The RSS Microwave Ocean Surface Emissivity Model

Meissner – Wentz Model

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Outline

I. Overview of RSS Emissivity Model
- Publications
- Code
- Dielectric Model
- Wind Emissivity Model 6 – 90 GHz
- L-band (1.4 GHz)
- High Winds

II. Important Topics (Discussion)
- Derivation + Validation of RTM
- Uncertainty Assessment
- Atmosphere
- Sensor Calibration

Publications (1)

- Theoretical Background
  - Wentz, F. and T. Meissner, AMSR-E ATBD, 2000, www.remss.com.
- Dielectric Constant (Permittivity) of Sea Water:
  - 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.
- Wind Emissivity (6 – 90 GHz)
  - 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.

Publications (2)

- Wind Emissivity (L-band, 1.41 GHz)
  - Meissner, T., F. Wentz, and L. Ricciardulli, The emission and scattering of L-band microwave radiation from rough ocean surfaces and wind speed measurements from Aquarius, J. Geophys. Res. Oceans, vol. 119, doi:10.1002/2014JC009837, 2014. (Aquarius)
  - Meissner, T, F. Wentz, and D.Le Vine, The Salinity Retrieval Algorithms for the NASA Aquarius Version 5 and SMAP Version 3 Releases, Remote Sensing, 10, 1121, doi:10.3390/rs10071121, 2018. (Aquarius, SMAP).
- Atmosphere
  - Wentz, F. and T. Meissner, Atmospheric Absorption Model for Dry Air and Water Vapor at Microwave Frequencies below 100 GHz Derived from Spaceborne Radiometer Observations, Radio Science, 51, doi:10.1002/2015RS005858, 2016.
  - Largely based on Phil Rosenkranz 1998 + Hans Liebe et al. 1992.
  - Adjustment of water vapor continuum (see AMSR ATBD) and non-resonant O_2 continuum.
  - New Rosenkranz model (2016).

Code

- Code (FORTRAN 90 + tables) publicly available.
  - Dielectric model.
  - Wind roughness model 6 – 90 GHz.
  - Wind roughness at L-band (1.41 GHz) separate.
  - We ask not to re-distribute it outside your institution and cite appropriate references if used in publication.
- RSS website: www.remss.com.
- U Michigan Remote Sensing Code Library: https://rscl-grss.org/.
- UCAR is putting it as an option in their CRTM code.

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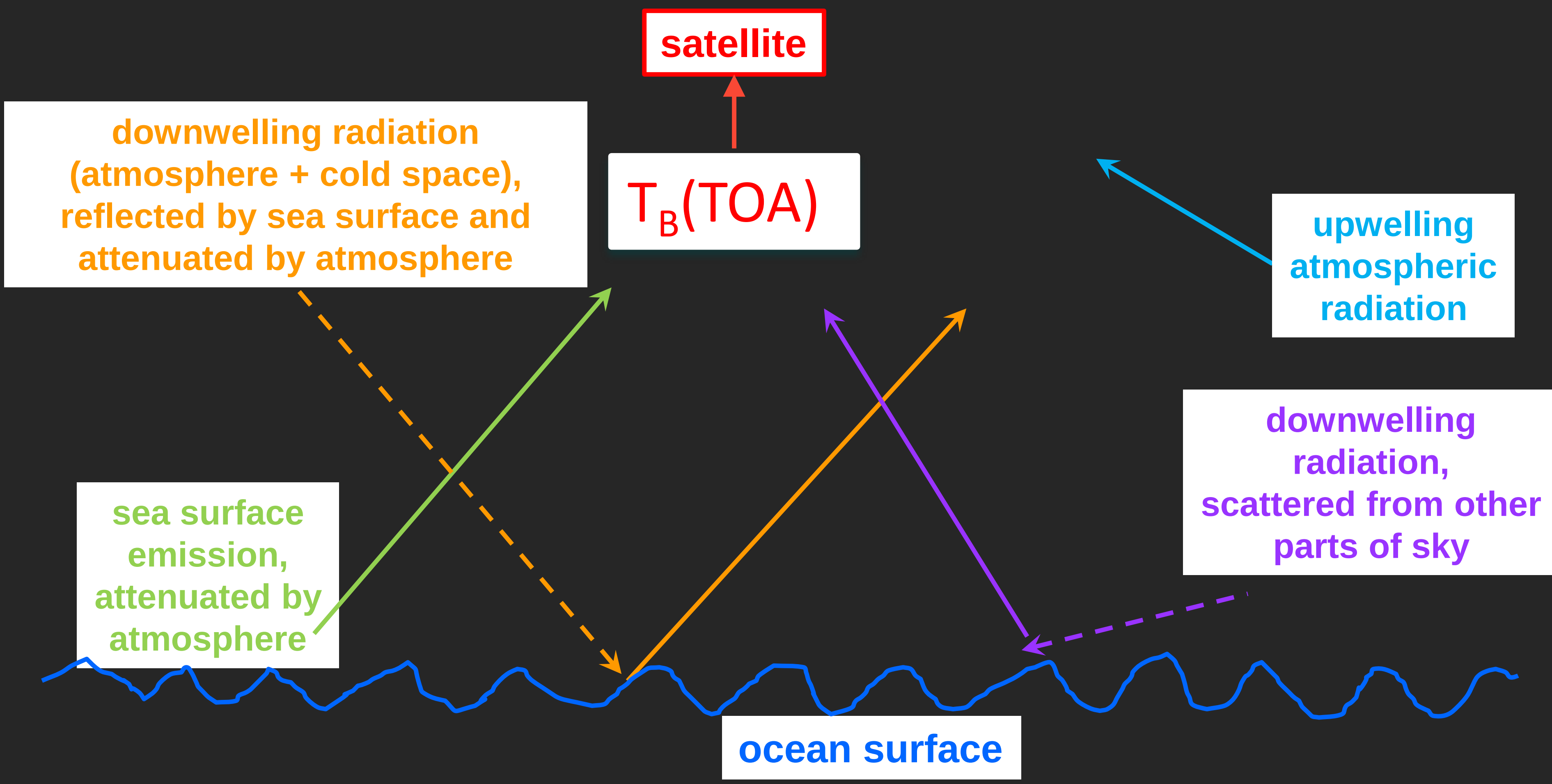
Radiative Transfer Model (RTM)

Top of the Atmosphere (TOA) for Ocean Scenes
Non-Scattering Atmosphere



Radiative Transfer Model (RTM)

Top of the Atmosphere (TOA) for Ocean Scenes

Non-Scattering Atmosphere

$T_B(TOA) =$

upwelling atmosphere	T_{BU} +
surface emission	$\tau \cdot E \cdot T_s$ +
downwelling atmosphere reflected at surface	$\tau \cdot (1\text{-}E) \cdot (T_{BD} + \tau \cdot T_{CS})$ +
downwelling atmosphere scattered at surface	$\tau \cdot T_{B,scat}$

E → surface emissivity

T_s → SST

T_{CS} → cold space

τ → atmospheric transmittance

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)

Conductivity (measured)

$i = \sqrt{-1}$

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

1st Relaxation Frequency (empirical)

2nd Relaxation Frequency (empirical)

Vacuum Permittivity

DC at Infinite Frequency (empirical)

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

Models for Dielectric Constant

- **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 89 GHz.
  - Double Debye relaxation.

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.
- The MW model is used in all RSS passive microwave ocean retrievals (L – Ka band).

Wind Emissivity Model (Excess Emissivity)

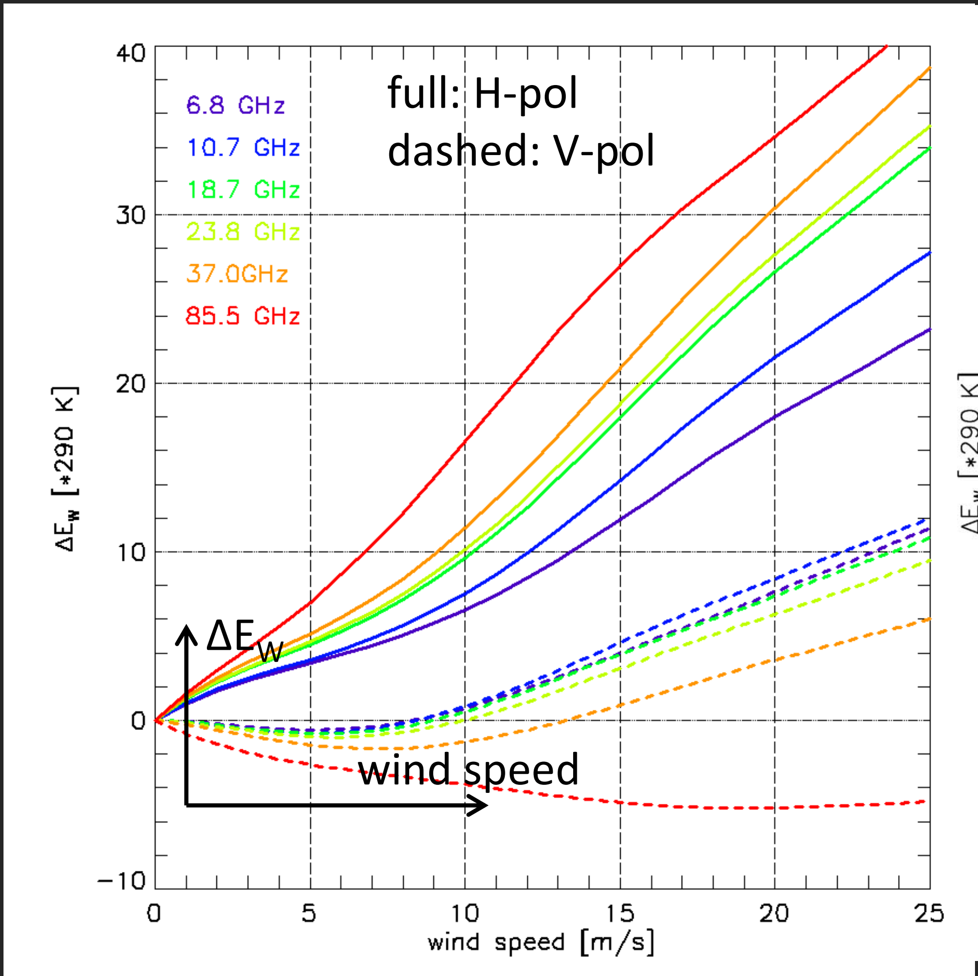
isotropic wind-direction signal

$$\Delta E\left(f,\theta_i;W,\varphi_r,T_S\right) = \Delta E_W + \Delta E_\varphi$$

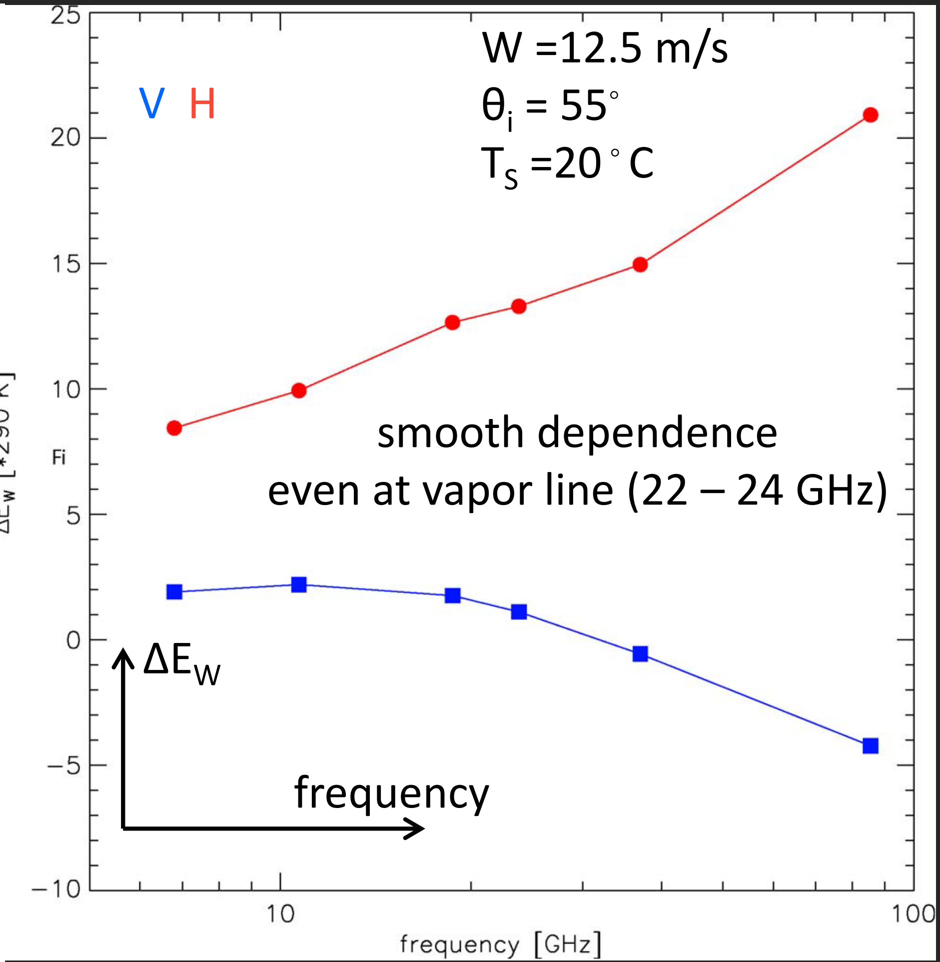
- Empirically model based on physical principles.
  - Comprises geometric optics, Bragg scattering ,foam emission
  - Derived from WindSat + SSMI
  - Tested on GMI, AMSR's, ….
  - L-band: Aquarius, SMAP.
- Can be tied into physical models (2-scale, foam) by fitting the model parameters.
  - Paul Hwang (NRL), Al Gasiewski (UC)
- Depends on frequency f, EIA θ_i, wind speed W, relative wind direction φ_r, sea-surface temperature T_S.
  - Validated for EIA range of instruments mentioned above.

Wind Emissivity Model ΔE_W

wind speed dependence



frequency dependence



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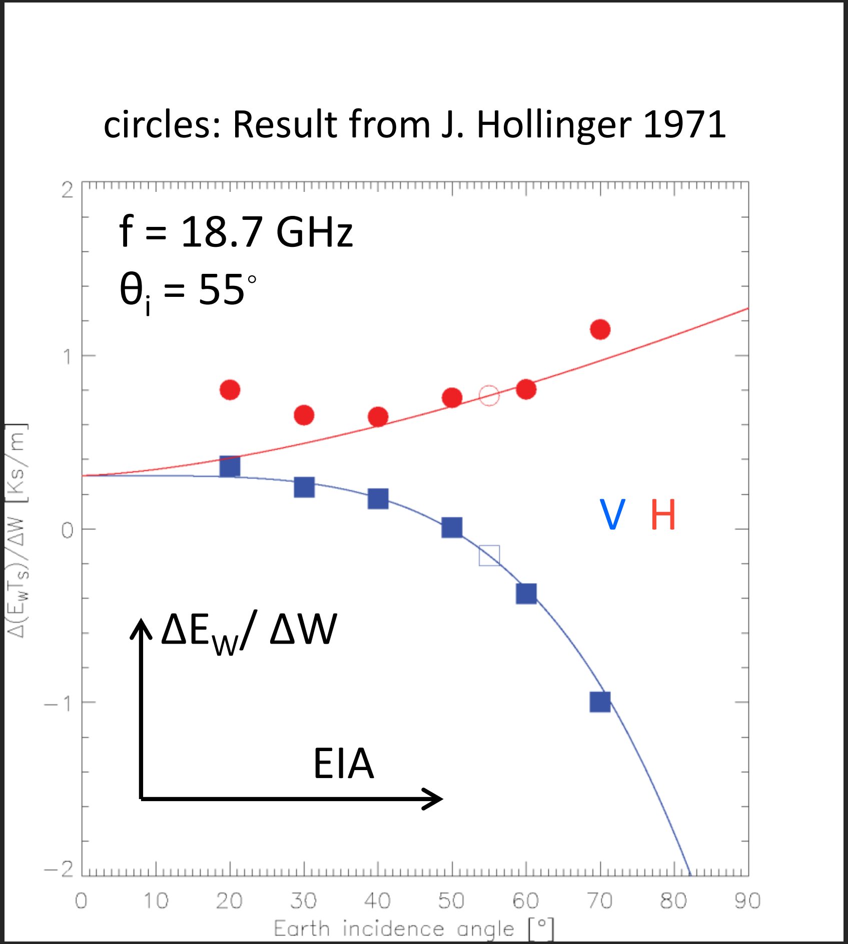
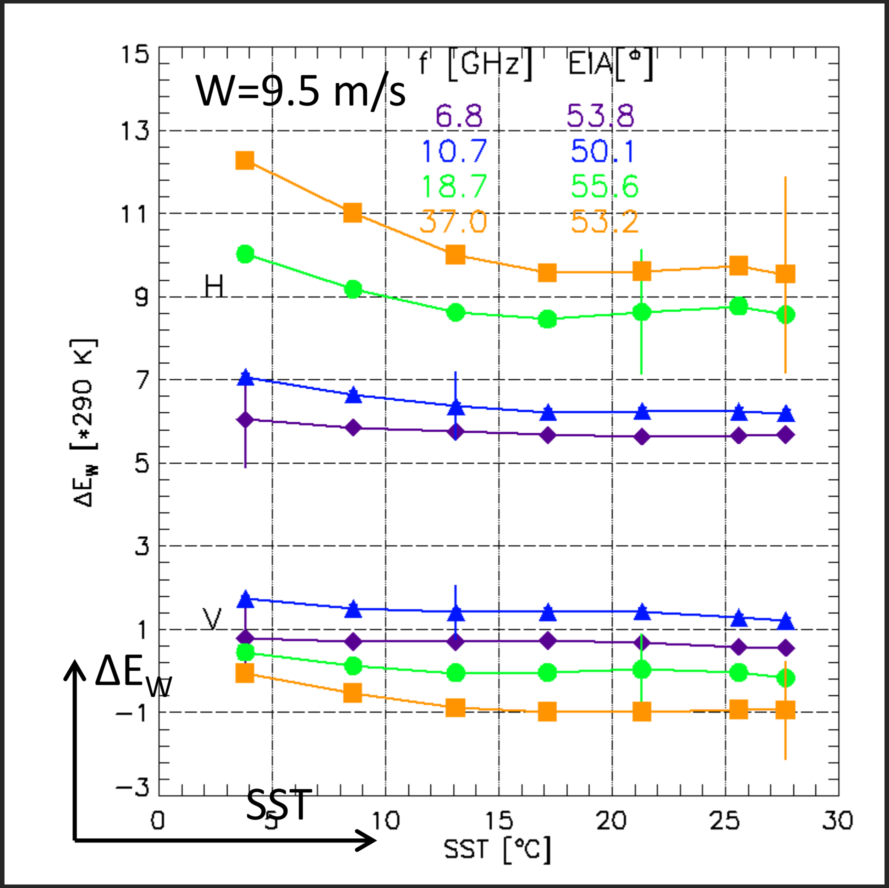
Wind Emissivity Model ΔE_W

EIA dependence



SST dependence



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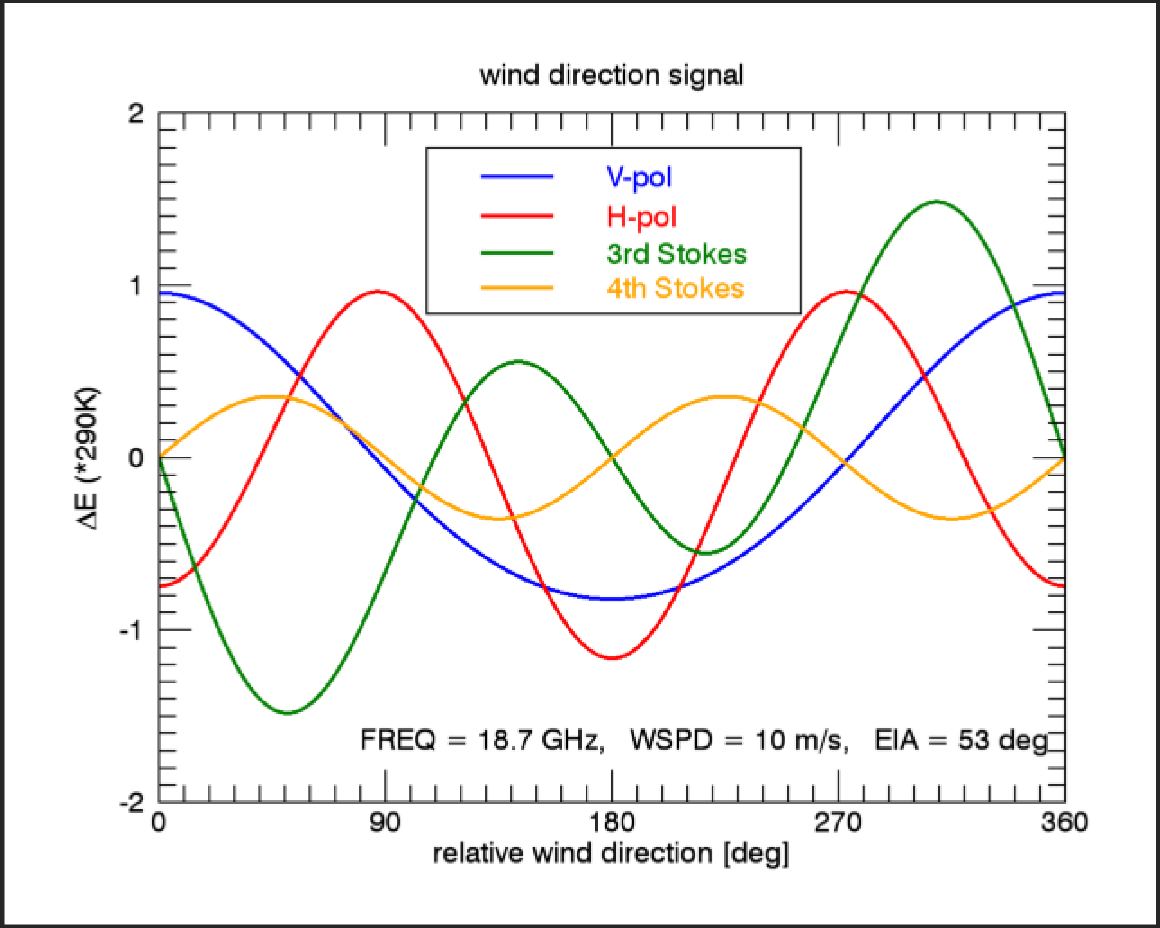
Wind Direction Model ΔE_φ

Four Stokes V-pol, H-pol, S3, S4
Based on WindSat and SSM/I.

$$\Delta E(W,\varphi) = A_0(W) + A_2(W)\cdot\cos(\varphi) + A_2(W)\cdot\cos(2\varphi), \quad V,H$$

$$\Delta E(W,\varphi) = B_1(W)\cdot\sin(\varphi) + B_2(W)\cdot\sin(2\varphi), \quad S_3,S_4$$



Atmospheric Path Length Correction $T_{B,scat}$

Ω-Term. Scattered downwelling radiation. (MW 2012, Section V).

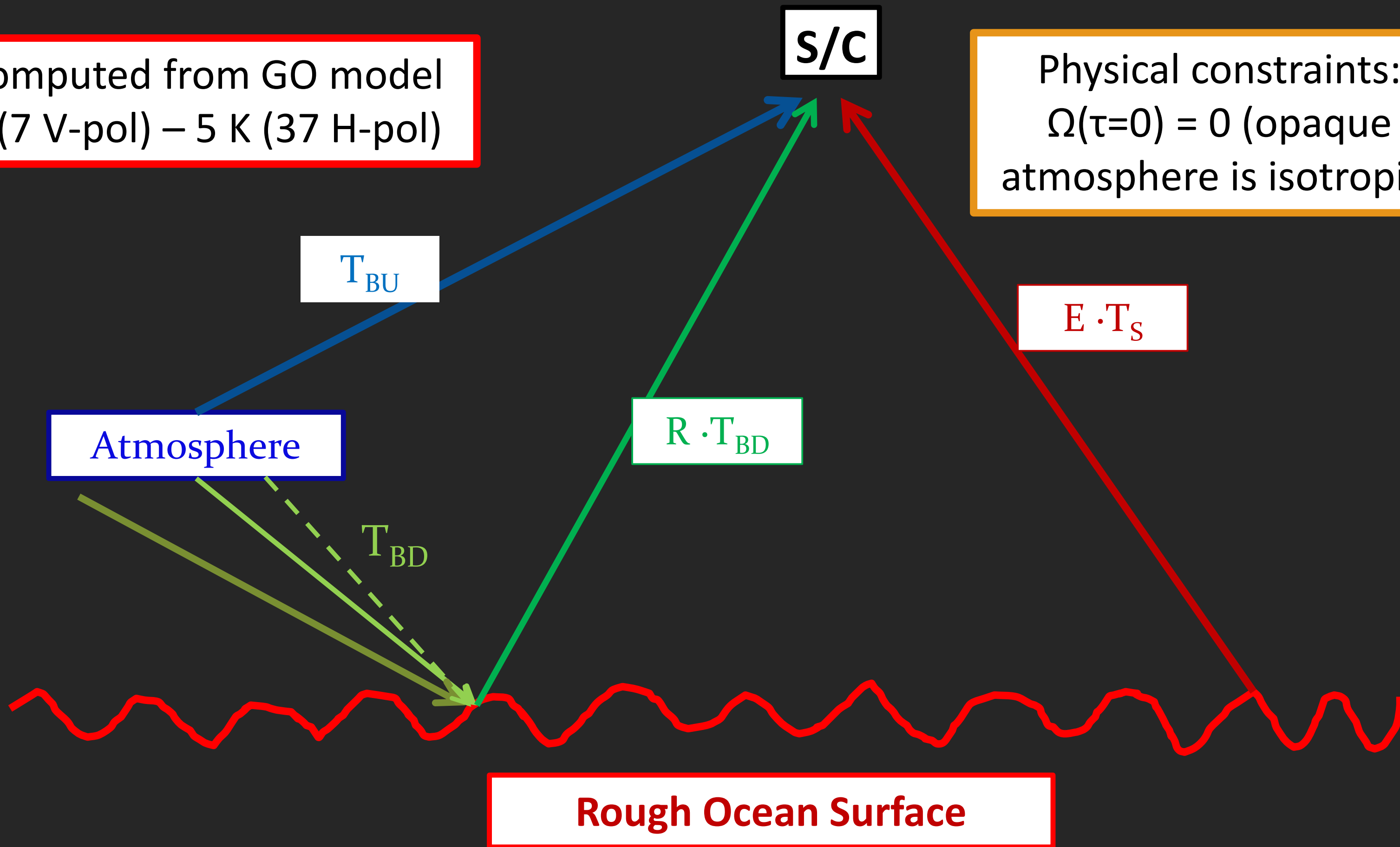
Depends on wind speed AND transmittance τ.

Some RTM include it effectively in the surface reflectivity.

$$T_{B,\,scat,\,p} = \Omega_p\left(\tau, W\right)\cdot\left[T_{BD} + \tau\cdot T_{cold} - T_{cold}\right]\cdot R$$

Pre-computed from GO model
0.2 K (7 V-pol) – 5 K (37 H-pol)

Physical constraints:
Ω(τ=0) = 0 (opaque atmosphere is isotropic)



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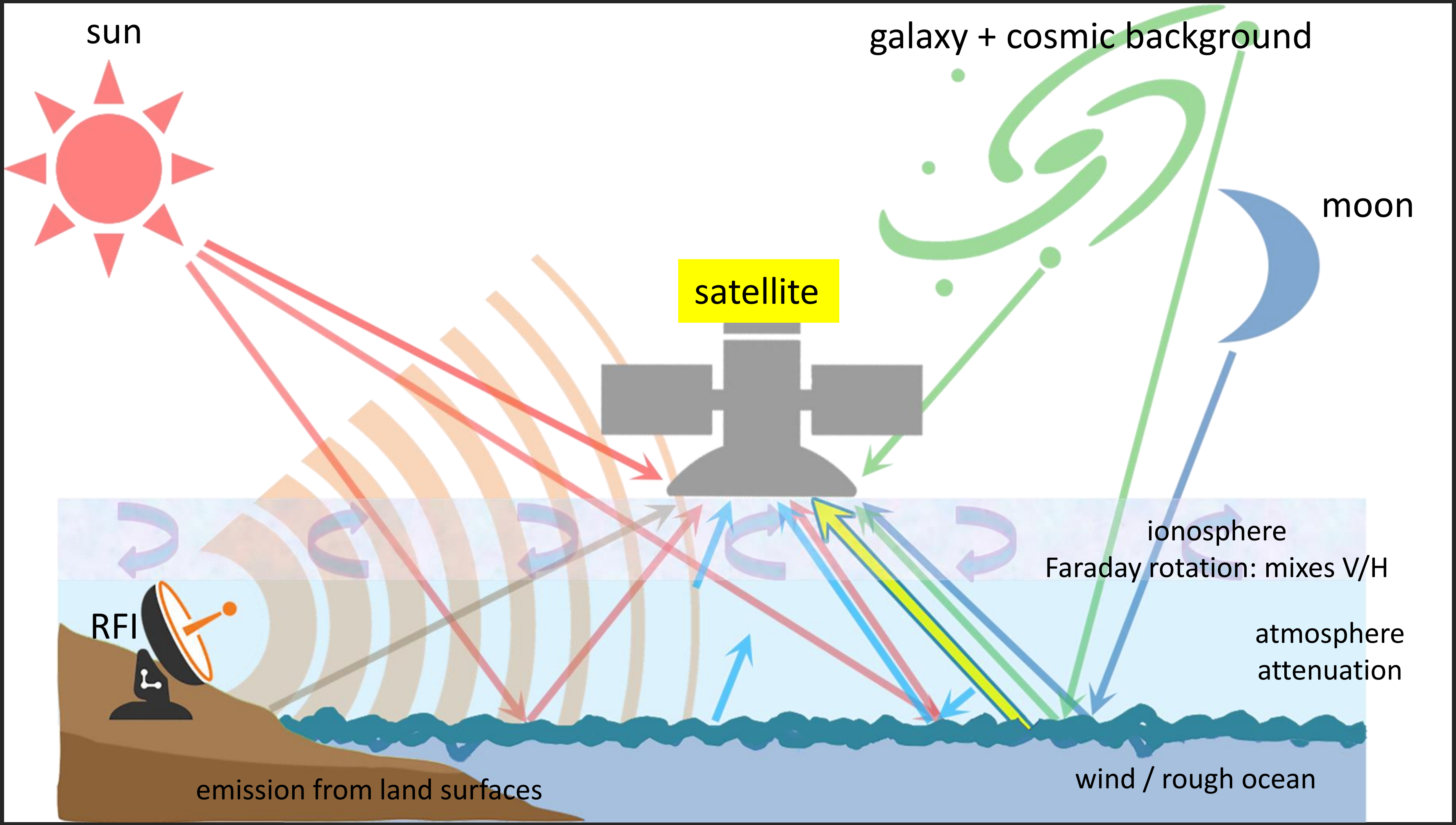
L-Band

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

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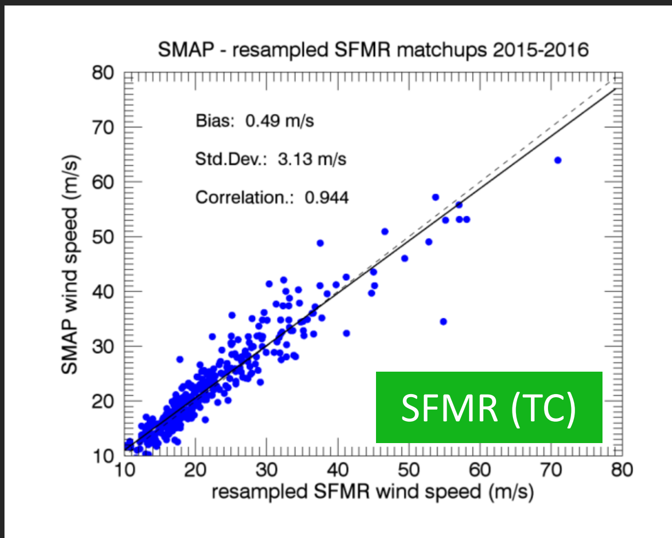
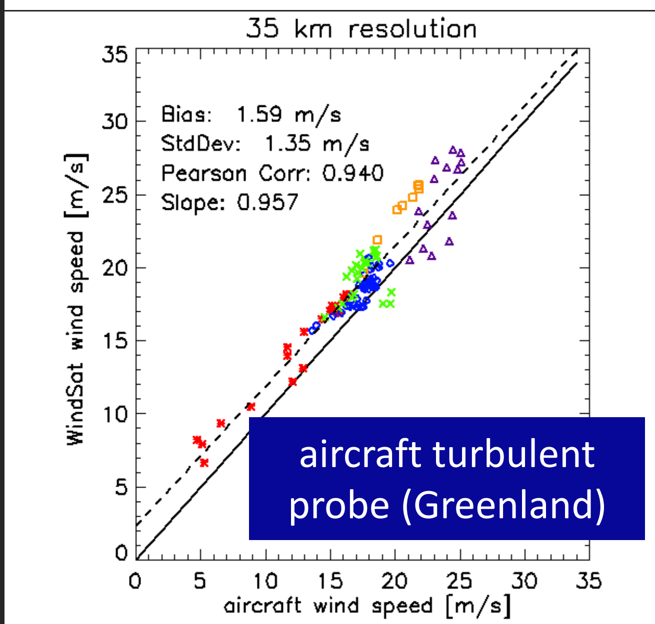
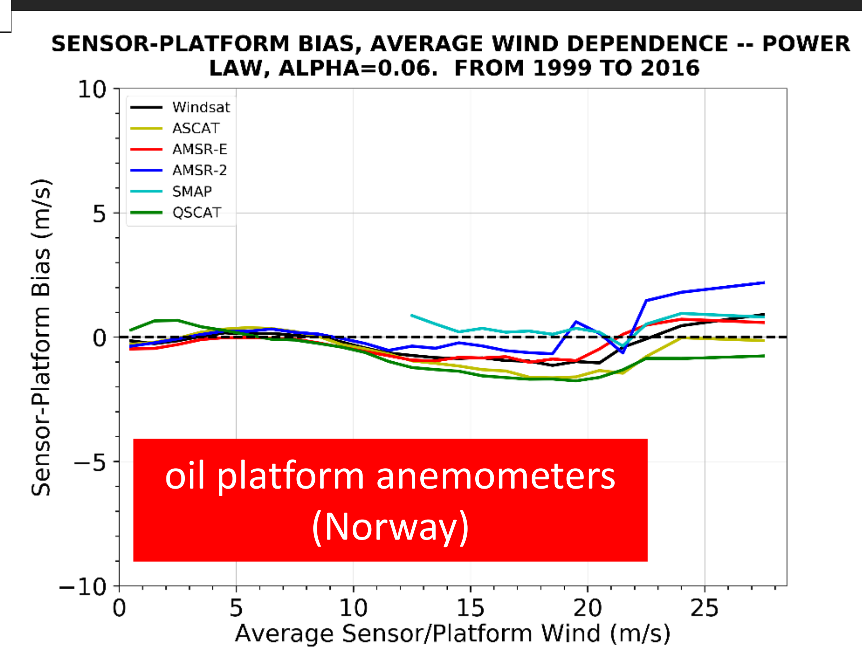
High Wind Speeds

Challenge: Sparse Ground Truth

- Passive MW emission signal sensitive to wind at high winds (foam).
- $\Delta E_W \sim W$ at all frequencies
- Several validation sources show good consistency.







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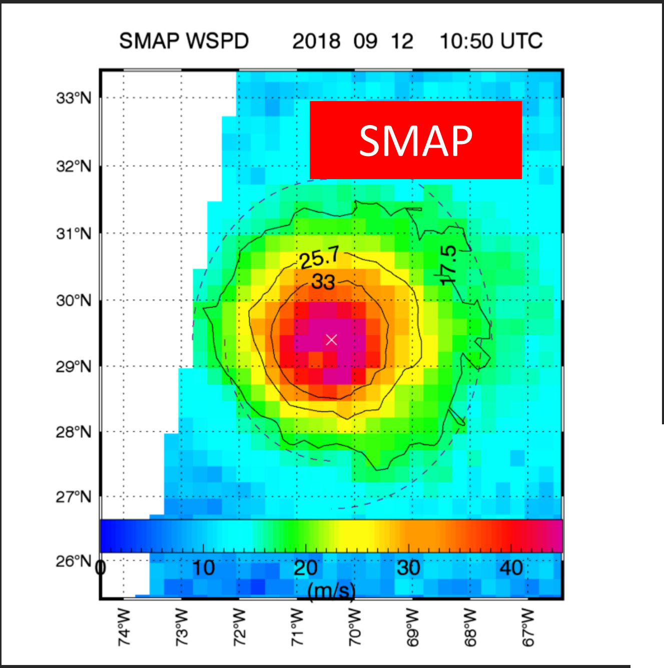
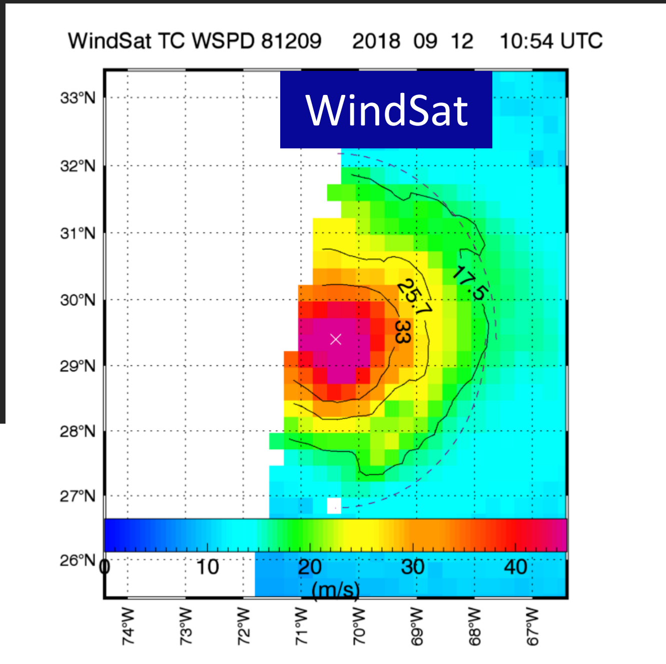
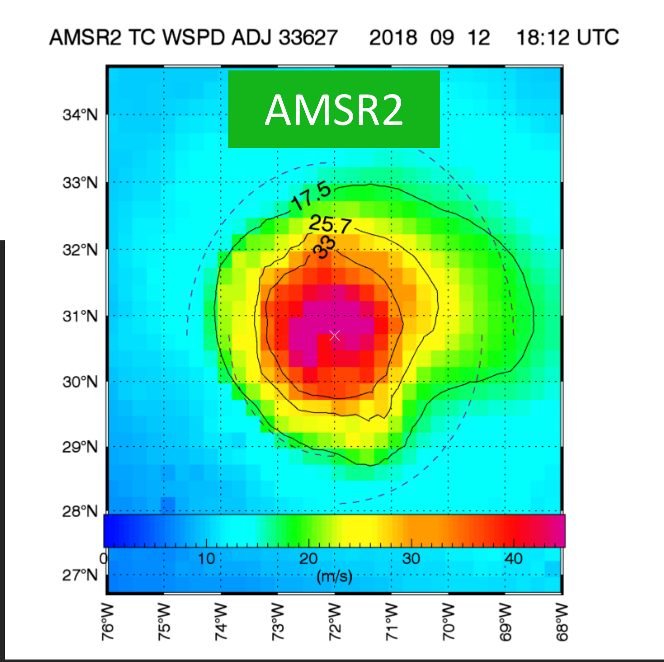
Tropical Cyclone Winds

L-band (SMAP, SMOS), C/X-band (AMSR, WindSat)



Hurricane FLORENCE
SEP 2018





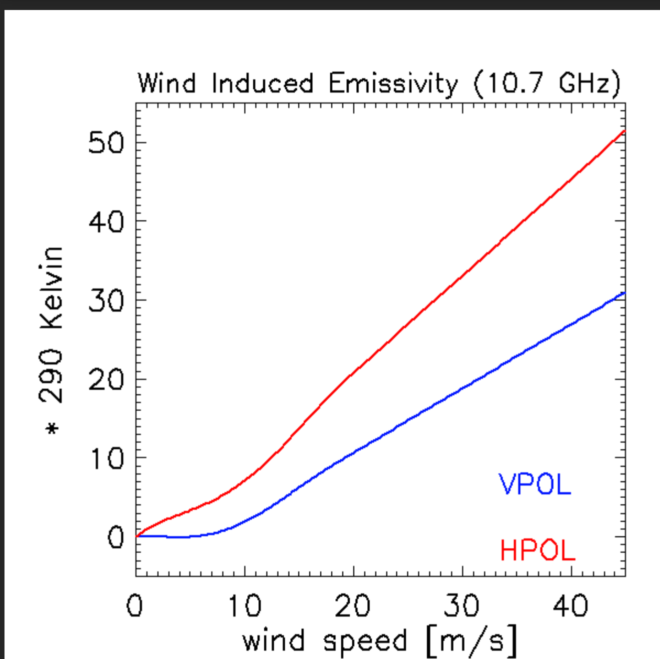
Development of Wind Emissivity Model

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.

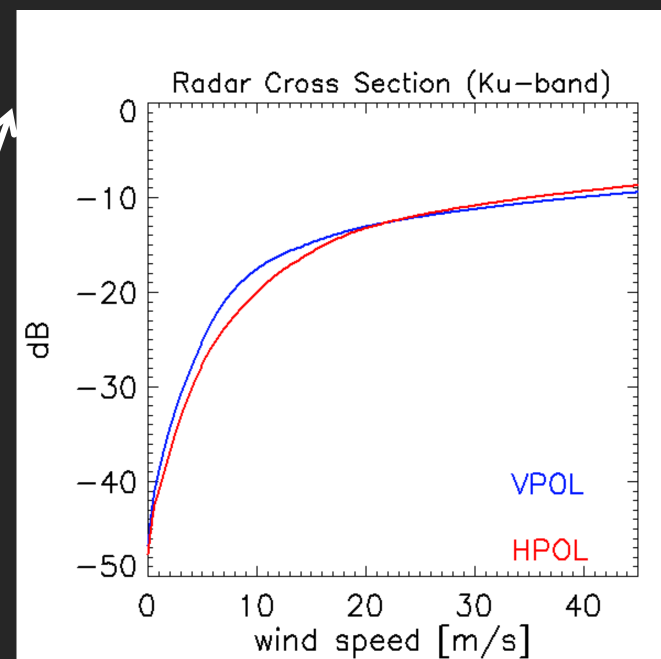
Active (scatterometer)

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



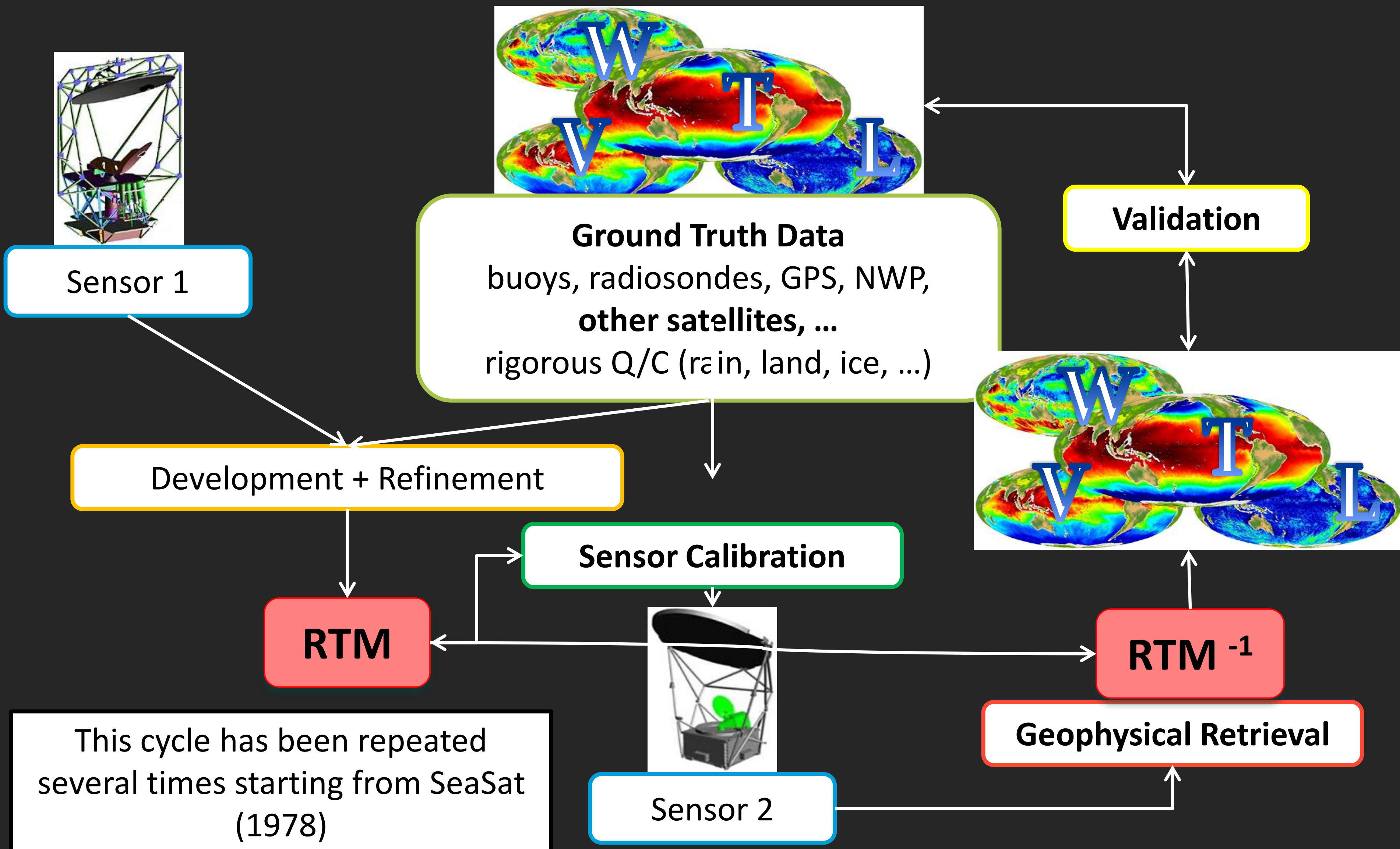
Calibration

Ground truth:
Buoys
NWP wind speeds



Four Cornerstones:

RTM, Sensor Calibration, Retrieval, Validation



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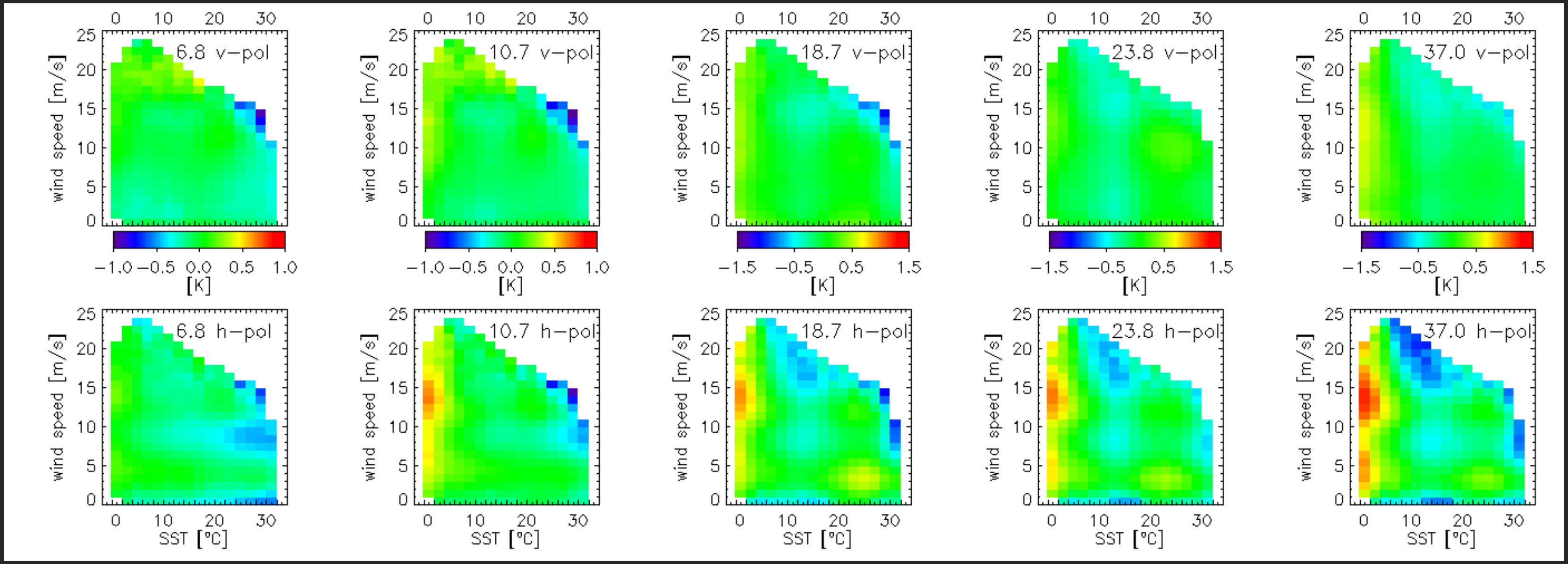
RTM Validation



- 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).
- Input needs to be validated = unbiased versus ground truth.
- Ideally: Independent from TB measurement.

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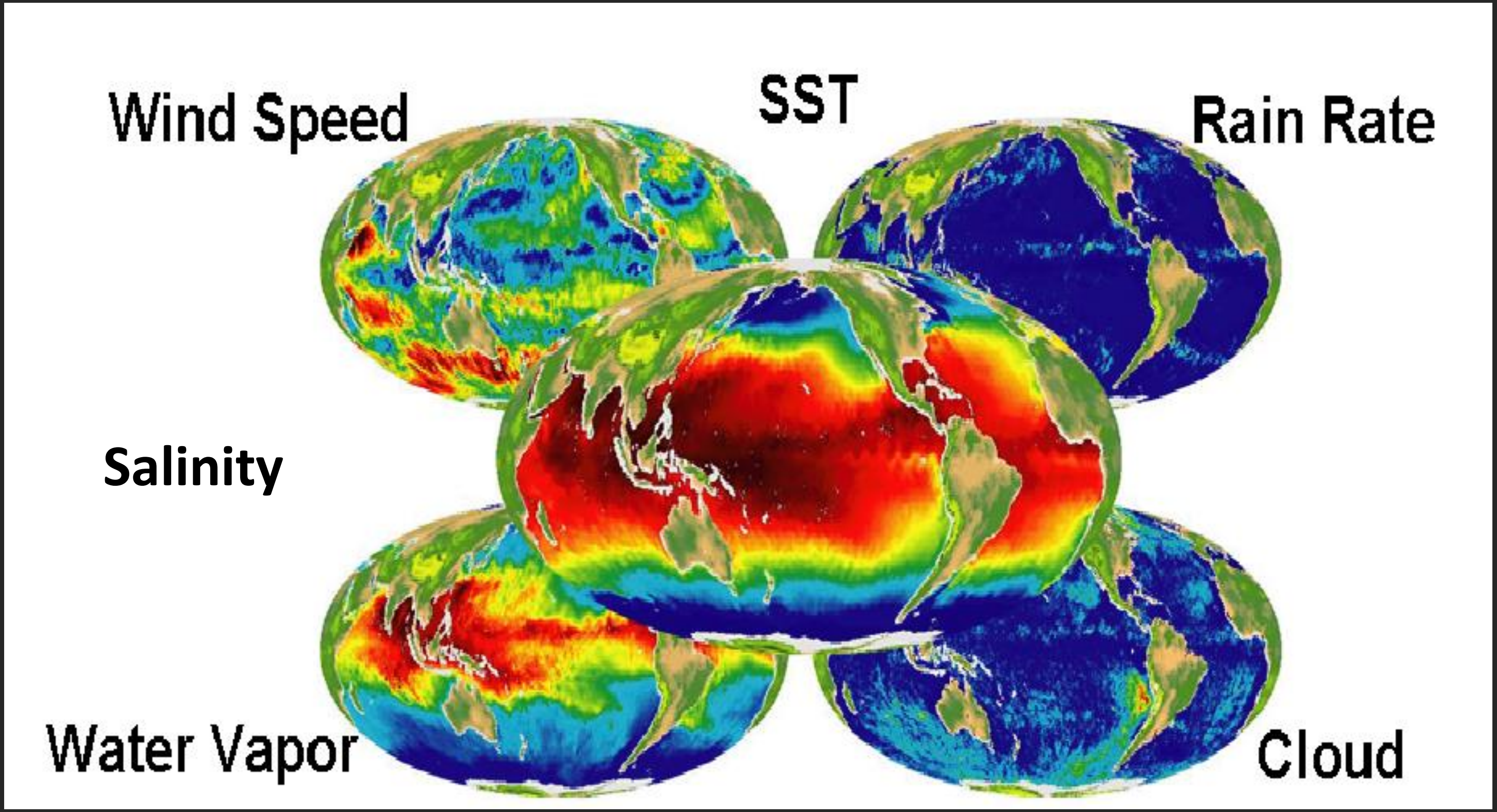
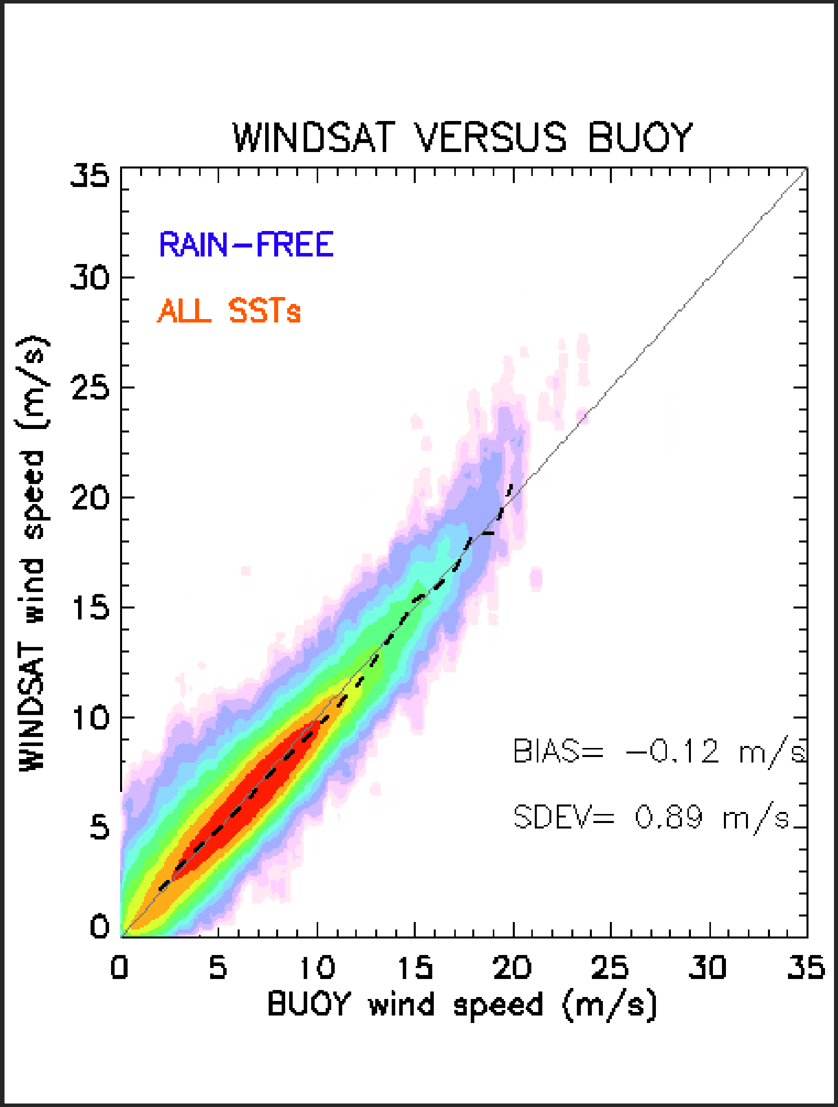
Ultimate Criterion for Using RTM

Quality of Retrieved Environmental Parameters



Extensive Validation versus Ground Truth

Wind Speed



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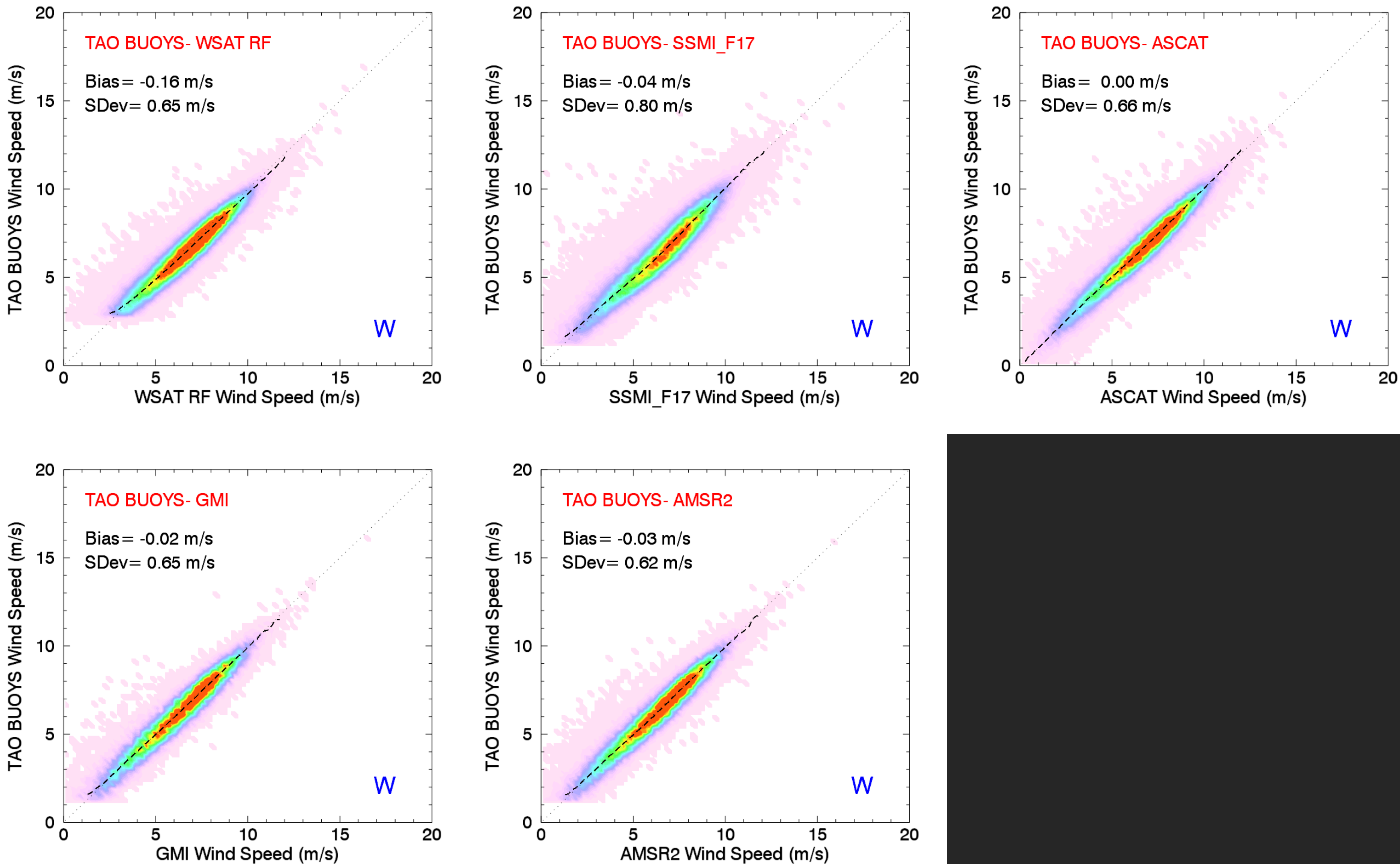
Extensive Validation versus Ground Truth

Wind Speed



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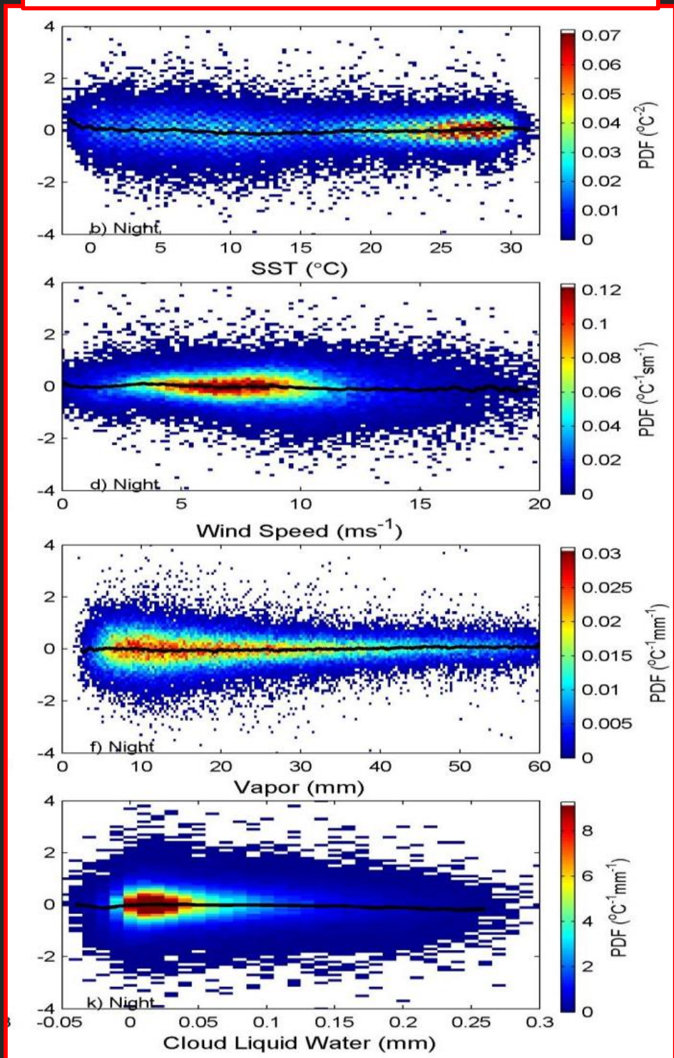
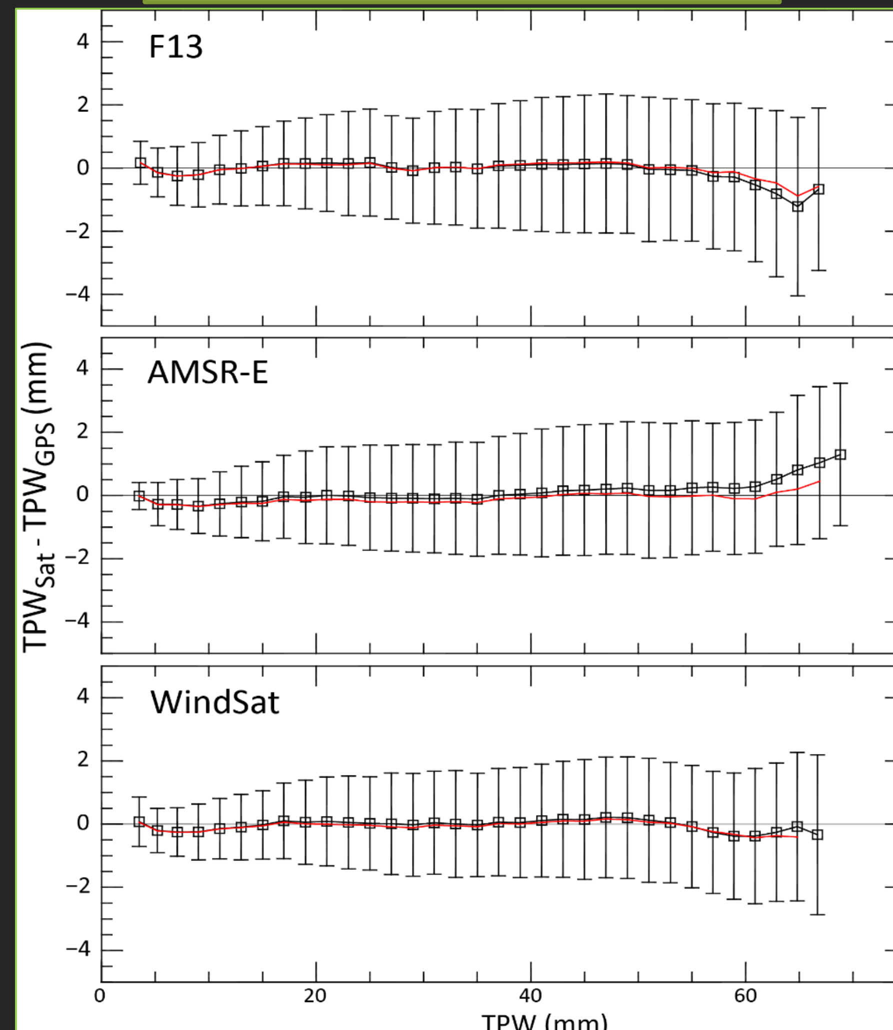
Validation (cont.)

SST, Vapor

AMSR2 SST vs Buoys
(Gentemann + Hilburn, 2015)



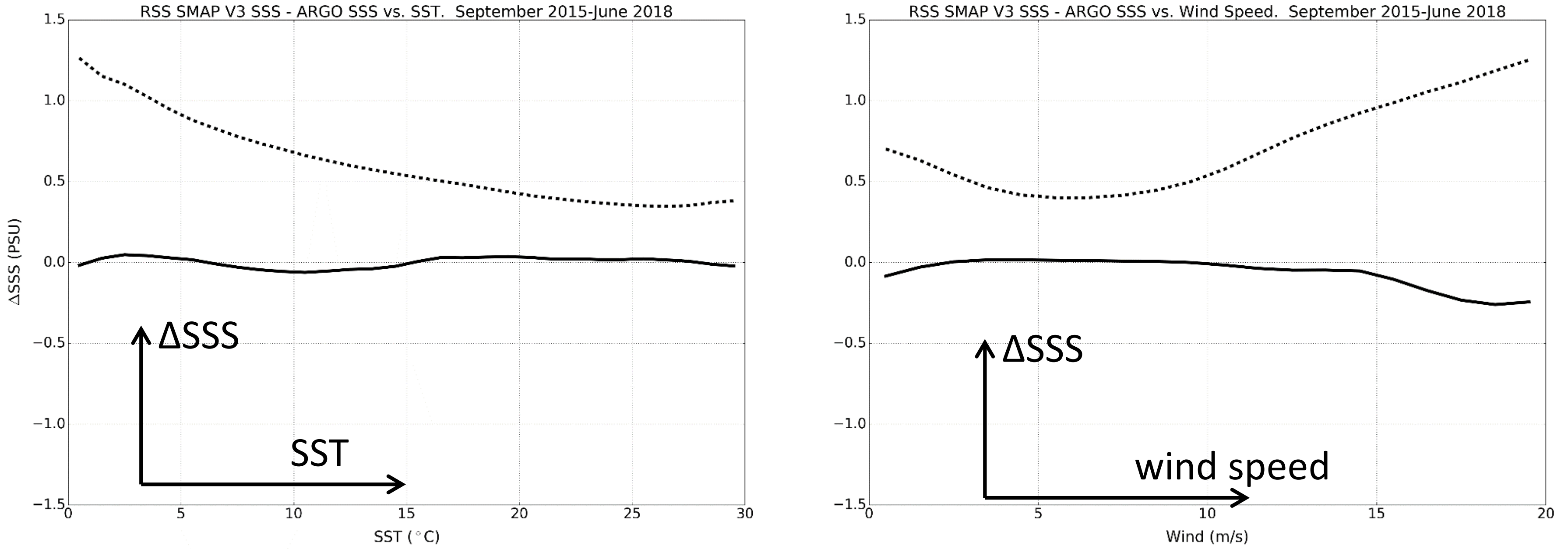
Water Vapor vs GPS
(Mears et al. 2015)



Validation (cont.)

Salinity

SSS SMAP – ARGO floats



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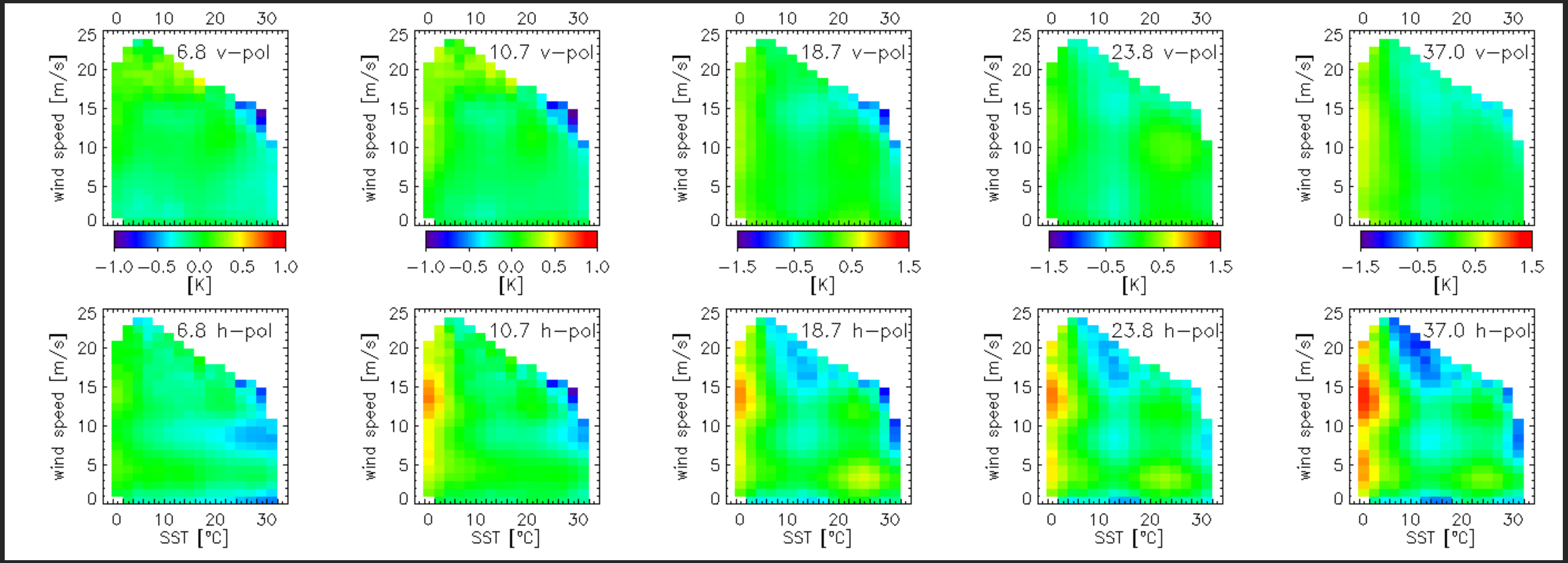
RTM Validation



- TB measured – RTM computed for 10 WindSat V/H channels.
- Stratified versus SST and wind speed.
- Input to RTM computation: QuikScat wind speed, NOAA OI SST (IR, no MW).
- Input needs to be validated = unbiased versus ground truth.
- Ideally: Independent from TB measurement.

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

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

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

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

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

Sensor Calibration

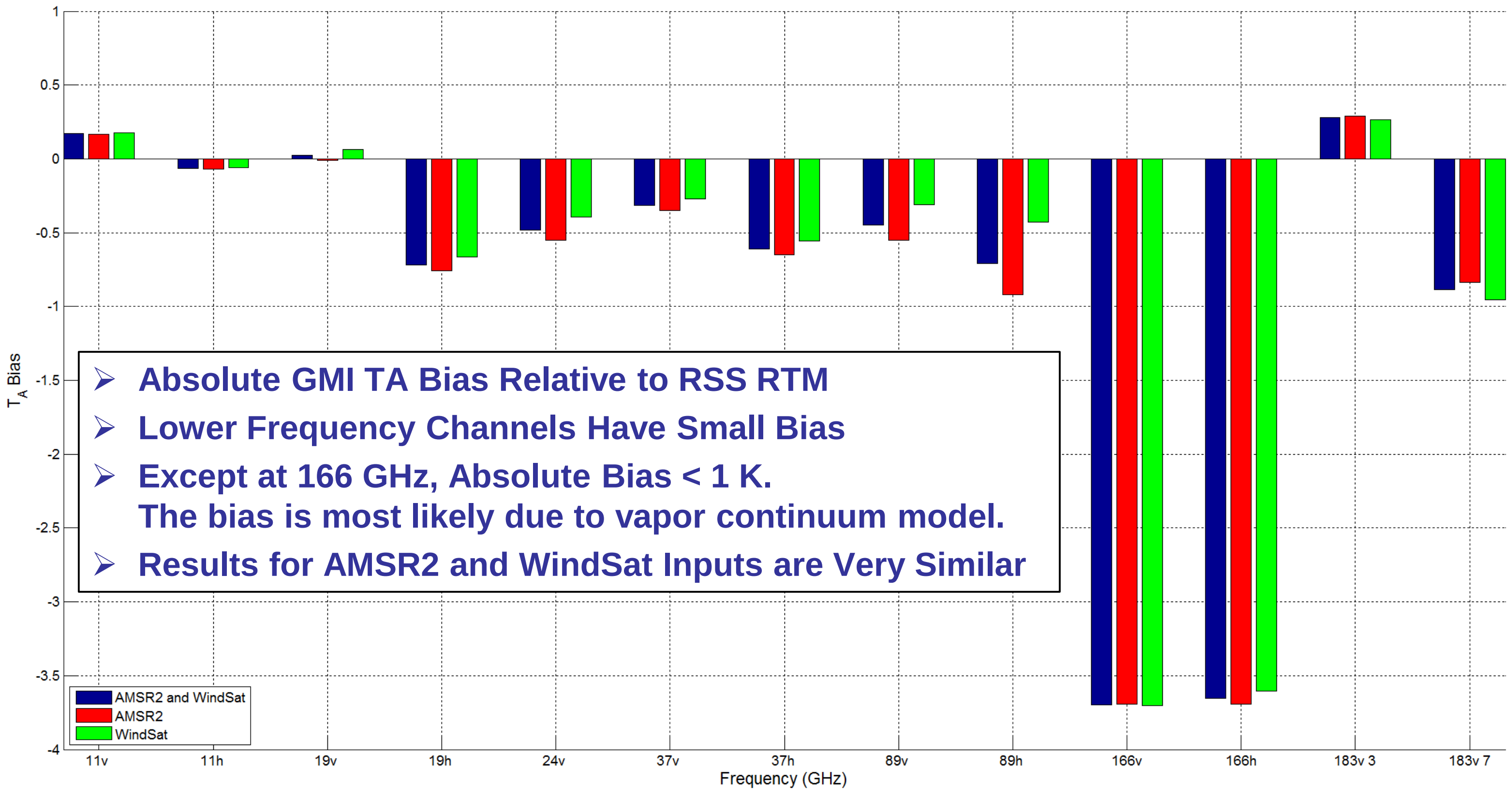
Tied to RTM Validation

- 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.**

Best Calibrated Radiometer: GMI

Excellent Agreement between Pre-Launch and Post-Launch Antenna Pattern

4-Point Calibration



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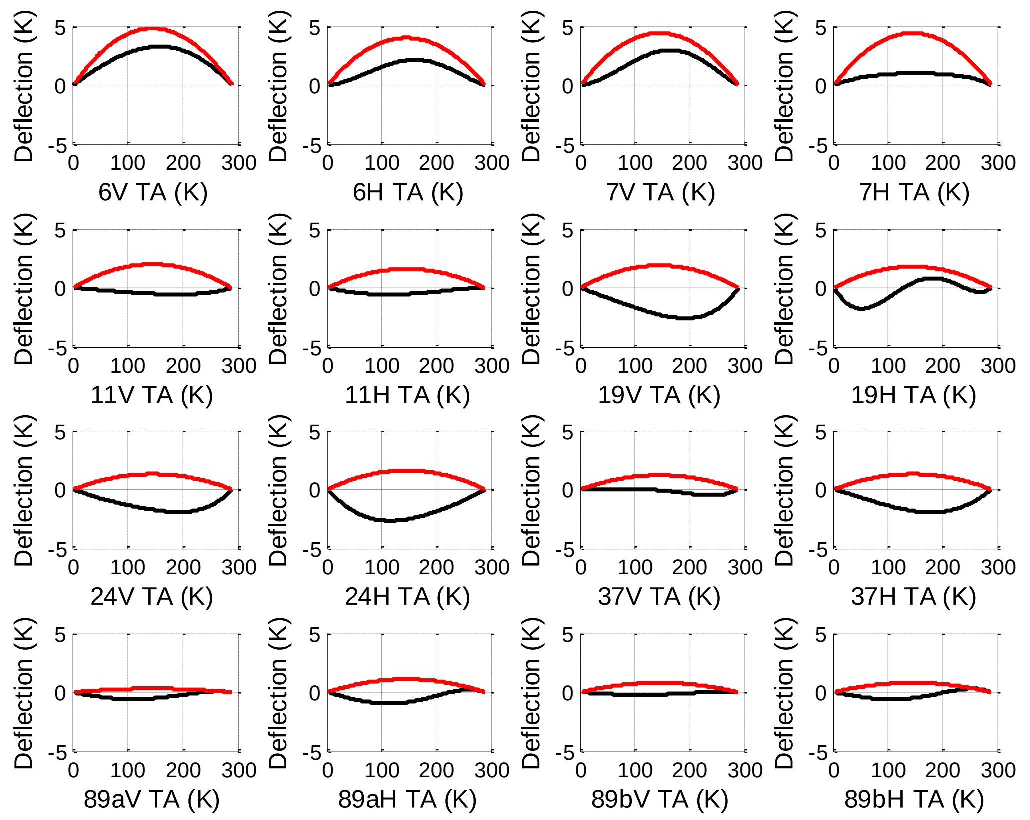
Calibration Anomalies

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 characteri-zation.
- Impact on quality of ocean retrievals.



Non-Linear Correction

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

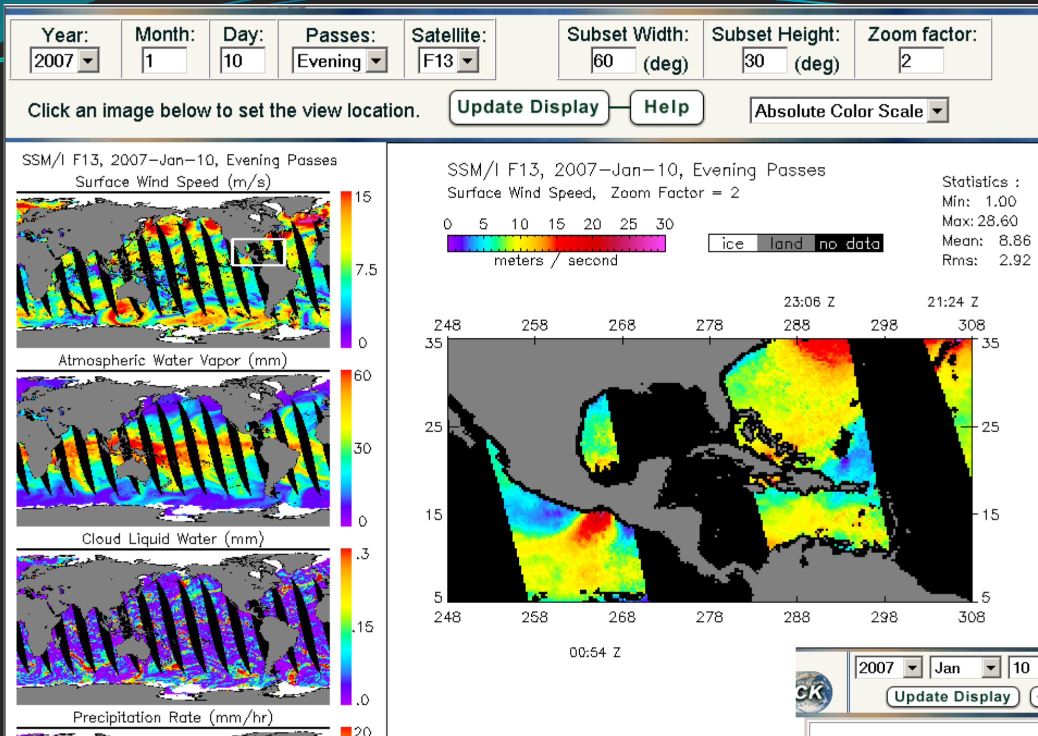
$$T'_A = T_A + \sum_{i=1}^{5} a_i x^i \qquad x = \frac{T_A - T_C}{T_H - T_C} \qquad \sum_{i=1}^{5} a_i \equiv 0$$

Summary + Conclusions
RSS MW Ocean Emissivity Model

- Valid Range
  - 1 – 90 GHz
  - Maybe usable at higher frequencies
  - 0 – 60 m/s wind speed
  - EIA: 0 – 60 deg. Best: 49 – 55 deg.
- Special case: L-band emissivity model (EIA: 28 – 45 deg)
- Extensive validation versus ground truth
  - RTM (TB measured – computed)
  - Environmental parameters that are retrieved with the RTM (SST, wind, vapor, cloud, rain, wind direction).
- Sensors used for development and testing:
  - WindSat, GMI, AMSR-E, AMSR2, SSM/I, SSMIS, TMI, Aquarius, SMAP

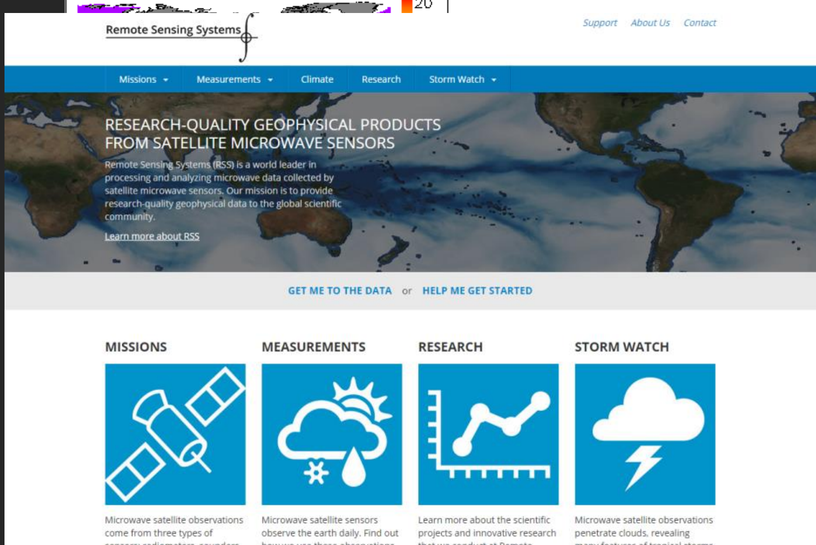
Additional Slides

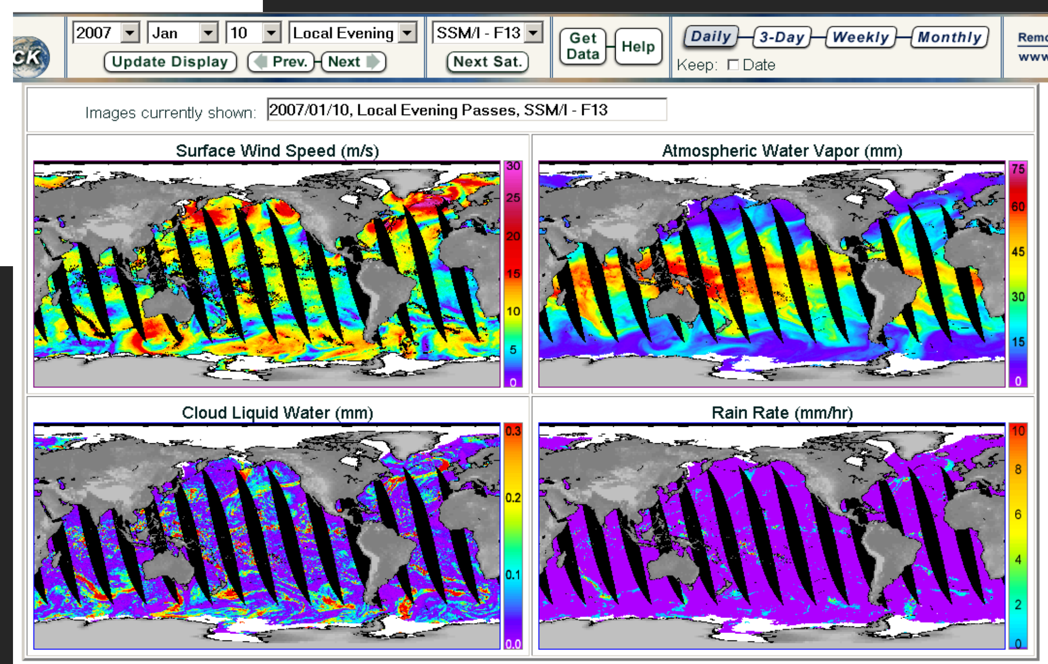
Microwave Data Products



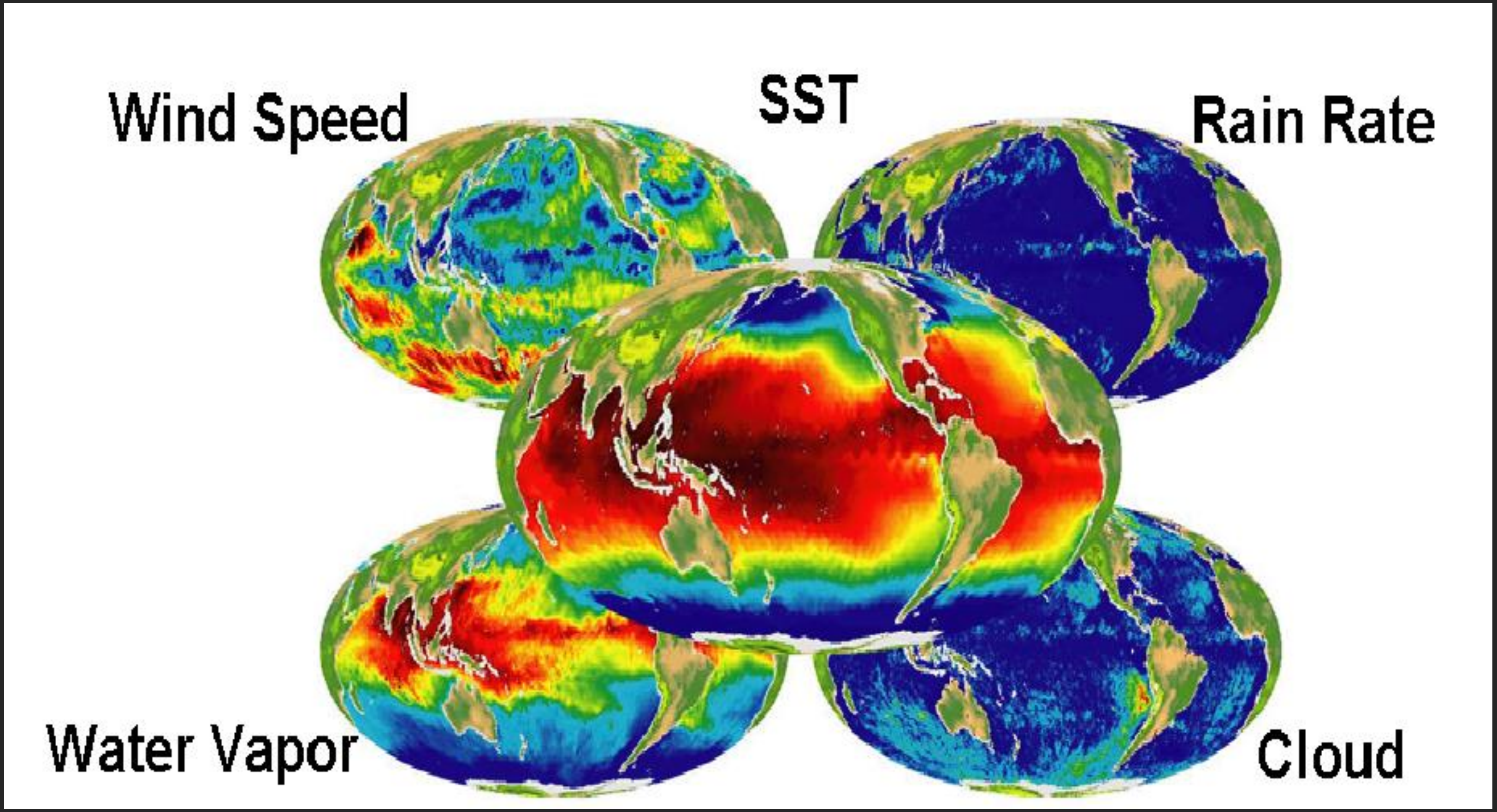
Version 7 Ocean Suite released 2011

Data available as:
ascending/descending swaths
3-day, weekly and monthly averages
merged geophysical products





Remote Sensing Systems Provides
Critical Environmental Parameters



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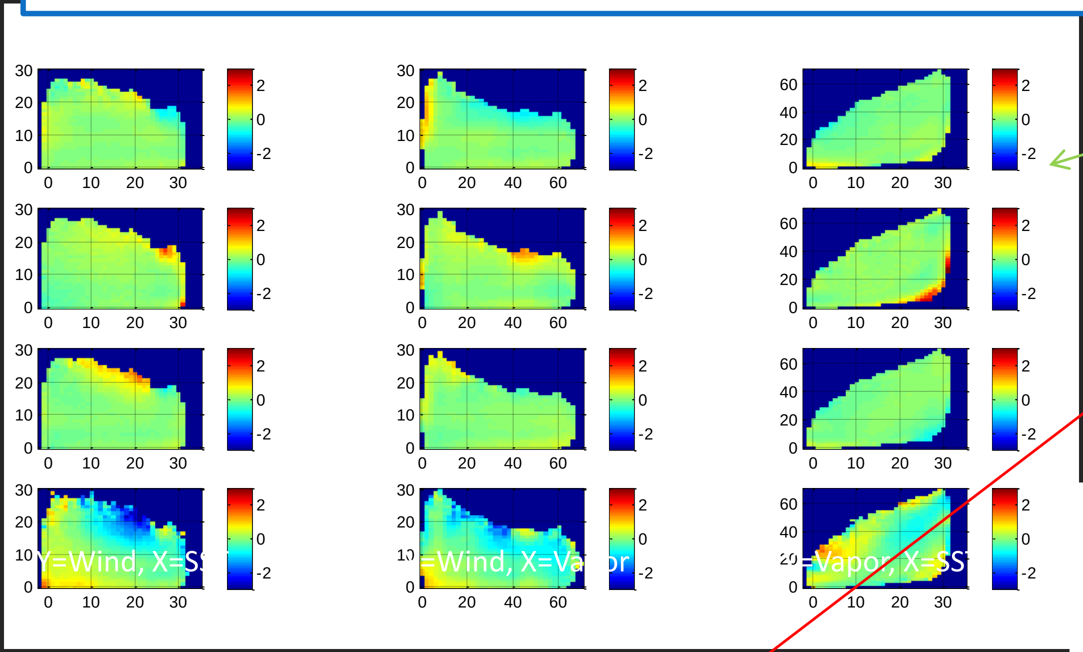
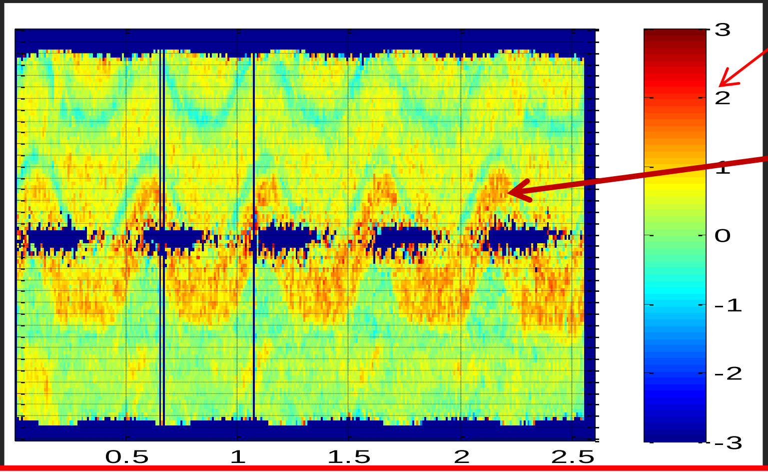
Distinguishing Sensor Errors from RTM Errors

Same ΔTa (simulated minus measured) plotted versus different parameters
Same color scale: ΔTa goes from -3K to +3K

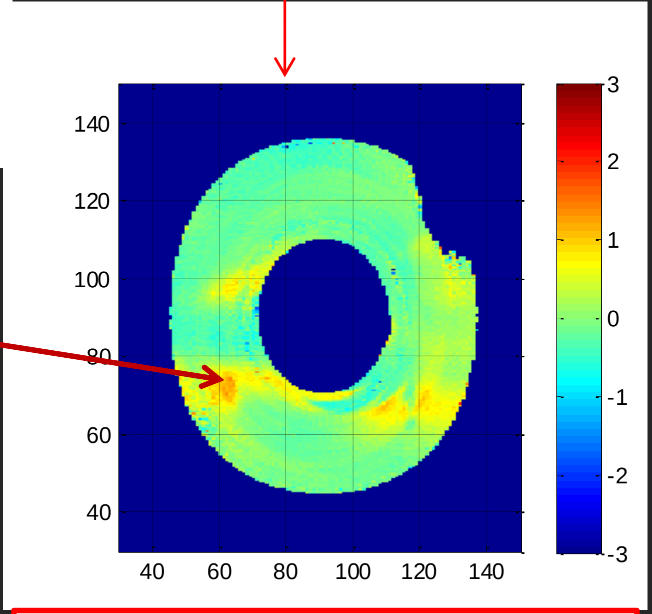


RTM
Error Diagnostics

Sensor Calibration
Error Diagnostics



Sun intruding
Into hot load

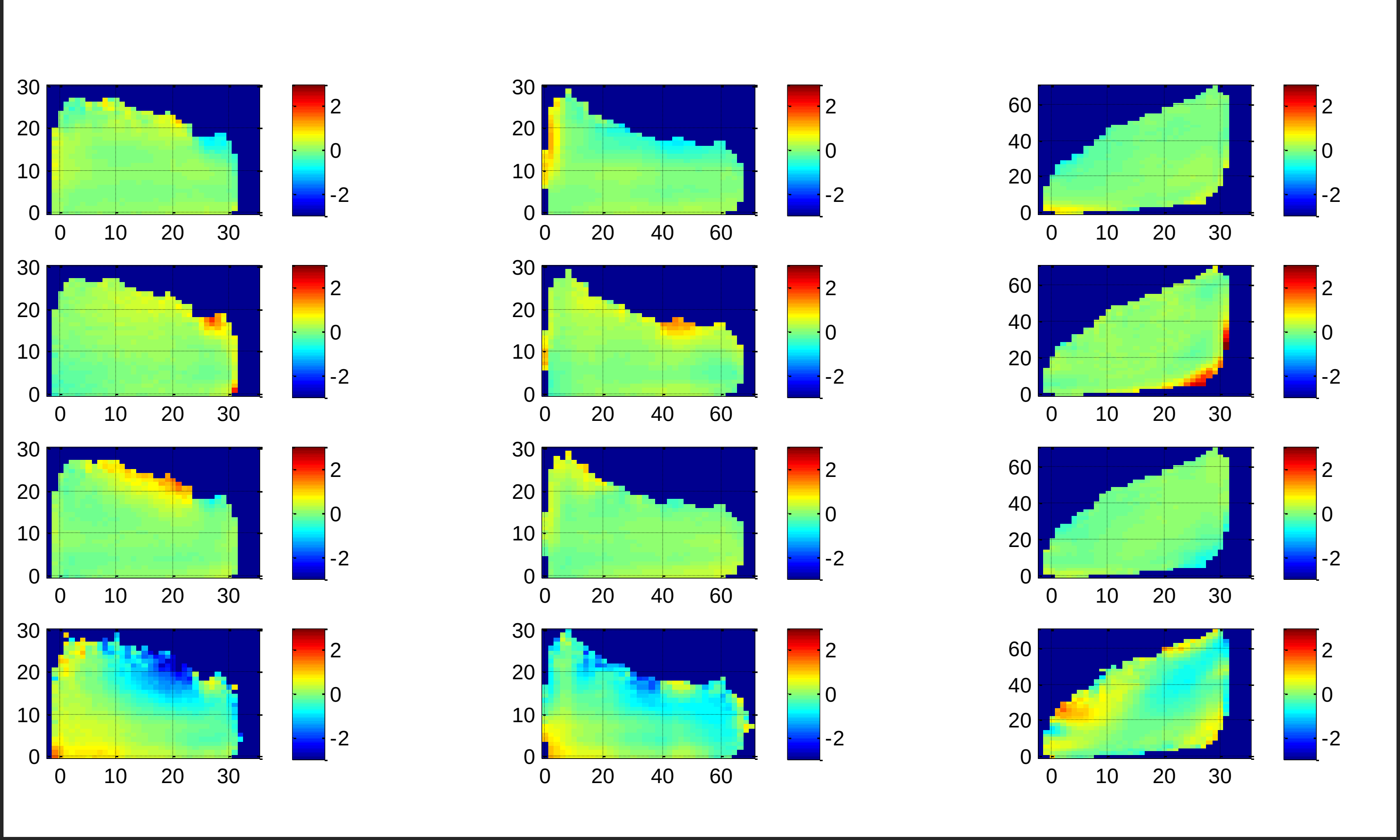


Y=Orbit Position, South Pole to South Pole, X=Orbit number (5 years)

Y=Sun Polar Angle, X=Sun Azimuth Angle

RTM Adjustments

Minimize Biases between TB measured – computed for all Channels



Y=Wind, X=SST

Y=Wind, X=Vapor

Y=Vapor, X=SST

Color Scale: -3 to + 3 K

Antenna Pattern Correction (APC)
Derived Pre-Launch

- TA determined from TB by 4π integration over antenna gain pattern

$$\mathbf{T_A} = \int d\Omega \, \Gamma'(\theta,\varphi) \cdot \mathbf{T_B}(\theta,\phi)$$

- Approximation of TB to TA transformation by linear relation

$$\begin{pmatrix} \tilde{T}_{A,v} \\ \tilde{T}_{A,h} \end{pmatrix} = \begin{pmatrix} 1-a_{vh} & a_{vh} \\ a_{hv} & 1-a_{hv} \end{pmatrix} \begin{pmatrix} T_{B,v} \\ T_{B,h} \end{pmatrix}$$

1. cross polarization correction

$$T_{A,v} = \eta_v \tilde{T}_{A,v} + (1-\eta_v) T_{CS}$$
$$T_{A,h} = \eta_h \tilde{T}_{A,h} + (1-\eta_h) T_{CS}$$

2. spillover correction
(intrusion of cold space radiation into Earth field of view)

- Determine APC coefficients a_{vh}, a_{hv}, η_v, η_h through least-square fit.
- Can be easily inverted once the APC coefficients are determined.

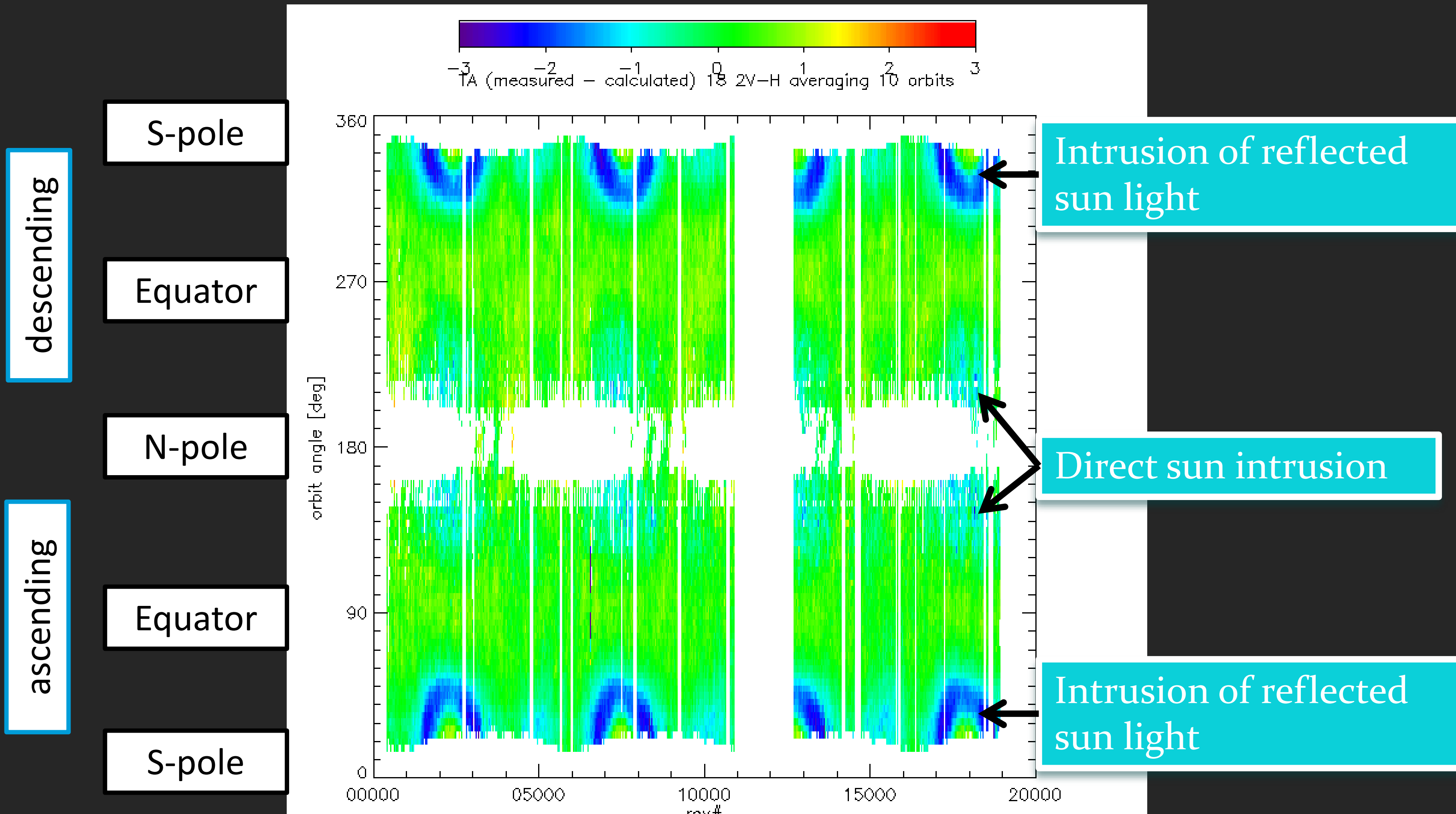
Absolute Calibration

Post-Launch Determination of APC

- **Key: Compare TOA TB measured with RTM computation.**
- Example: GMI
  - Earth Scenes come from
    - WindSat and AMSR2 (1 hour collocation) for wind speed, vapor, cloud water.
    - NOAA OI SST
    - NCEP wind direction.

Calibration Anomalies

Solar Intrusion into Hot Load: WindSat



WindSat 18 GHz measured - computed TB (2 V-pol – H-pol)
as function of time and orbit position.

Calibration Anomalies

Derivation of Effective Hot Load Temperature

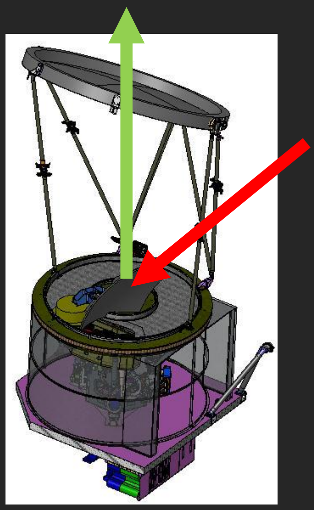
- Using the RTM we can compute what the effective temperature of the hot load should be:
- Use channel combination 2V – H, which is insensitive to vapor or cloud.
- Assume that $T_{H,eff}$ is independent of polarization.
- Determine difference between actual hot load temperature and computed hot load temperature.
- This is the hot load correction
- Tie this correction to the parameter that causes the anomaly.
- WindSat: Sun angle (between sun vector and spin axis).

$$T_X = 2 \cdot T_V - T_H$$

$$\textit{relationship between } T_B \textit{ and hot load } T_H :$$

$$\Delta T_B = \left(T_{Xmea} - T_{X\,\mathrm{mod}} \right) \approx \frac{T_B}{T_h} \Delta T_H$$

$$\Delta T_H = \frac{T_H}{2 \cdot T_V - T_H} \left(T_{Xmea} - T_{X\,\mathrm{mod}} \right)$$



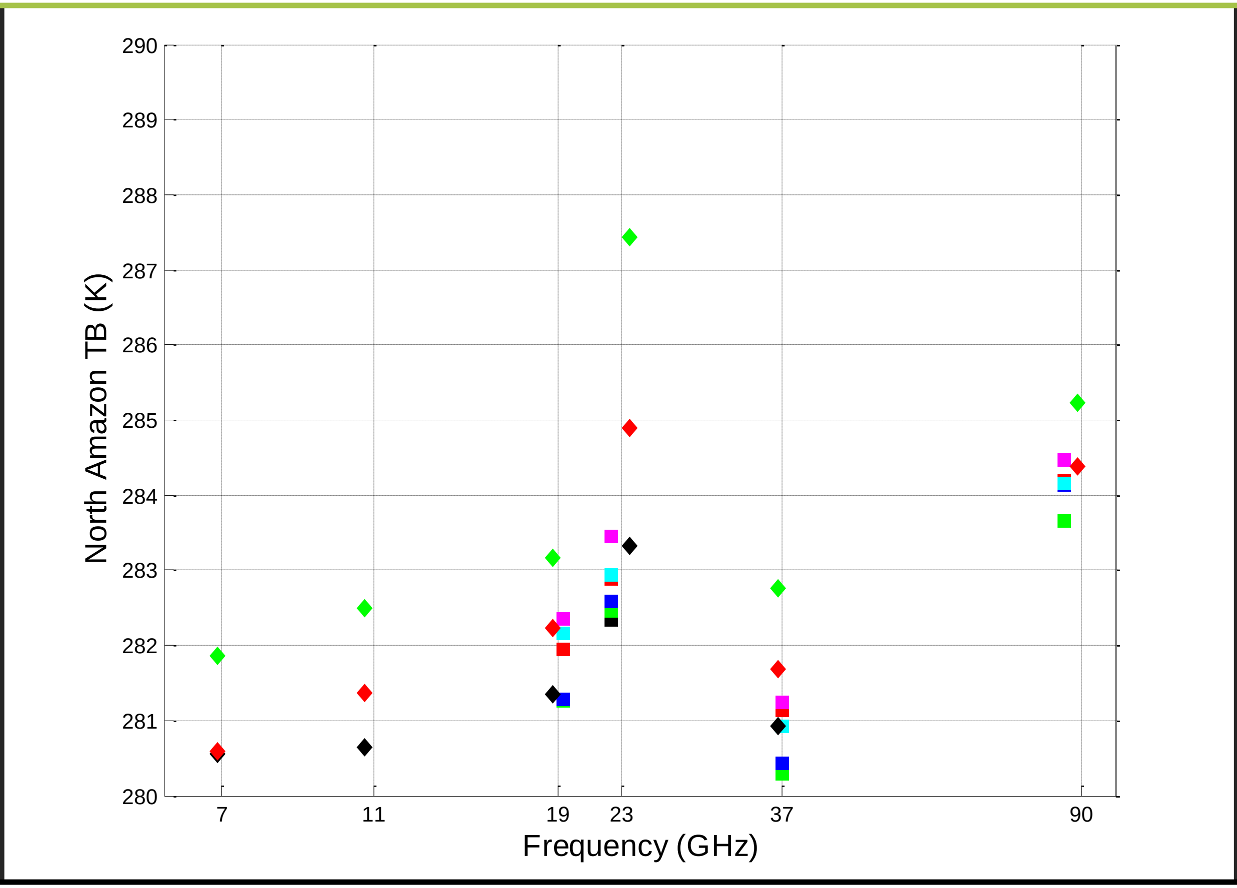
Calibration Anomalies
Non-Linear Receivers: AMSR2 (1)

TB over Amazon rain forest using JAXA values for T_{hot}, APC and non-linear parameters

WindSat

AMSR-2

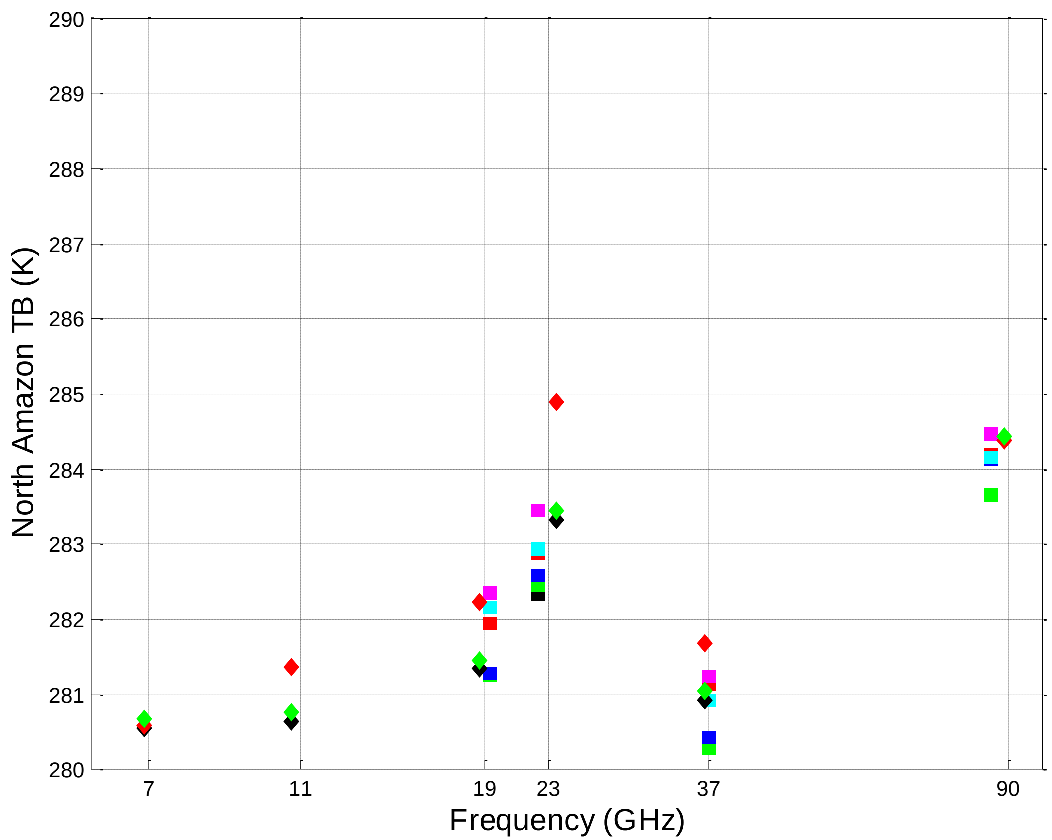
AMSR-E



Black diamonds are WindSat. **Red diamonds are AMSR-E**. **Green diamonds are AMSR-2.**
Colored squares are the 6 SSM/Is.
Same months used for averages, but averaging years are different.

Calibration Anomalies
Non-Linear Receivers: AMSR2 (2)

TB over Amazon rain forest using values for T_{hot}, APC and non-linear parameters from RSS analysis



WindSat

AMSR-2

AMSR-E

Black diamonds are WindSat. **Red diamonds are AMSR-E**. **Green diamonds are AMSR-2.**
Colored squares are the 6 SSM/Is.
Same months used for averages, but averaging years are different.

Calibration Anomalies

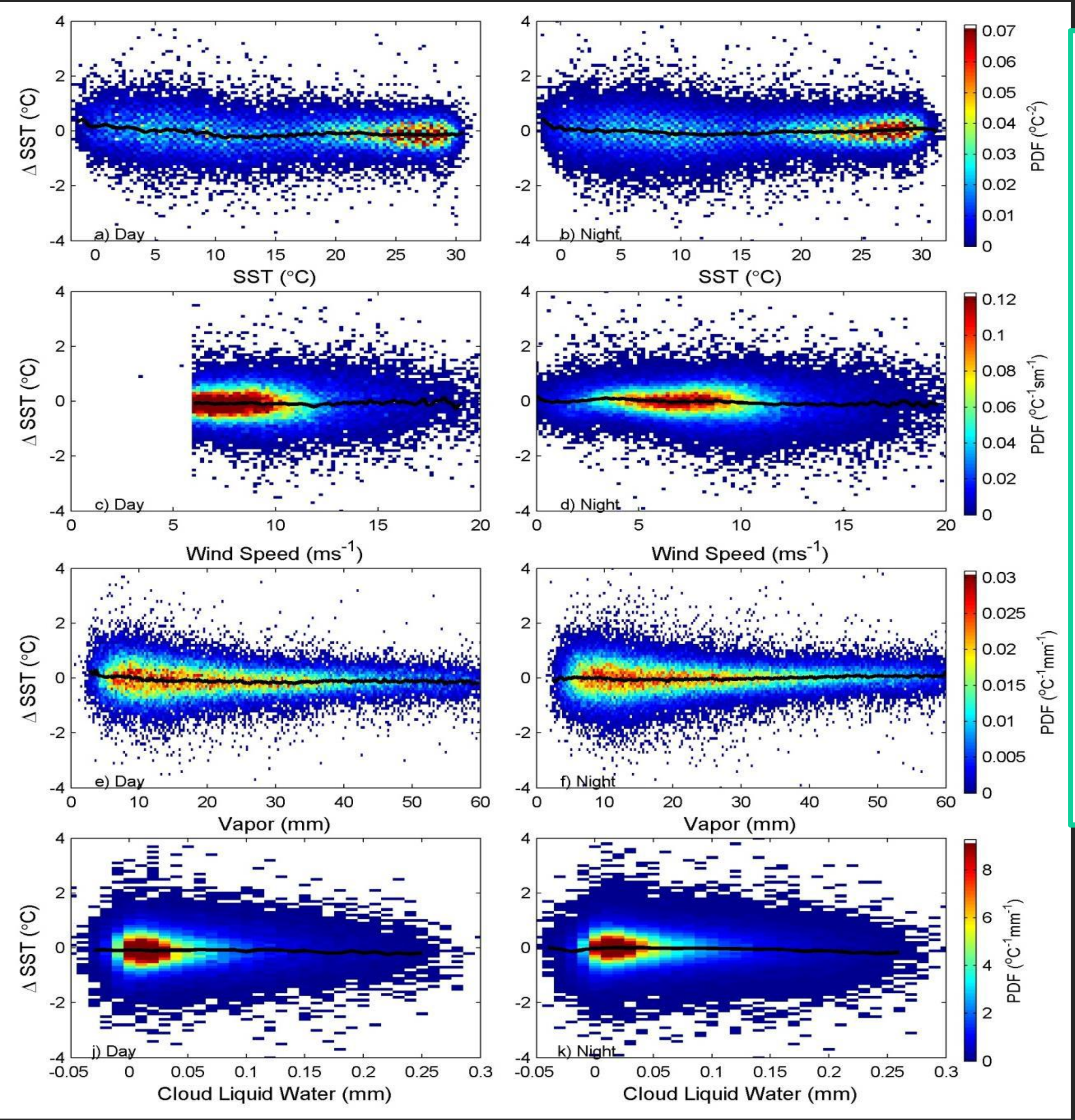
Can affect RTM validation of not properly removed

- Solar intrusion into hot load.
  - AMSR-E, AMSR-J, TMI, WindSat, SSMI(s)
- Emissive antenna.
  - TMI, SSMIS F16, F17
- Receiver non-linearities.
  - AMSR-E, AMSR2

Remote Sensing Systems
www.remss.com

Geophysical Validation

SST: AMSR-2



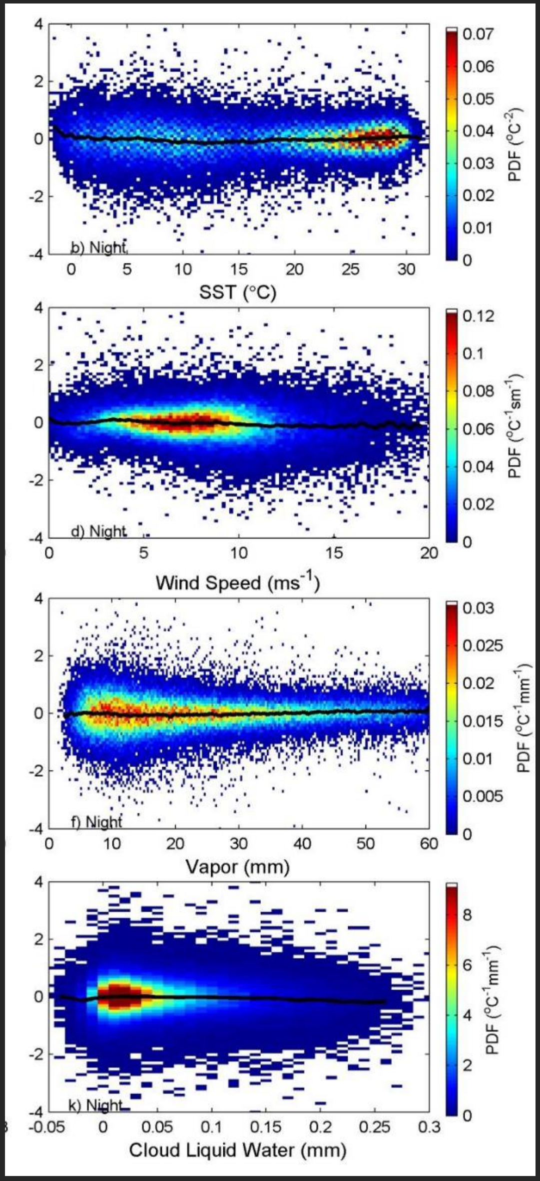
Mean bias between SST from AMSR-2 and moored and drifting buoys and PDF as a function of:

SST for (a) day and (b) night;
wind speed for (c) day and (d) night;
water vapor for (e) day and (f) night;
cloud liquid water for (j) day and (k) night.

The background color shows the PDF, with the color-bar on the right 833 side of each row, and the black line shows the mean bias at each value.

Geophysical Validation

SST: AMSR-2



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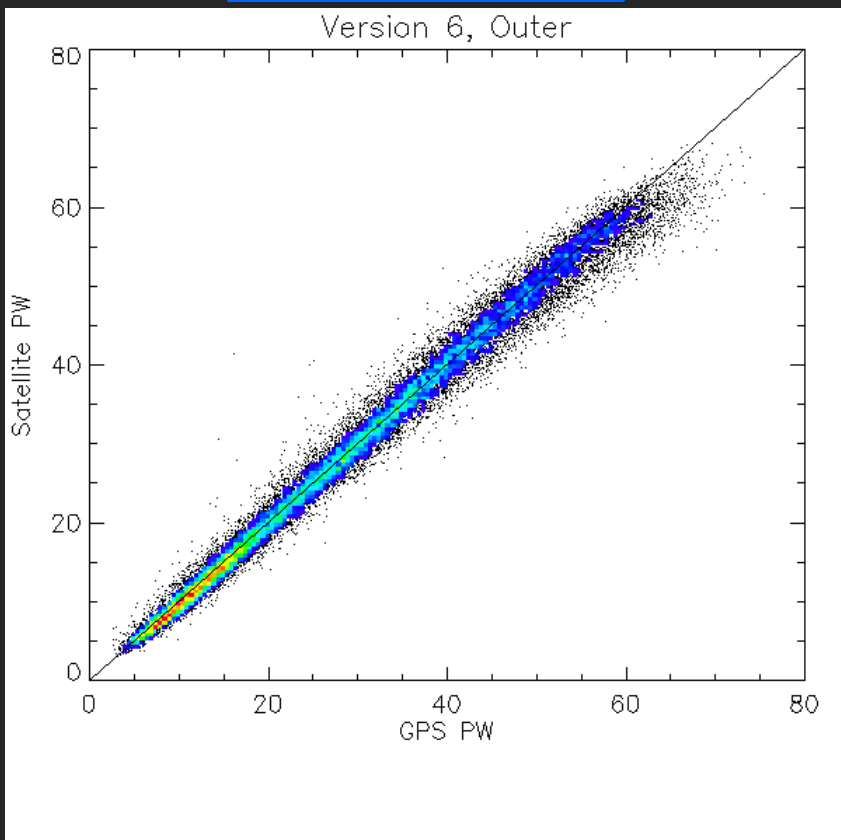
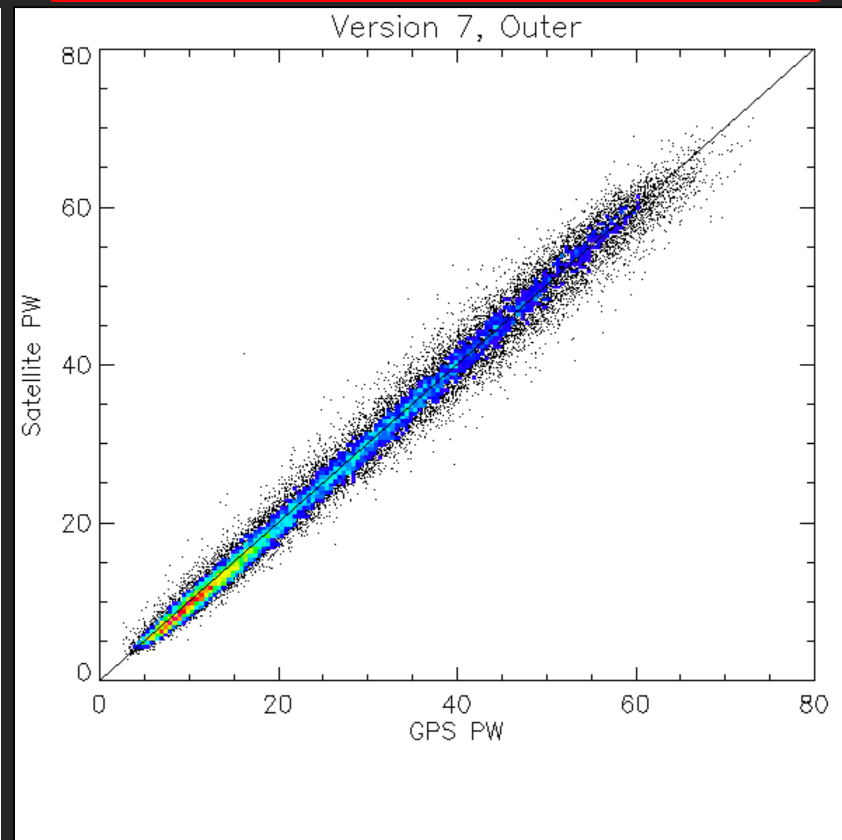
Geophysical Validation

Columnar Water Vapor

Version 6

Version 7: released in 2011





Columnar Water Vapor from SSM/I F13 compared with GPS radiosondes.
Total bias: -0.07 mm. Total standard deviation: 1.9 mm.
The improvement at high water vapor is due to adjustments in the RTM.

Large Error Source: Reflected Galactic Radiation

Needs to be Modelled Very Accurately