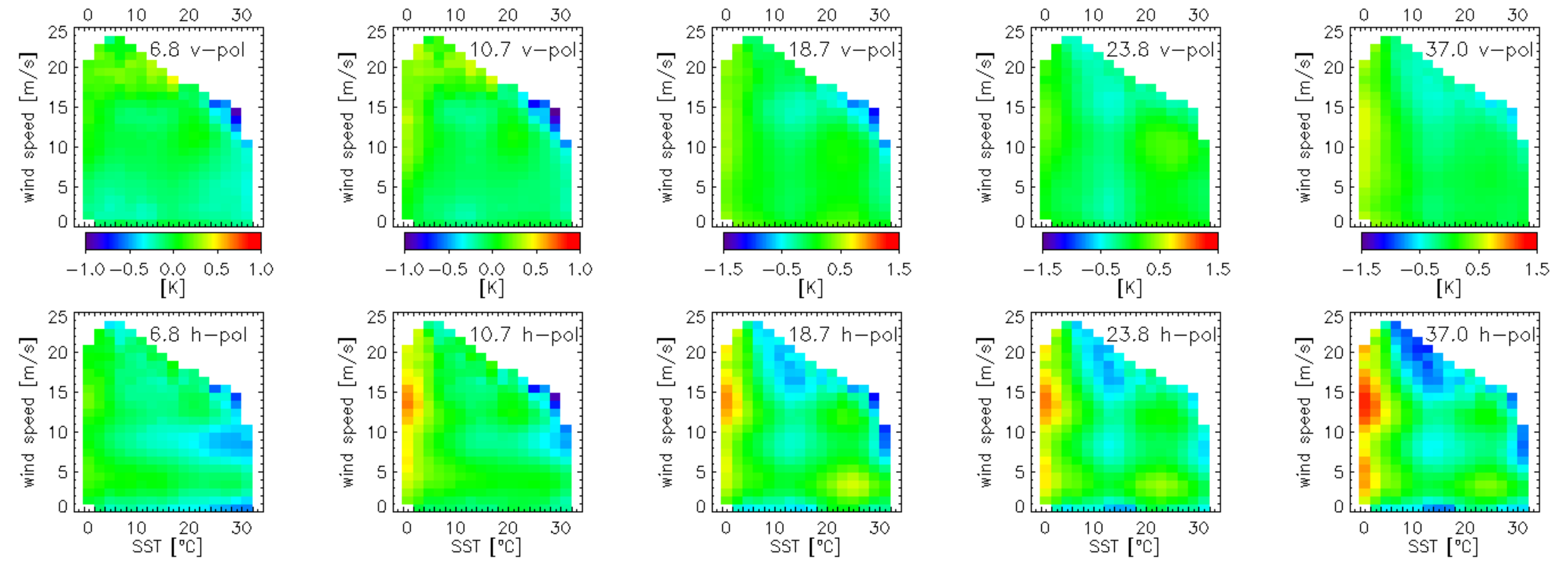
- All of the dielectric models are based on fits of the model parameters (Debye relaxation parameters) as functions of SST and SSS.
  - Use analytical functions: higher order polynomials, rational functions, exp(…), …
  - For practical use.
  - In most instances NOT (or little) based on physics.
  - Those analytical fits are only valid and **should only be used within the SST and SSS intervals that were used to derive them**.
  - You can expect to degrade them rather quickly if you leave the validity intervals. It can lead to very unrealistic results. (If it does work, it is pure luck), even if the model works fine within the valid SST and SSS intervals.
  - It is doomed to fail. Let’s not do it, please!
- Examples:
  - Klein-Swift has polynomial fits that were derived from data that did NOT include cold water. So, you cannot extend them to cold SST.
  - Same applies to Liebe et al. model for pure water.
  - General: Salinity fits extend to 40 psu at most. You cannot expect them wo work at the Uyuni Salt Flats (Bolivia) or Great Salt Lake (Utah).

Four Cornerstones:
RTM, Sensor Calibration, Retrieval, Validation



This cycle has been repeated several times starting from SeaSat (1978)

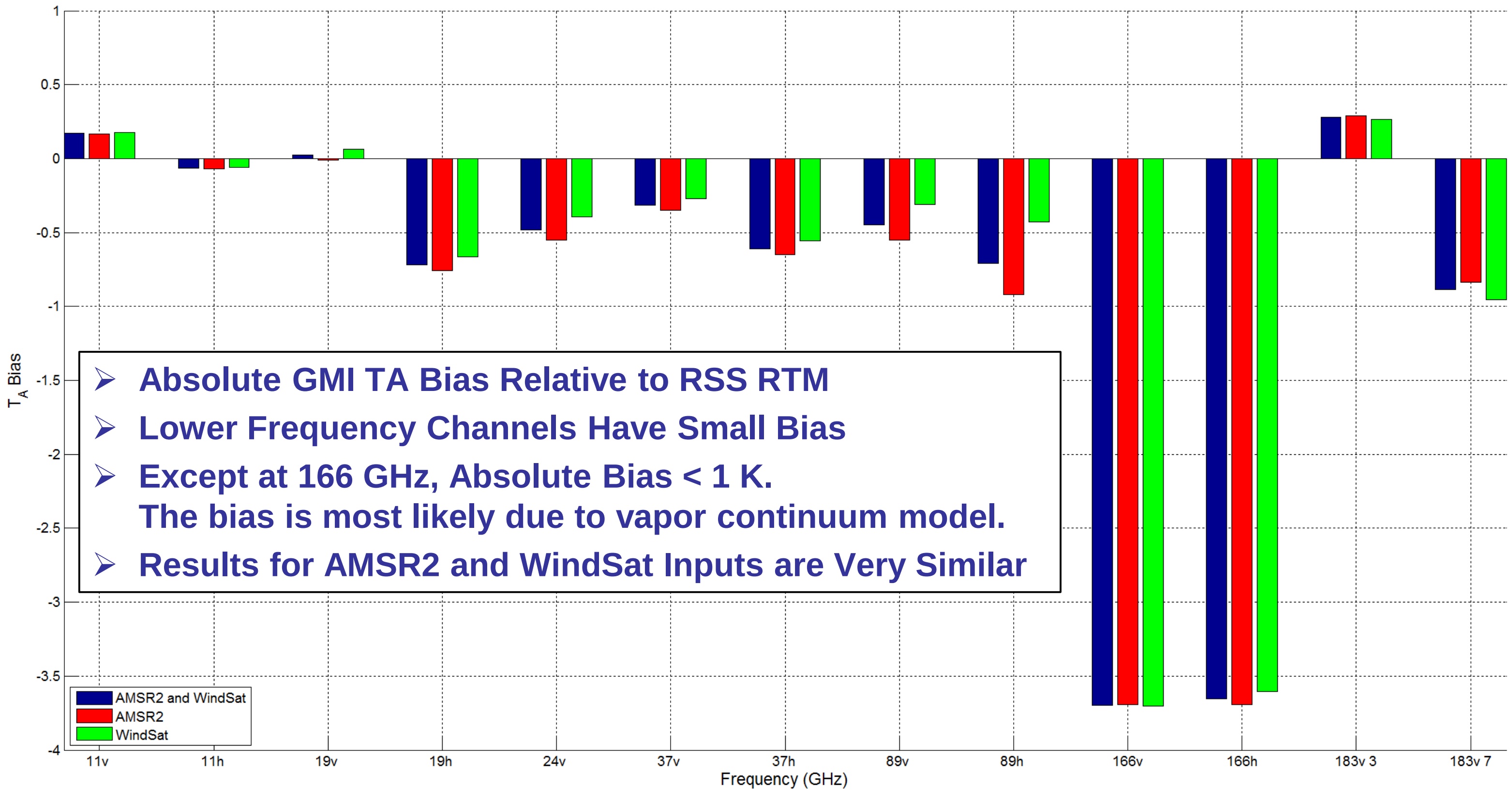
RTM Validation



- TB measured – RTM computed for 10 WindSat V/H channels.
- Stratified versus SST and wind speed.
- Error chart.
- Input to RTM computation: QuikScat wind speed, NOAA OI SST (IR, no MW).
- V-pol chart at low wind speed is most relevant for dielectric model (little surface roughness effect).

Best Calibrated Radiometer: GMI

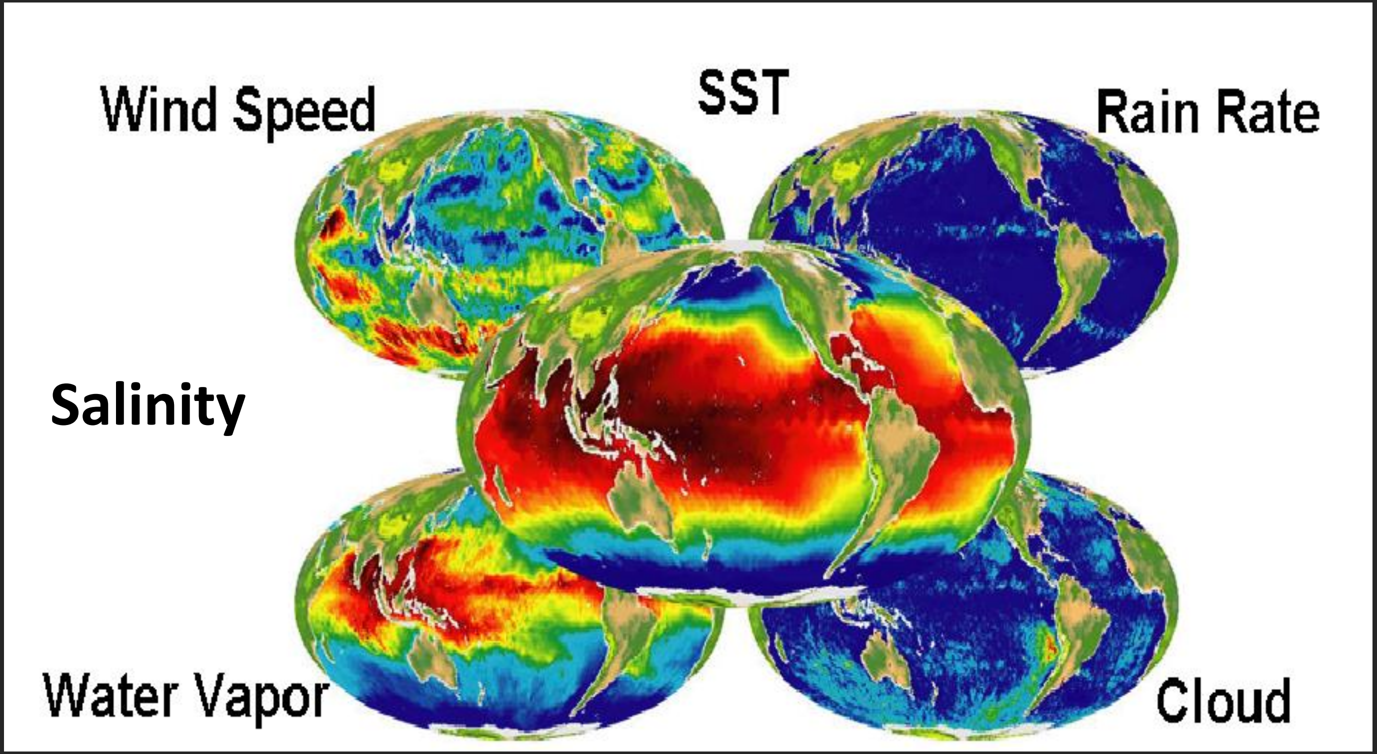
Excellent Agreement between Pre-Launch and Post-Launch Antenna Pattern
4-Point Calibration



- **Absolute GMI TA Bias Relative to RSS RTM**
- **Lower Frequency Channels Have Small Bias**
- **Except at 166 GHz, Absolute Bias < 1 K.**
  The bias is most likely due to vapor continuum model.
- **Results for AMSR2 and WindSat Inputs are Very Similar**

Ultimate Criterion for Using RTM

Quality of Retrieved Environmental Parameters

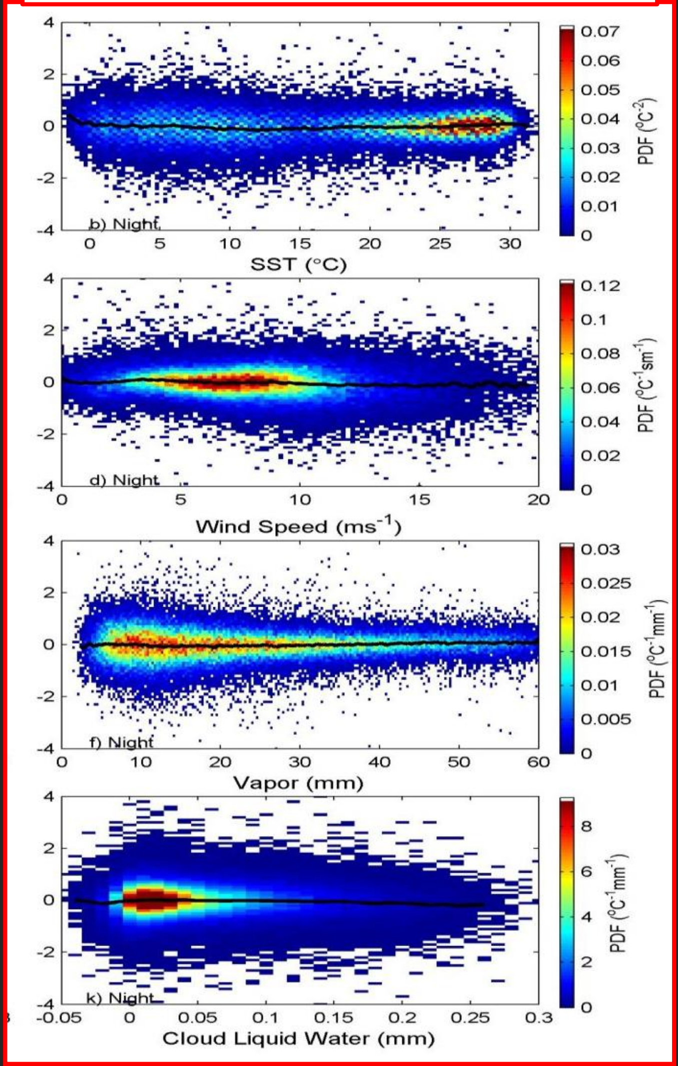


We do not want to compromise EDR quality.

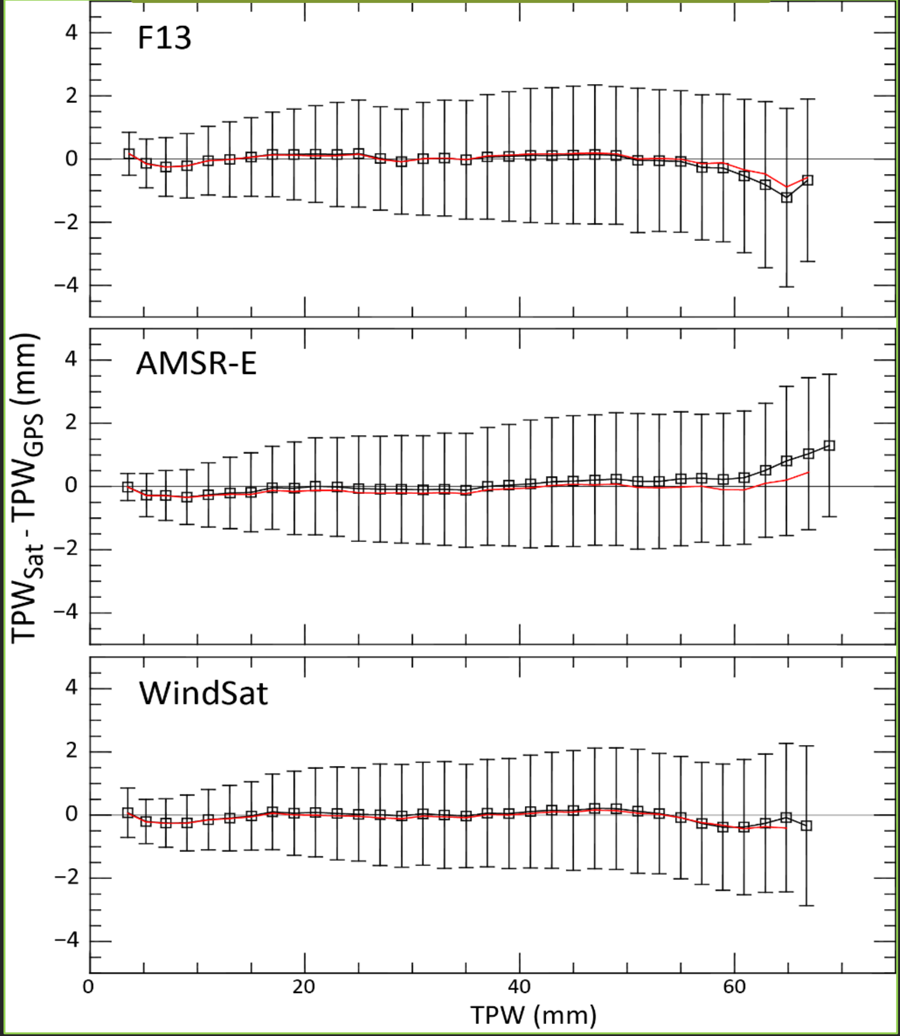
Validation (cont.)

SST, Vapor, Wind Speed

AMSR2 SST vs Buoys
(Gentemann + Hilburn, 2015)

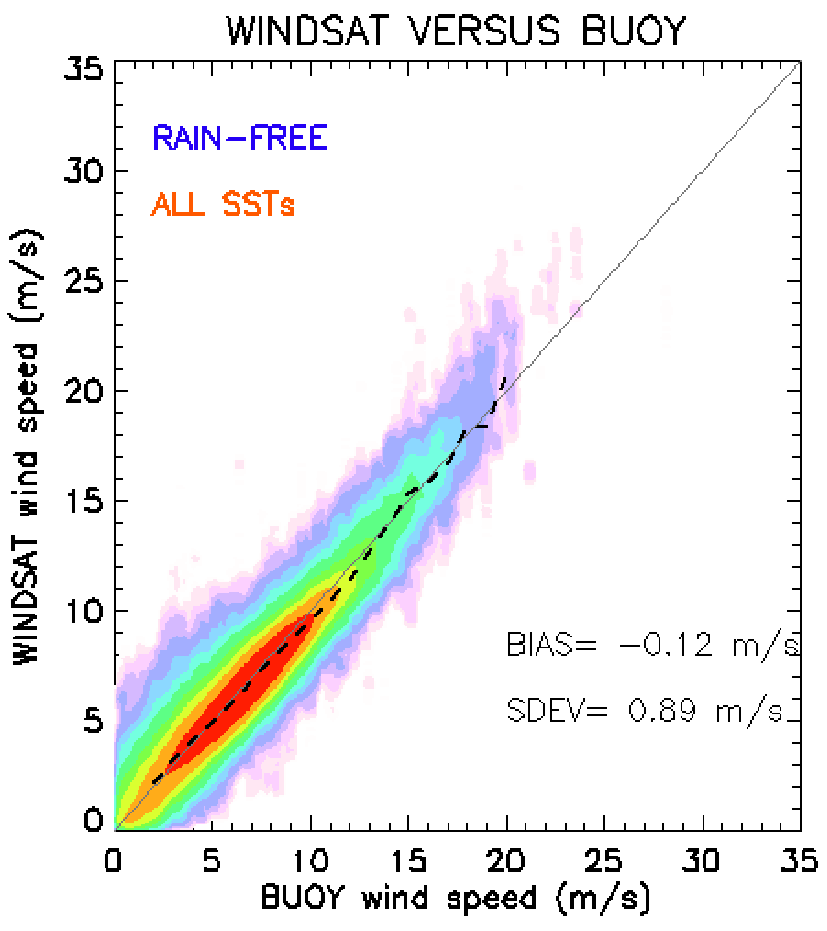


Water Vapor
(Mears et al. 2015)



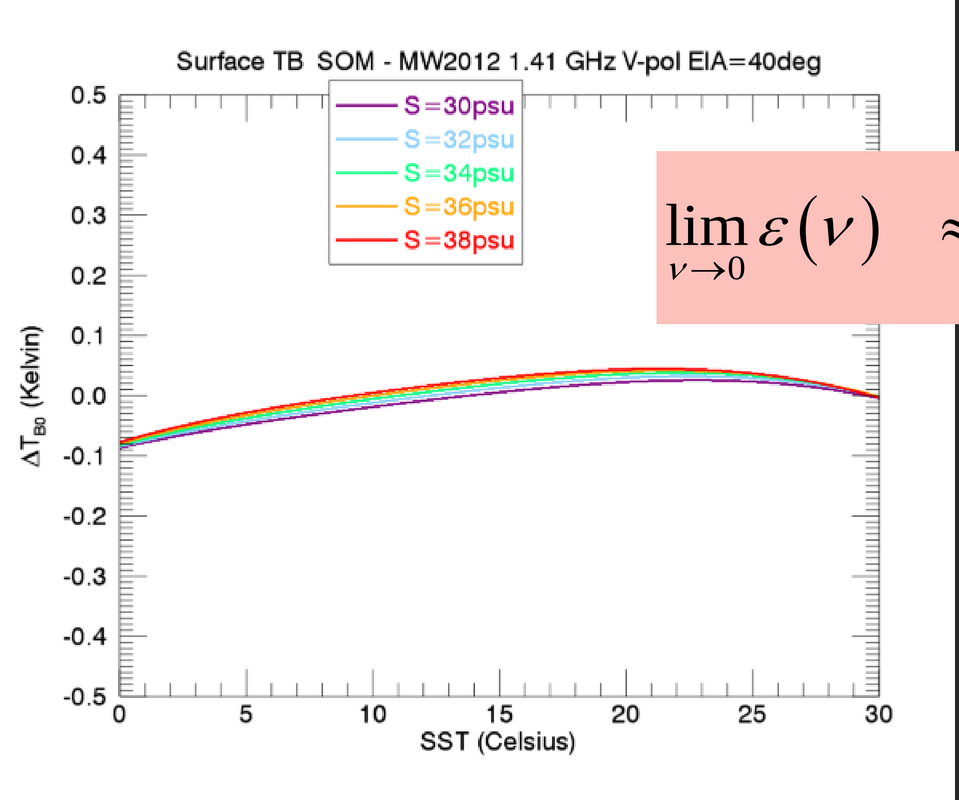
Extensive Validation versus Ground Truth

Wind Speed



L-Band Dielectric Models

Somaraju - Trumpf versus Meissner - Wentz 2012



$$\lim_{\nu \to 0} \varepsilon(\nu) \approx \varepsilon_S + i\frac{\sigma}{(2\pi\varepsilon_0)\nu}$$

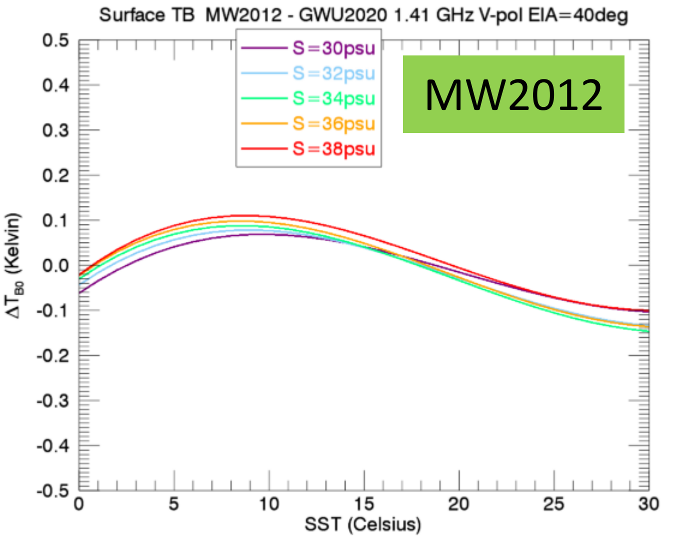
Bias: +0.02 K

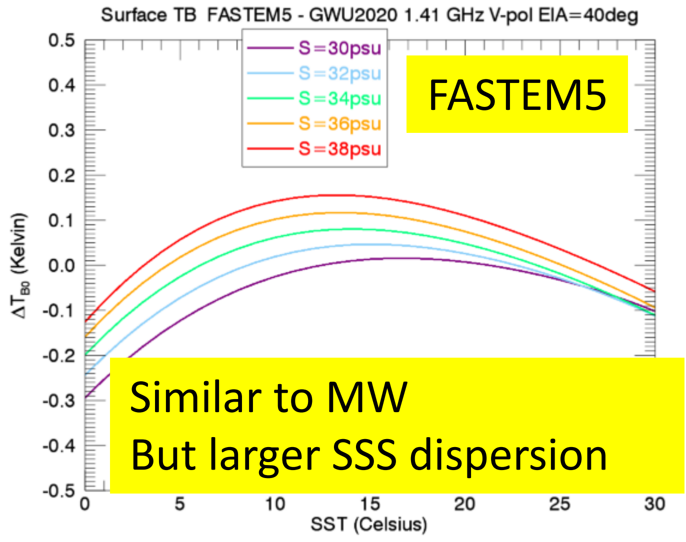
STD.DEV: 0.04 K

- Somaraju-Trumpf and Meissner Wentz 2012 are very close at L-band.
  - Both SST and SSS dependence
- Physical model for ε_S from Somaraju-Trumpf consistent with MW fit.
- Conductivity σ based on laboratory measurements in both models.

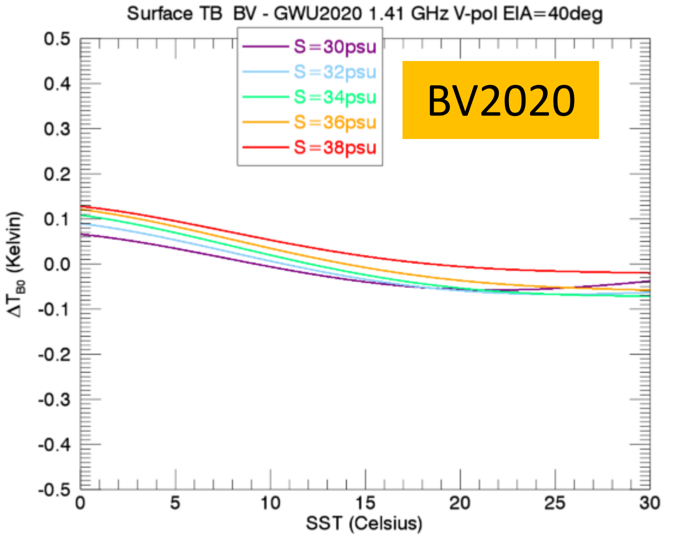
Comparison with GWU 2020

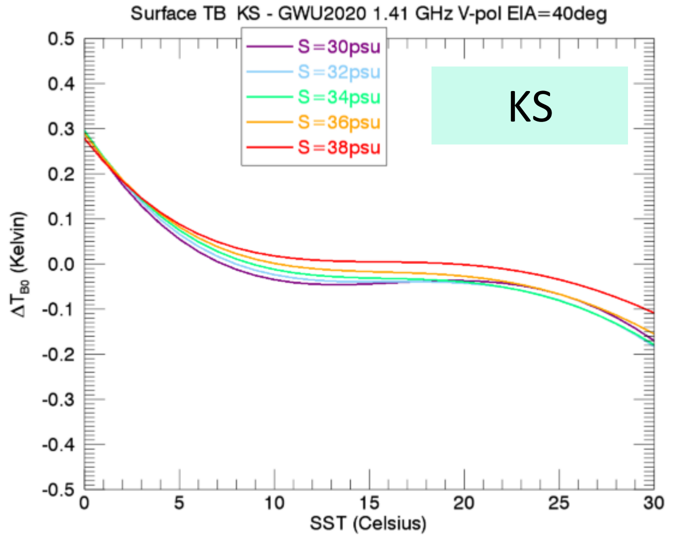
FREQ=1.41GHz, EIA=40°, V-pol


Surface TB MW2012 - GWU2020 1.41 GHz V-pol EIA=40deg


Surface TB FASTEM5 - GWU2020 1.41 GHz V-pol EIA=40deg

Similar to MW
But larger SSS dispersion


Surface TB BV - GWU2020 1.41 GHz V-pol EIA=40deg


Surface TB KS - GWU2020 1.41 GHz V-pol EIA=40deg

- SST from 0°C to 30°C in steps of 1°C.
- SSS from 30 psu to 38 psu in steps of 1 psu.
- ΔTB surface = ΔEmissivity ·SST (Kelvin).

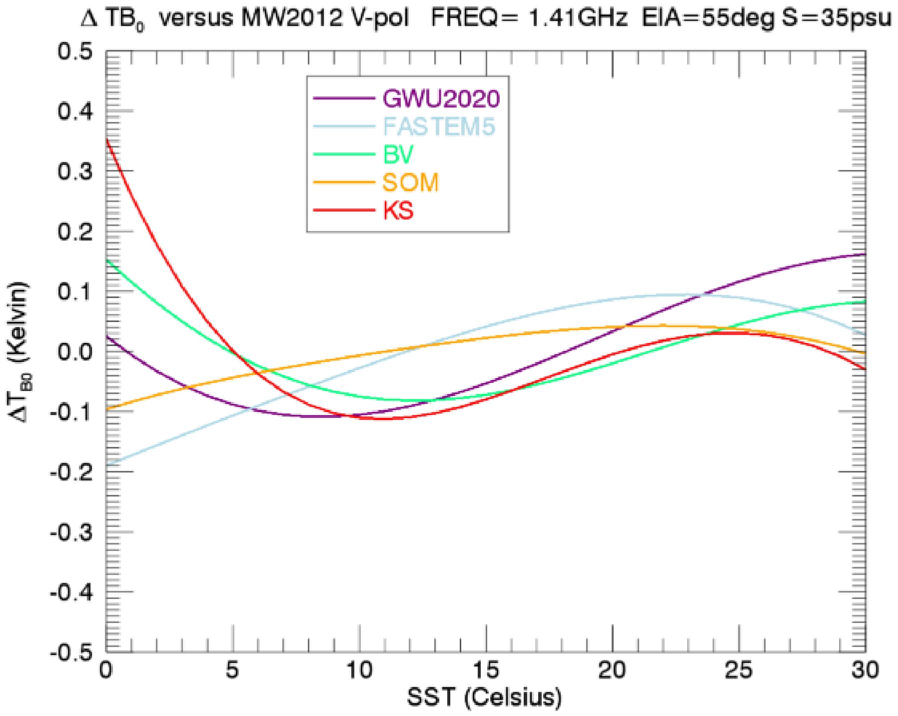
Higher Frequencies: L – W Bands

Any dielectric model needs to work over wide frequency range.

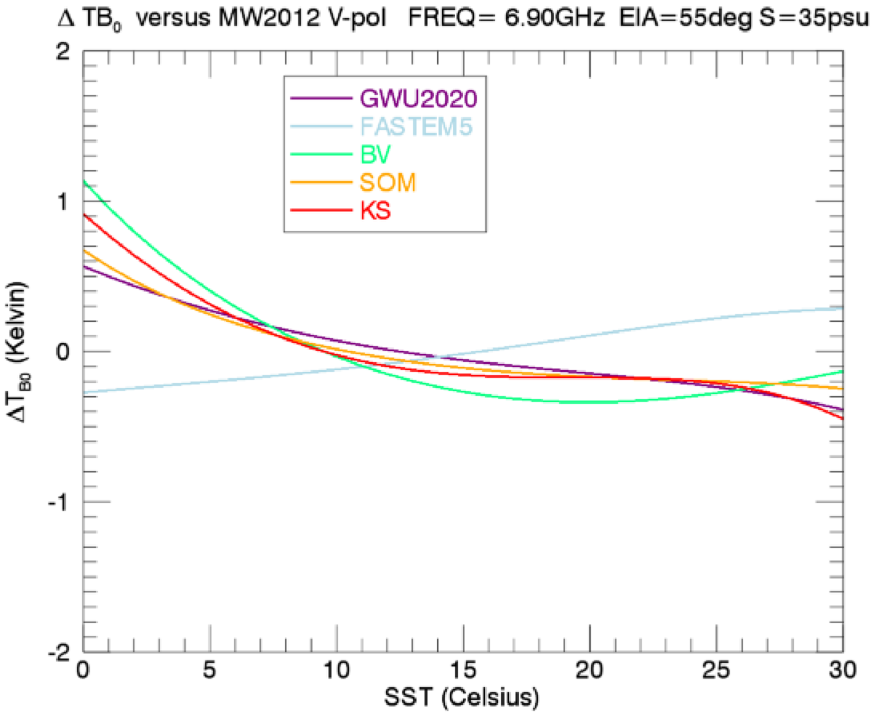
Surface TB versus Meissner-Wentz 2012

EIA=55° V-pol SSS=35psu Debiased

L-band



C-band

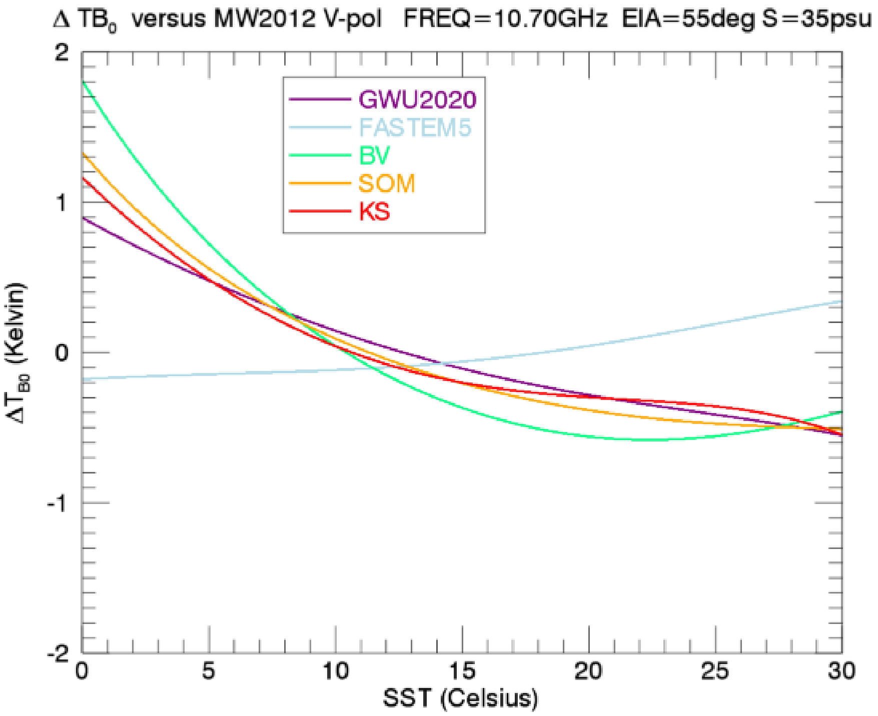


- FASTEM5 stays very close to MW.
- All other models ramp up significant SST gradient.
  - Unlikely to be usable in AMSR2 retrievals (SST, Wind).

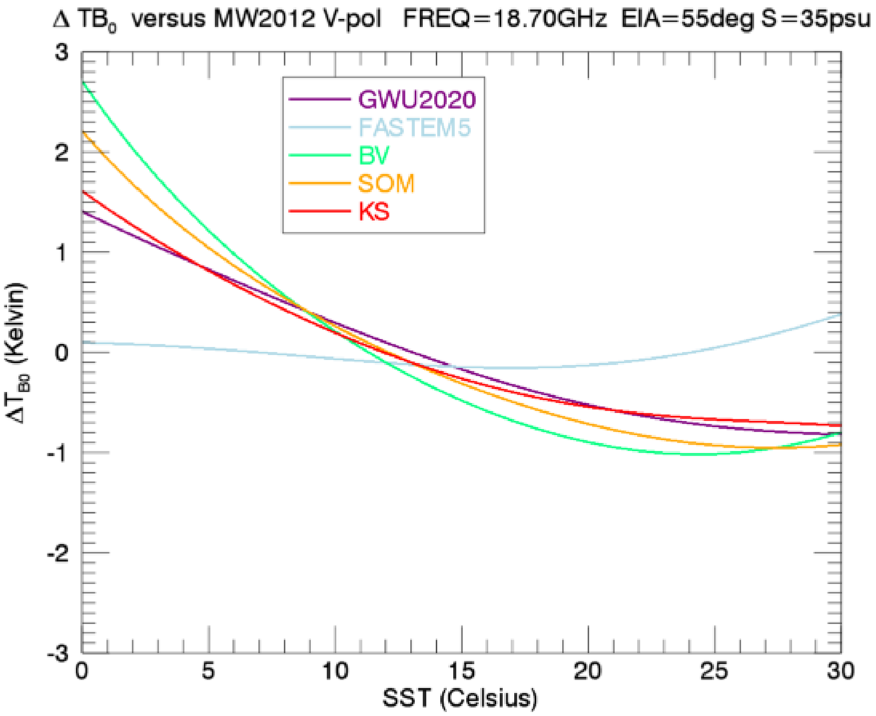
Surface TB versus Meissner-Wentz 2012

EIA=55° V-pol SSS=35psu Debiased

X-band



K-band

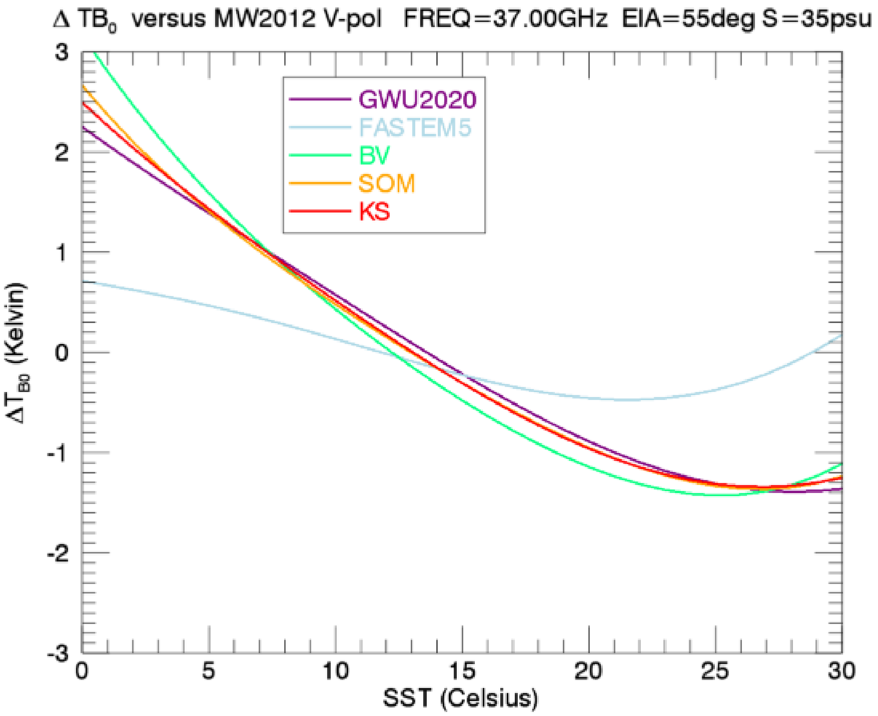


- FASTEM5 stays very close to MW.
- All other models ramp up significant SST gradient.
  - Unlikely to be usable in AMSR2 retrievals (SST, Wind).

Surface TB versus Meissner-Wentz 2012

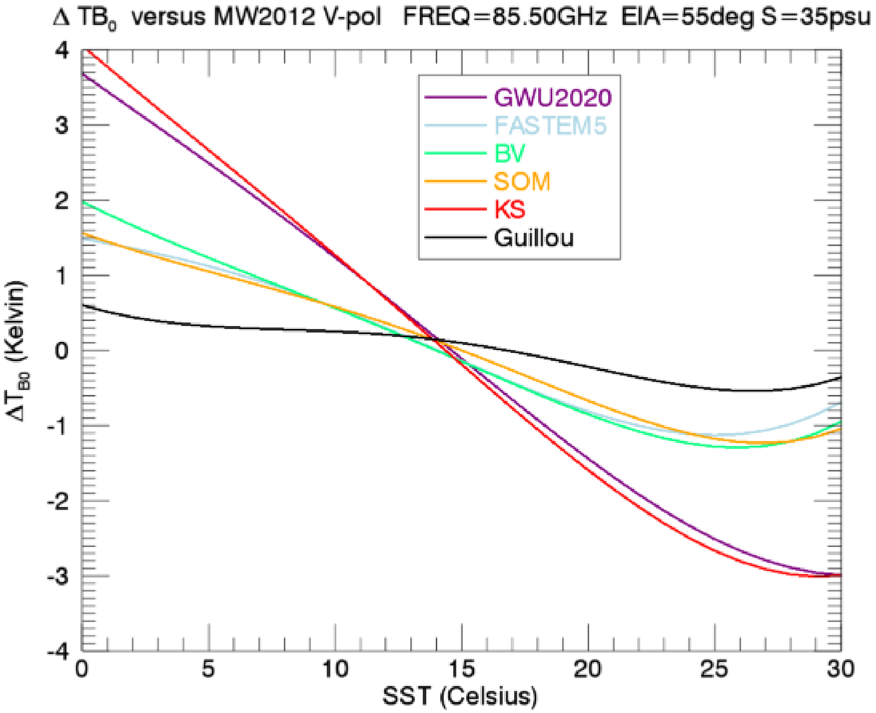
EIA=55° V-pol SSS=35psu Debiased

Ka-band



Δ TB$_0$ versus MW2012 V-pol FREQ=37.00GHz EIA=55deg S=35psu

W-band



Δ TB$_0$ versus MW2012 V-pol FREQ=85.50GHz EIA=55deg S=35psu

W-band dominated by ε_∞, ε_1 and ν_2

Uncertainty Assessment

Radiometric Differences

Surface TB EIA=55° V-pol SSS=35psu 0°C<SST<30°C

Overall bias

- Can be removed in sensor calibration.
- Could be bias in experimental set-up.

Of interest in the variability with SST and SSS over dynamic range encountered over ocean (last column).

Frequency [GHz]	Comparison	Bias (Kelvin)	Std.Dev (Kelvin)
1.41	GWU2020 - MW2012	-0.24	**0.09**
	SOM - MW2012	0.02	**0.04**
	FASTEM5 – MW2012	0.14	**0.09**
6.9	FASTEM5 - MW2012	0.18	**0.18**
10.7		0.07	**0.16**
18.7		-0.16	**0.14**
37.0		-0.33	**0.39**
89.0		0.01	**0.94**
85.5	Guillou1998 - MW2012	-0.56	**0.36**

using laboratory measurements

Permittivity Differences

SSS=35psu 0°C<SST<30°C

Measurements – MW2012 fit

Frequency [GHz]	Measurements	Re(ε) Bias	Re(ε) Std.Dev	Re(ε) Rel. Prec.	Im(ε) Bias	Im(ε) Std.Dev.	Im(ε) Rel. Prec.
1.41	GWU2020 – MW 1)	0.51	**0.30**	**0.4%**	0.28	**0.28**	**0.4%**
85.5	Guillou1998 – MW 2)	1.78	**0.11**	**1.3%**	0.30	**0.14**	**1.1%**

1) Has NOT been used in fit of MW model
2) Has been used in fit of MW model

Summary and Conclusions

1. GWU 2020

- 1.4 GHz laboratory measurements.
- Single-Debye fit.
- Shortcomings of earlier versions (unrealistic salinity dependence) have been corrected.
- Can be considered for remote sensing applications
  - Salinity retrievals with L-band sensors (SMOS, Aquarius, SMAP).
  - Will likely require small adjustments in GMF, e.g. the SST dependence of the wind emissivity.
- Comparison with MW: within +/-0.1 K over dynamical ocean range.
- The GWU fit can only be used at L-band.
- General Remark:
  It took 10+ years to complete all measurements and fits.
  - That reflects the challenge to measure the dielectric constant of sea-water in the laboratory.
  - Beware regarding published laboratory data as *truth*.
  - Screening with ocean remote sensing data is important and necessary.

2. Somaraju - Trumpf

- Good physical model for $\varepsilon_S(T_S,SSS)$.
- Valid at low frequencies (L-band).
- Unlikely usable at higher frequencies without further adjustments.
  - SST biases.
- Same applies to Boutin – Vergely.
- General small ambiguity in L-band spaceborne salinity retrievals (SMOS, Aquarius, SMAP):
  - Temperature dependence in dielectric constant model.
  - Small temperature dependence in wind emissivity.
  - Hard to distinguish.

3. FASTEM5

- General good agreement with Meissner-Wentz over very wide frequency range (L – W bands).
  - Both dielectric models are based on similar input.
- Expected to have similar performance when used in
  - Satellite retrievals.
  - Assimilation.
- Holds at S = 35 psu (global ocean average).
- Little exception: Unrealistic looking salinity dispersion seems rather large.
  - Already visible at L-band compared to GWU, MW, SOM.
  - Might be a problem for L-band salinity retrievals in fresh-water areas (sea-ice melt off, river plumes)
  - Dispersion increases at higher frequencies.

Code for Meissner Wentz Dielectric Model

- Code (FORTRAN 90 + tables) publicly available.
  - Dielectric model.
  - Wind roughness model 6 – 90 GHz.
  - Wind roughness at L-band (1.41 GHz) separate.
- RSS website: www.remss.com.
- U Michigan Remote Sensing Code Library: https://rscl-grss.org/.
- Please don't type it from some printed version. Typos possible.

Publications (1)

- Meissner Wentz 2004 (MW 2004):
  - Meissner, T., and F. Wentz, The complex dielectric constant of pure and sea water from microwave satellite observations, IEEE TGRS, vol. 42(9), pp 1836, 2004.
- Meissner Wentz 2012 (MW 2012)
  - Meissner, T., and F. Wentz, The emissivity of the ocean surface between 6 - 90 GHz over a large range of wind speeds and Earth incidence angles, IEEE TGRS, vol. 50(8), pp 3004, 2012.
    Contains small update to RSS dielectric model.
  - Meissner, T., F. Wentz, L. Ricciardulli, 2014, The emission and scattering of L-band microwave radiation from rough ocean surfaces and wind speed measurements from Aquarius, Journal of Geophysical Research: Oceans, 119, doi:10.1002/2014JC009837.
    Fixes typo.

Publications (2)

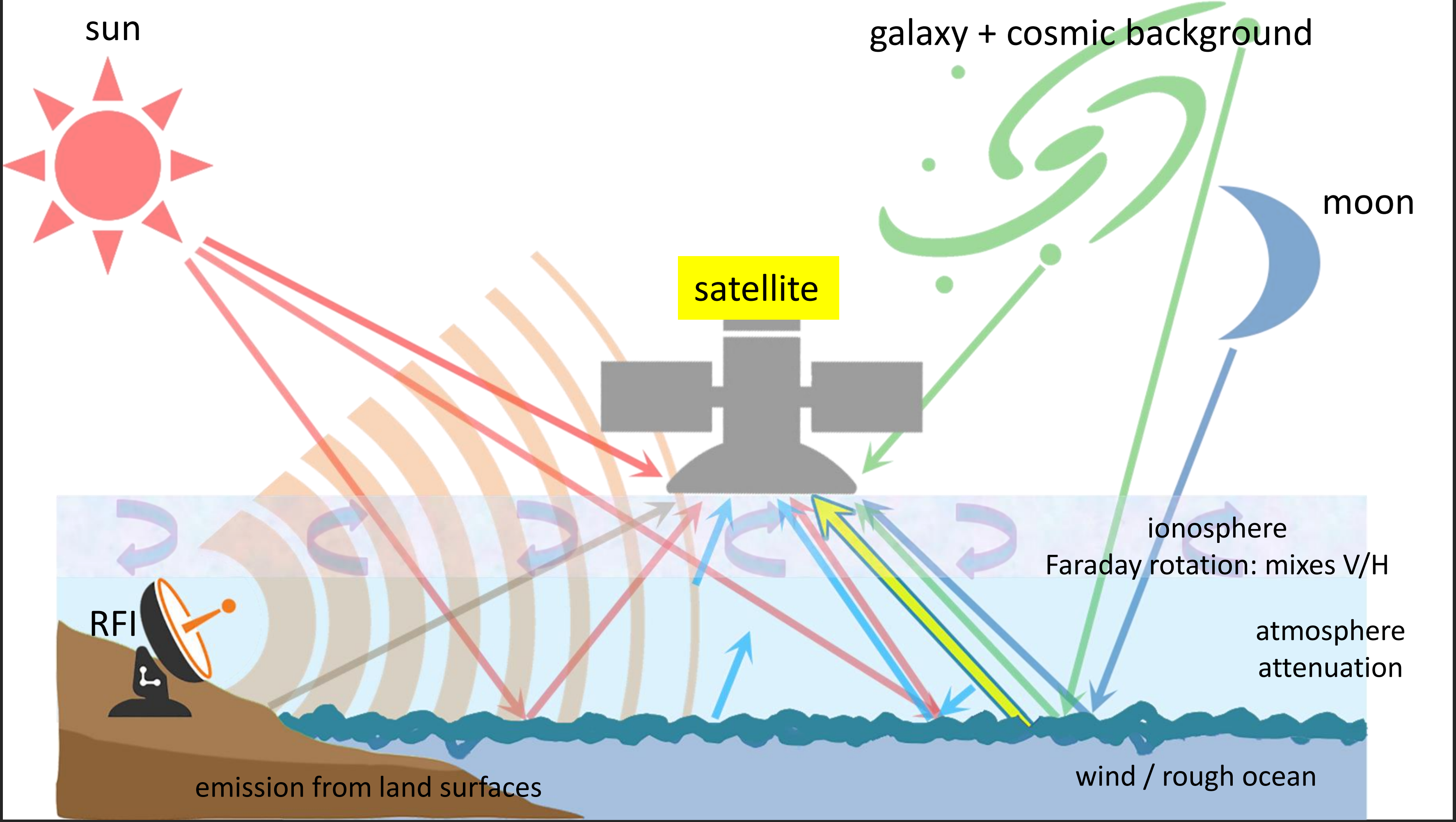
- Klein + Swift (KS)
  - L. A. Klein and C. T. Swift, An improved model for the dielectric constant of sea water at microwave frequencies, IEEE J. Oceanic Eng., vol. OE-2, pp. 104–111, 1977.
- FASTEM 2011
  - Q. Liu, F. Weng + S. English: An Improved Fast Microwave Emissivity Model, IEEE TGRS vol. 49(4), pp 1238 – 1250, 2011.
- Somaraju + Trumpf (SOM)
  - R. Somaraju + J. Trumpf: Frequency, temperature and salinity variation of the permittivity of sea-water, IEEE Ant. Prop., vol.54(11), pp. 3441-3448, 2006.
- Boutin + Vergely (BV)
  - J. Boutin, J.L. Vergely et al., IEEE TGRS, 2020, in print.
- GWU 2020 Laboratory Measurements at L-band
  - Zhou et al., IEEE TGRS, 2020 in print.

Additional Slides / Backup

L-Band

Challenge: Many additional spurious signals (galaxy, ionosphere, sun …)

Salinity: Need to be removed to very high level of accuracy (**0.1 K!**)



Credit: A. de Charon, U of Maine

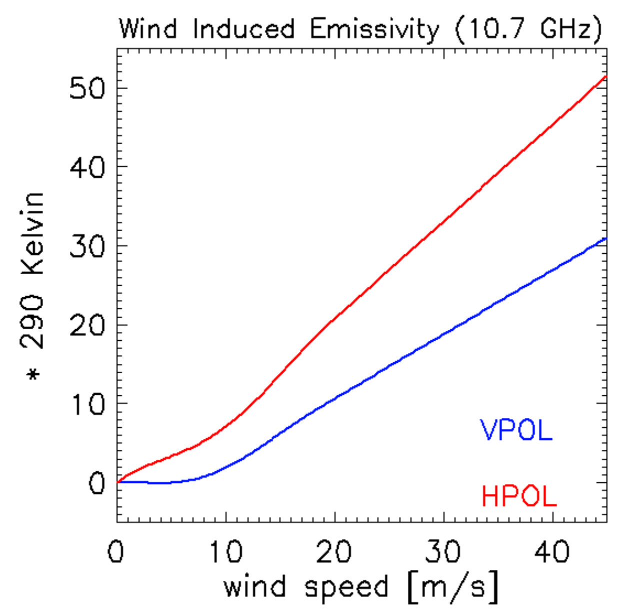
Development of Wind Emissivity Model

Passive (radiometer)

- Sees change in emissivity of wind roughened sea surface compared with specular surface
    - Low winds: Polarization mixing of large gravity waves.
    - High winds: Emissivity of sea foam.
- Radiative Transfer Model (RTM) function for wind induced surface emissivity.

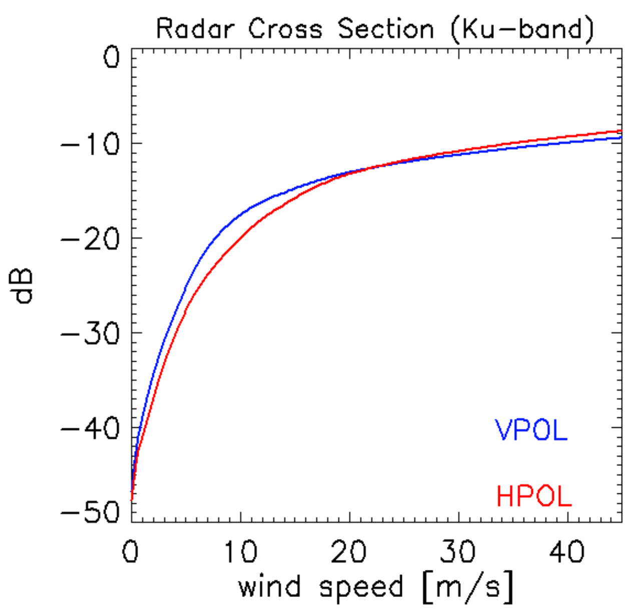
Active (scatterometer)

- Sees backscatter from the Bragg-resonance of small capillary waves.
- Geophysical Model Function (GMF) for wind induced radar backscatter.
- C-band + Ku-band



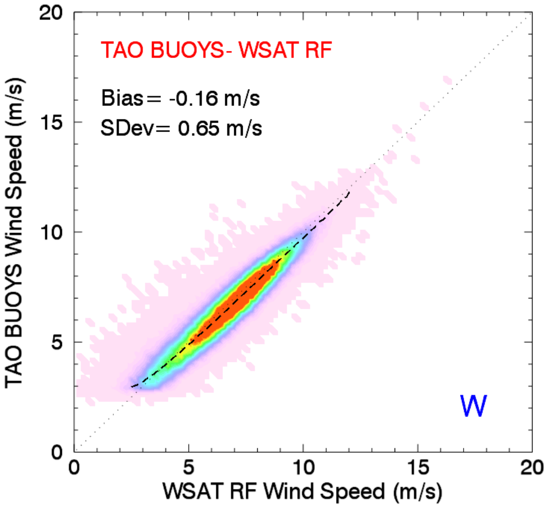
Calibration

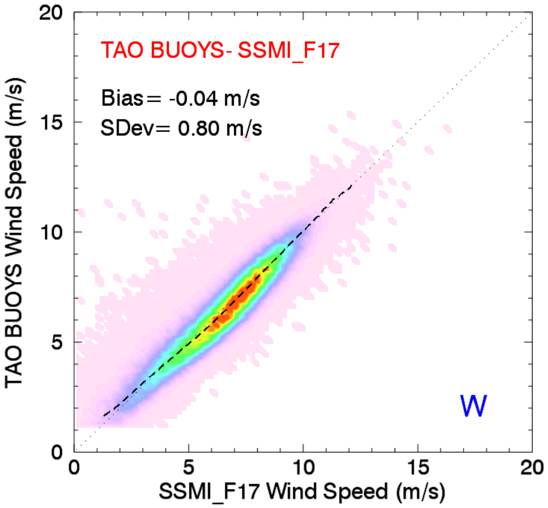
Ground truth:
Buoys
NWP wind speeds

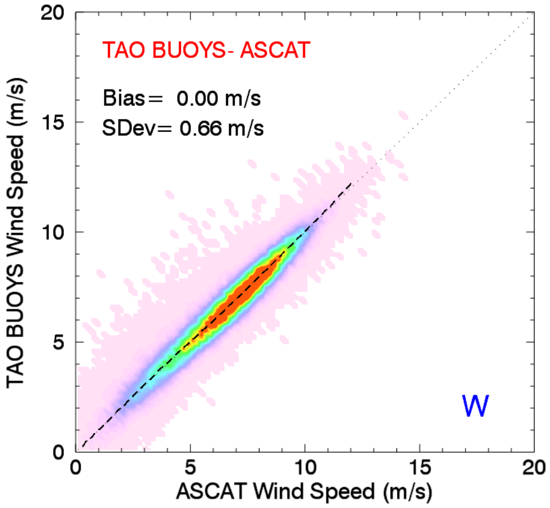


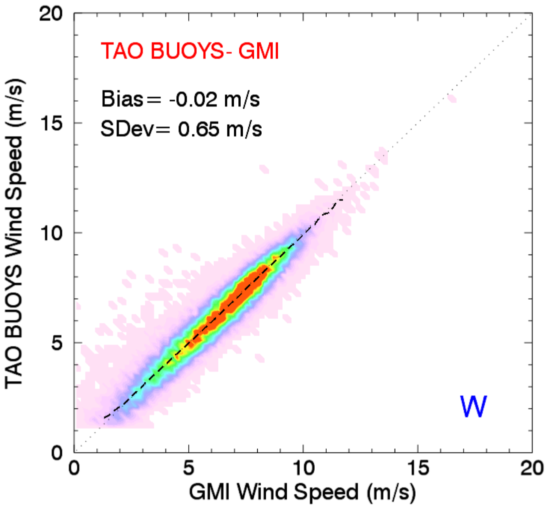
Extensive Validation versus Ground Truth

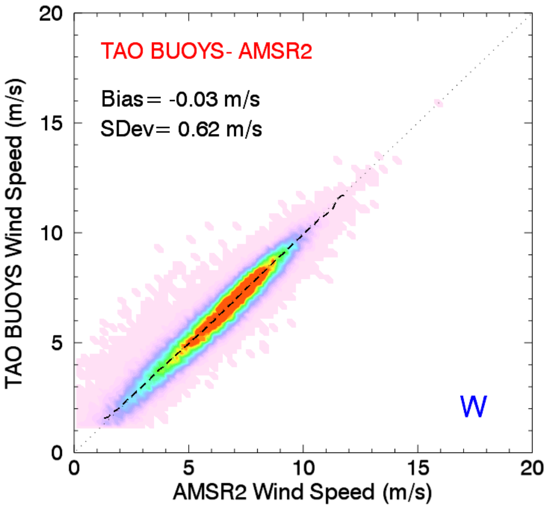
Wind Speed







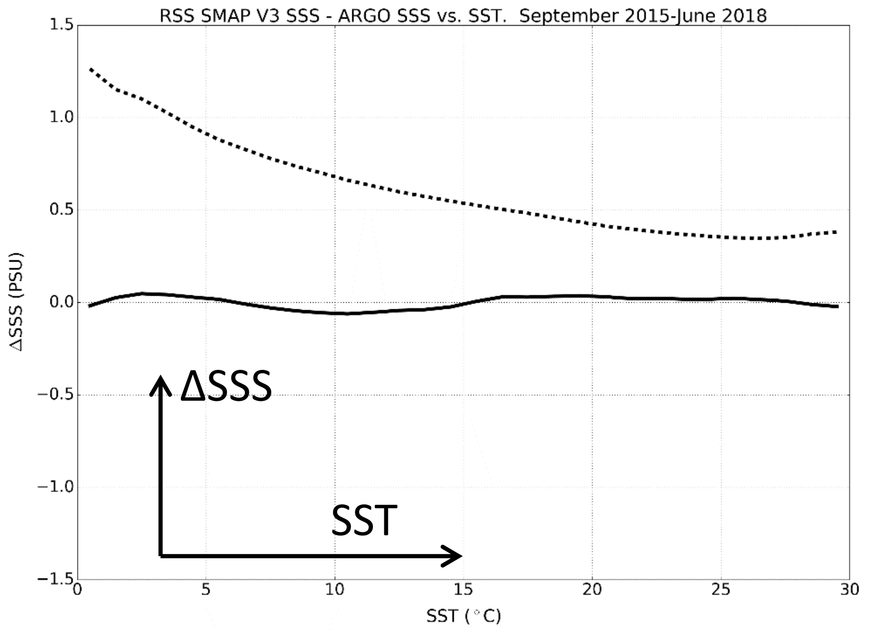


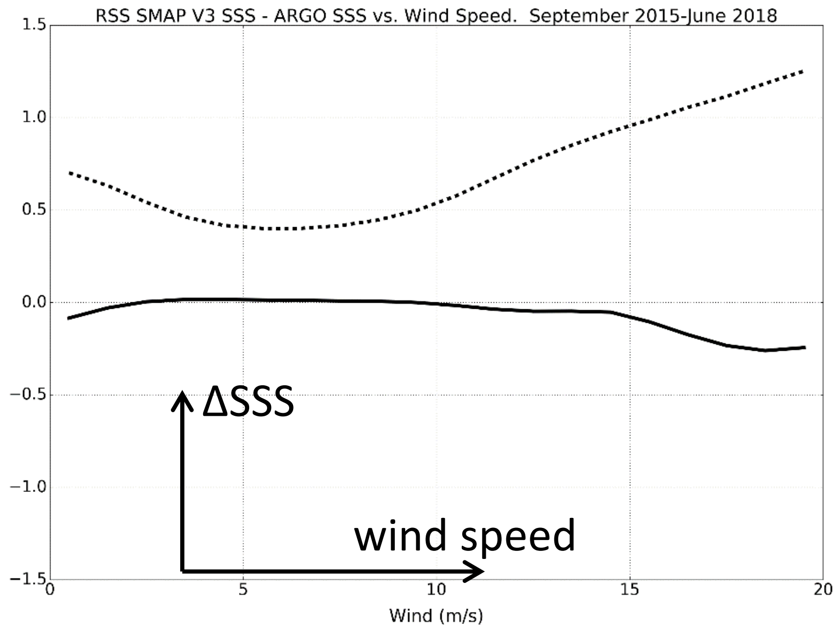


Validation (cont.)

Salinity

SSS SMAP – ARGO floats


RSS SMAP V3 SSS - ARGO SSS vs. SST. September 2015-June 2018


RSS SMAP V3 SSS - ARGO SSS vs. Wind Speed. September 2015-June 2018

Disentangle Atmosphere from Surface

- Rain-free. Low cloud water.
- Strong global correlation between SST and columnar water vapor.
- Difficult to distinguish surface component (dielectric, wind) form atmospheric component.
- Combination: **2 ·TB (V-pol) – TB (H-pol)**
    - Reduces atmospheric errors

$$T_B \approx \left(1 - R\cdot\tau^2\right)\cdot T_{eff} \qquad \Delta T_B \approx 2\cdot R\cdot\tau\cdot T_{eff}\cdot\Delta\tau$$

$$\alpha\cdot\Delta T_{B,V} - \Delta T_{B,H} \approx 2\cdot\tau\cdot T_{eff}\cdot\Delta\tau\cdot\left(\alpha\cdot R_V - R_H\right) = 0 \qquad \Rightarrow$$

$$\alpha = {}^{R_H}\!\big/_{R_V} \approx 2 \quad \text{for our sensors.}$$

- Compare 18/19 GHz with 22/23 GHz.
- Analyze TB is narrow vapor bins.

Sensor Calibration

Tied to RTM Validation

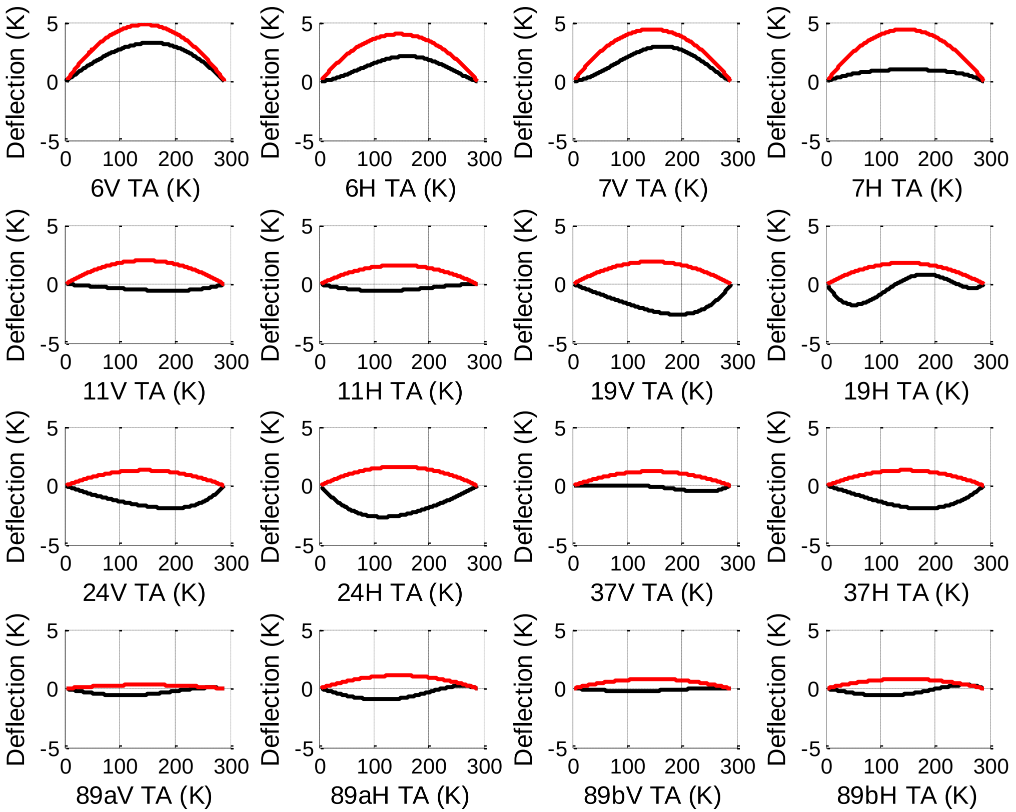
- Problem: Calibration Anomalies.
  - Each sensor has its own.
  - Need to be properly removed.
- Most important examples (list is not complete):
  - Solar intrusion into hot load.
    - AMSR-E, AMSR-J, TMI, WindSat, SSMI(s)
  - Emissive antenna.
    - TMI, SSMIS F16, F17, SMAP
  - Receiver non-linearities.
    - AMSR-E, AMSR2
- Antenna spillover (cold sky fraction)
  - Antenna backlobes are difficult to measure
- **Some sensor are better/worse than others for RTM validation.**

Calibration Anomalies

Non-Linear Receivers: AMSR2

Red Curves are JAXA values for spillover and non-linear correction.
Black Curves are values coming from RSS analysis.

- AMSR2 has some very large non-linearities.
- Poor pre-launch characterization.
- Impact on quality of ocean retrievals.



Non-Linear Correction

$$\sum_{i=1}^{5} a_i x^i$$

$$T'_A = T_A + \sum_{i=1}^{5} a_i x^i \qquad x = \frac{T_A - T_C}{T_H - T_C} \qquad \sum_{i=1}^{5} a_i \equiv 0$$