Roughness Correction for Aquarius (AQ) Brightness Temperature using MicroWave Radiometer (MWR)

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Dissertation Defense

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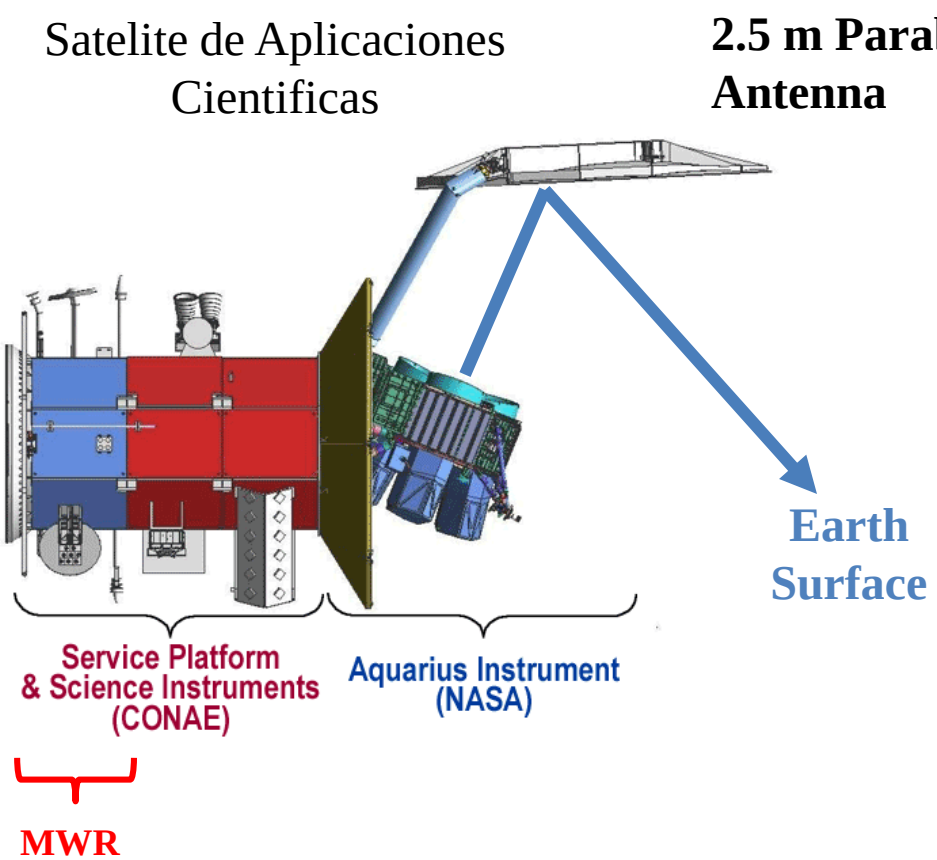
Presentation Outline

- Aquarius/SAC-D Mission
- Research Incentive and Dissertation Objective
- Background
- Radiative Transfer Theory
- Tuning the CFRSL Ocean Emissivity Model
- MWR Roughness Correction Algorithm
- AQ Salinity Retrieval
- SSS Validation Results
- Conclusion

Dissertation Research Objective

- My dissertation objective is to use CONAE MWR instrument onboard the Aquarius/SAC-D satellite to correct for the ocean surface roughness
  - To develop an EM radiative transfer model (RTM)
    - To characterize ocean roughness brightness (Tb) at the AQ L-Band and MWR Ka-Band
  - To develop signal processing algorithm to provide AQ roughness correction
    - Inputs: MWR Ka-band Tb's and ancillary environmental data
  - To perform roughness correction validation
    - To verify that MWR roughness correction is effective over the range of ocean surface wind speed conditions
    - To quantify impact of MWR roughness correction on AQ SSS retrievals

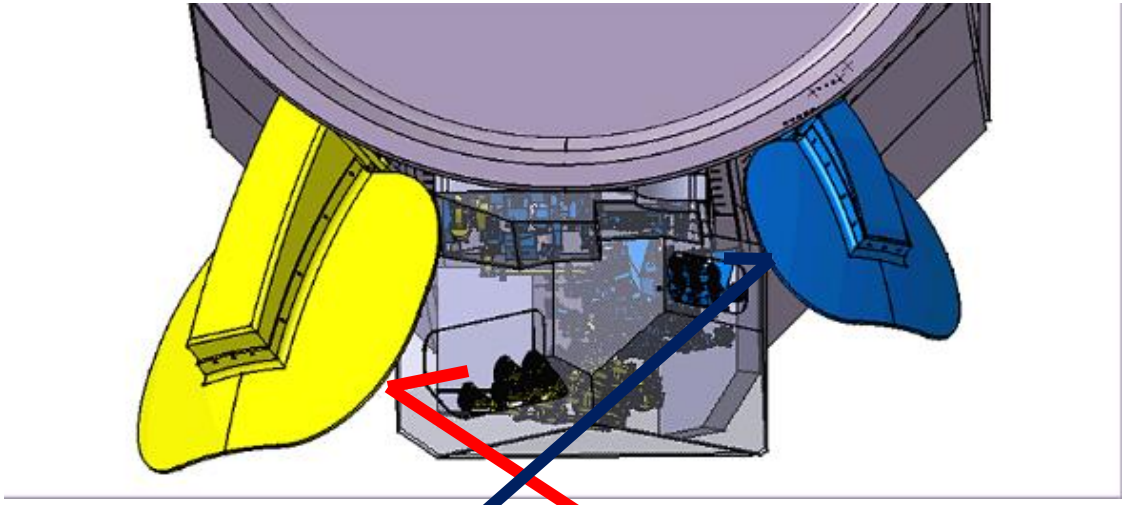
Aquarius/SAC-D Mission



- ❑ Collaborative Mission
  - NASA
  - CONAE (Argentina Space Agency)
- ❑ Mission Science:
  - Monitor earth water cycle by measuring biweekly global ***Salinity*** maps
- ❑ Salinity changes can be measured using L-band (1.4 GHz) passive microwave remote sensing

Aquarius/SAC-D
MicroWave Radiometer (MWR)

Flight Direction

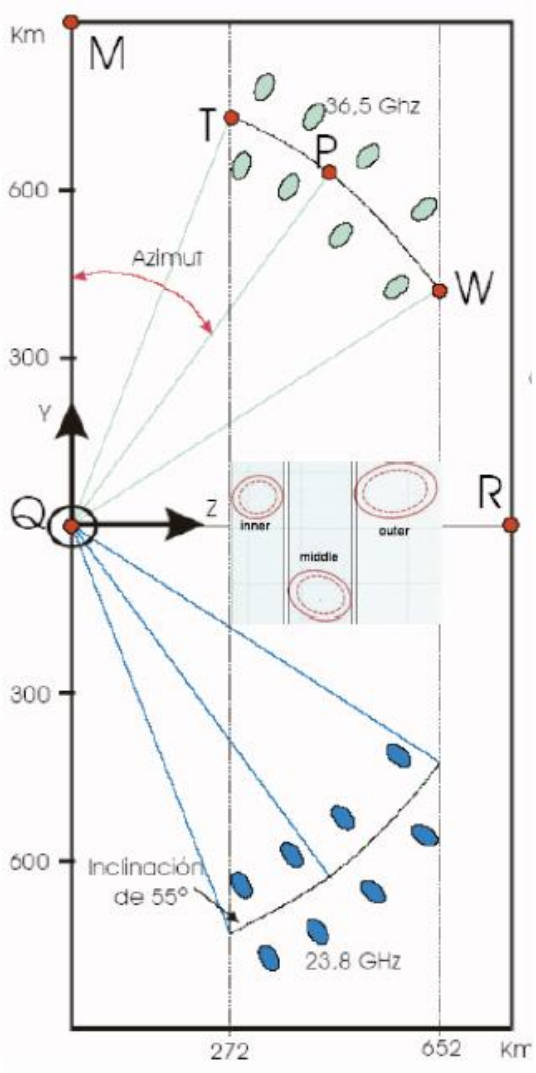


Ka-band forward looking beams (8) (36.5 GHz)

K-band backward looking beams (8) (23.8 GHz)

Aquarius SAC-D Satellite Sensor Geometry

- Aquarius (AQ) – NASA
  - L-band active/passive sensor
  - Frequency = 1.413 GHz
  - 3 Beams
    - Inner (# 1), Middle (# 2, Outer (# 3)
- MicroWave Radiometer (MWR) – CONAE
  - 16 Beams
    - 8 Forward looking (36.5 GHz, Ka-band)
      - Inner beams (odd beam number)
      - Outer beams (even beam numbers
    - 8 Backward looking (23.8 GHz, K-band)

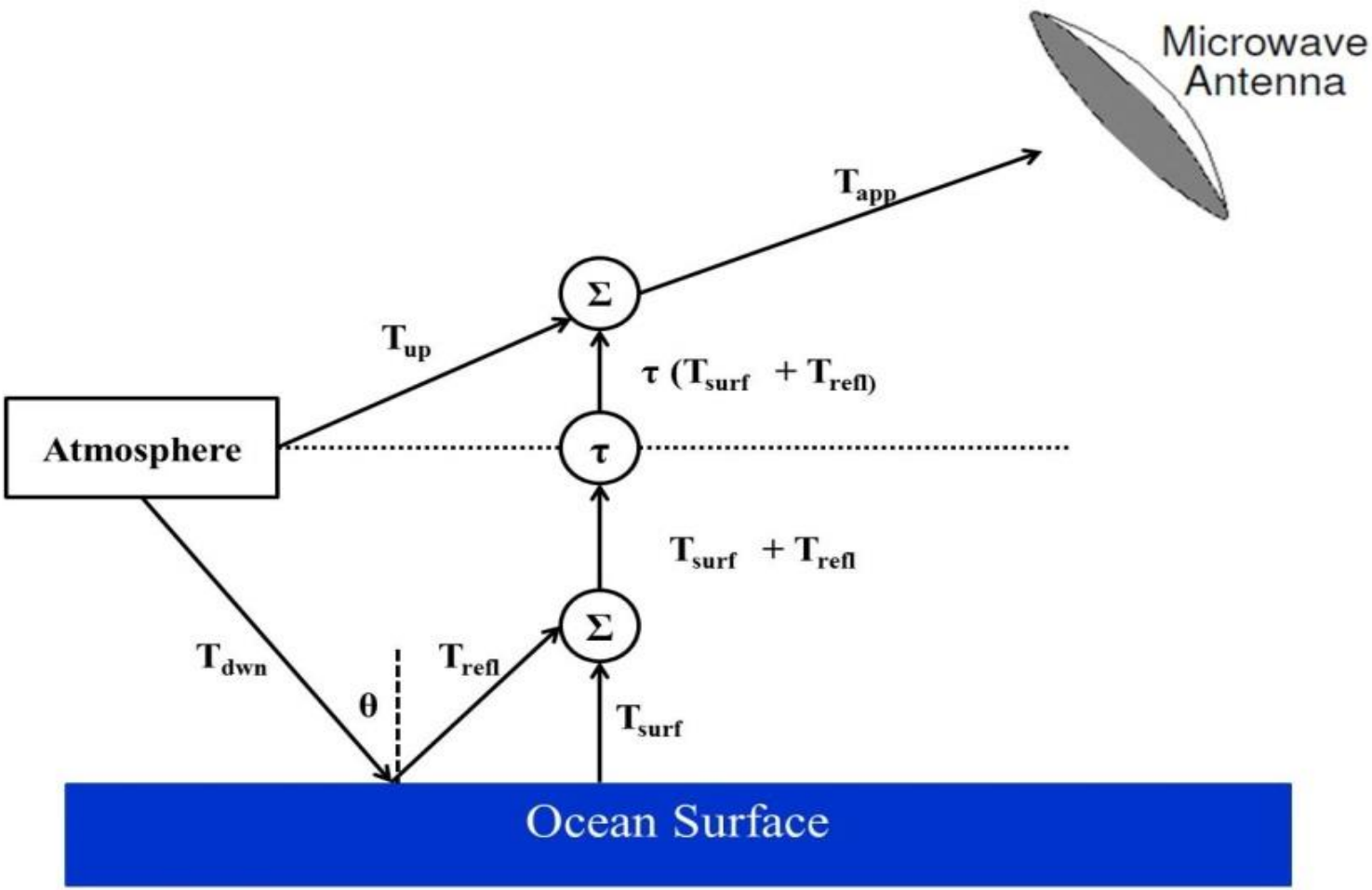


AQ Mission Requirements

- ***Salinity***: mass ratio of dissolved salt to the mass of water in a unit volume
- ***Unit***: Practical Salinity Unit (PSU)
- Salinity can be remotely sensed by measuring the ocean's electromagnetic energy (brightness temperature) at L-band (1.4 GHz)

- Aquarius to provide weekly global maps of SSS at ~150 km special resolution
  - SSS rms measurement accuracy ± 0.2 psu
    - Equivalent measure: $\frac{1}{8}$ tablespoon of salt in 1 gallon of water
  - This is translated to ± 0.4 Kelvin 1-sigma total error budget of measured Tb

Radiative Transfer Theory



$$T_{app} = T_{up} + \tau \times \left(T_{surf} + \Gamma \times T_{dwn}\right)$$ → **Forward Model**

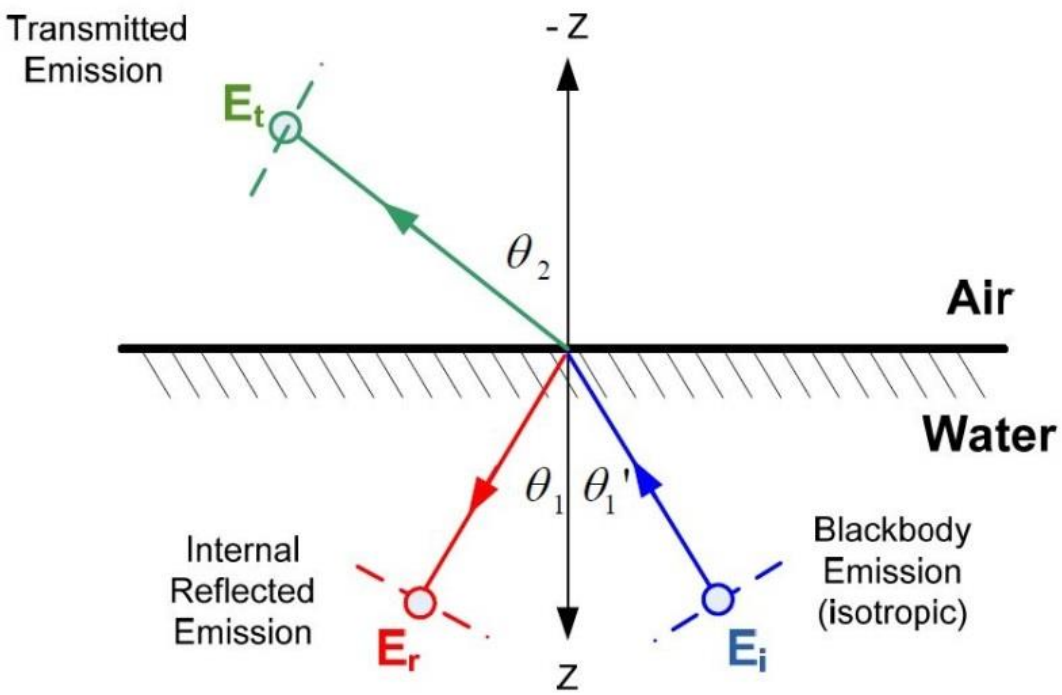
$$T_{surf} = \frac{T_{app} - T_{up}}{\tau} - \Gamma\, T_{dwn}$$ → **Reverse Model**

Ocean Brightness Temperature

- **Ocean Surface Brightness Temperature**
  - Radiated Electromagnetic Energy of sea water emitted through the water-air boundary
- **Ocean Surface Emissivity**
  - Ratio of Electromagnetic Energy emitted to the total Electromagnetic Energy radiation of a blackbody

ρ is a function of:

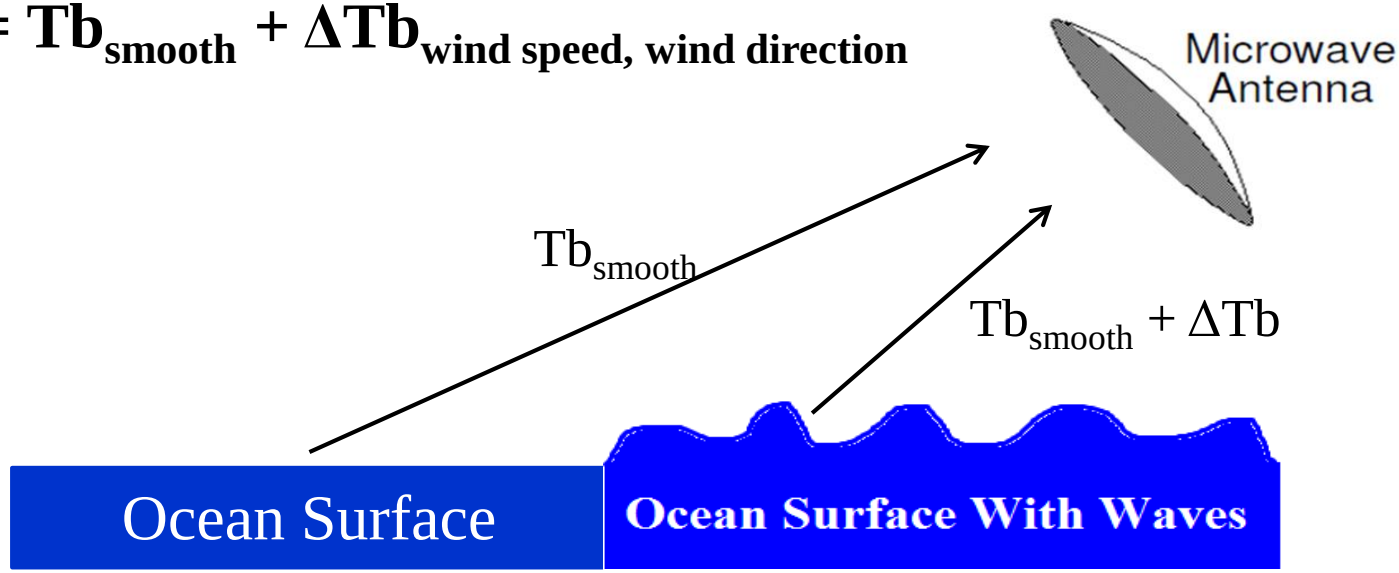
SST
SSS
Frequency
Polarization



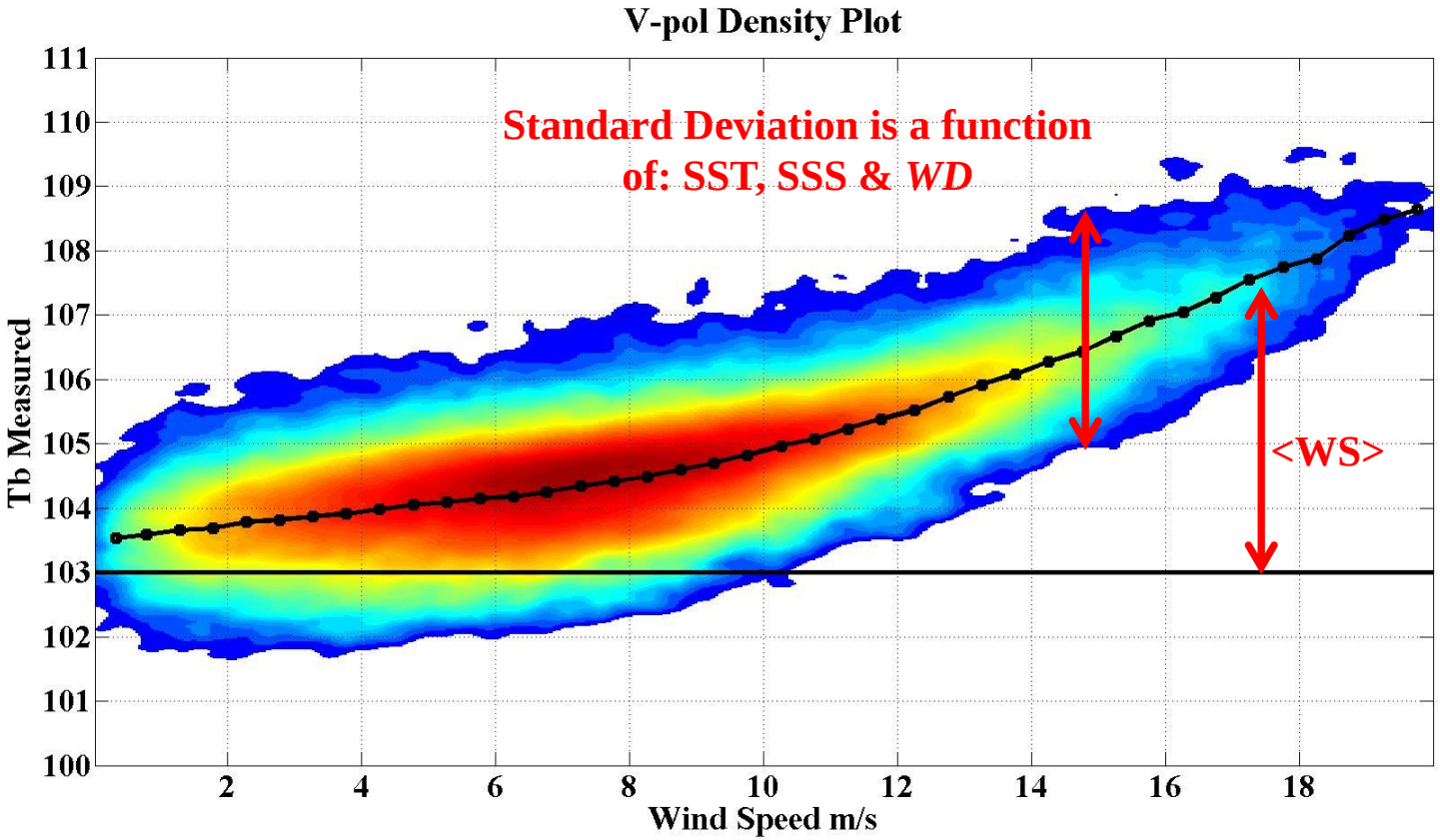
Ocean Roughness is major Tb Error Source

- Wind-driven ocean waves roughen the surface and cause ocean Tb to increase (become warmer)
  - After applying the wind speed correction, residual error is responsible for ¾ of total error budget

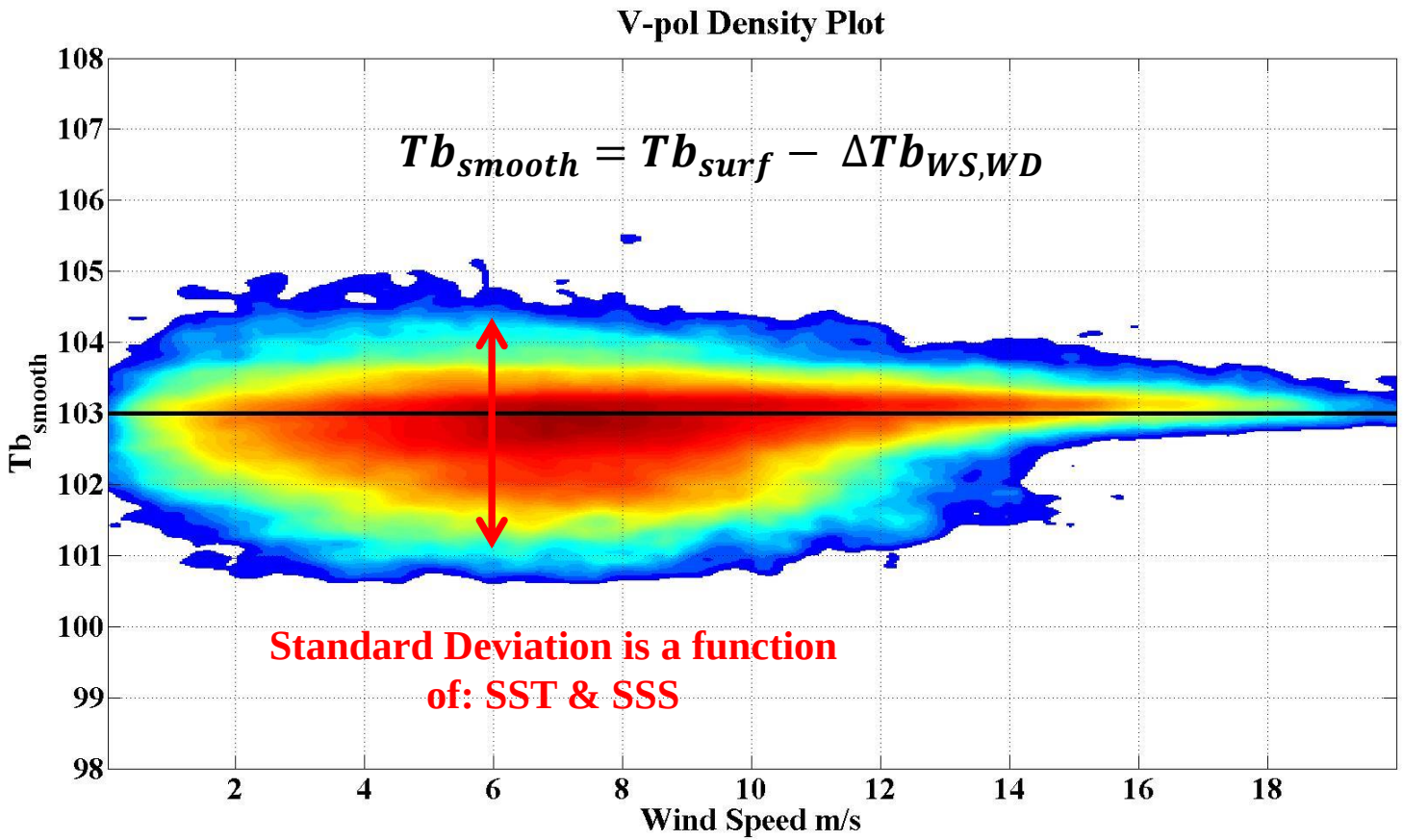
$$\mathbf{Tb_{surf} = Tb_{smooth} + \Delta Tb_{wind\ speed,\ wind\ direction}}$$



Measured Surface Brightness Temperature, Tb_{surf}

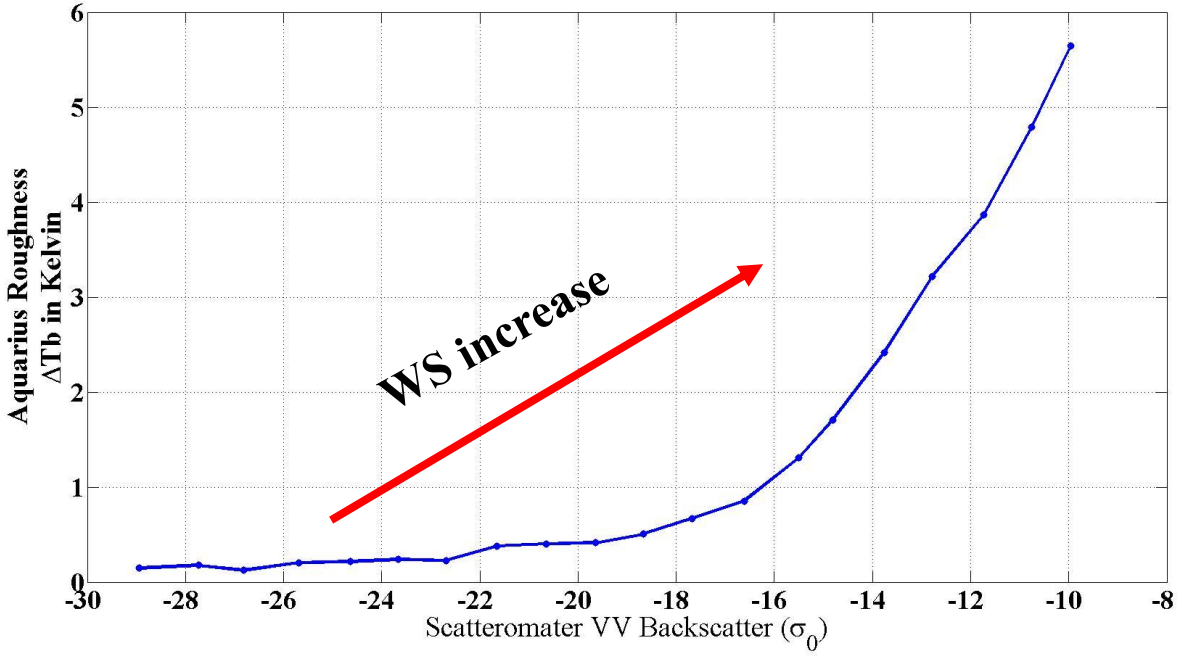


Smooth Surface Brightness Temperature, Tb_{smooth}



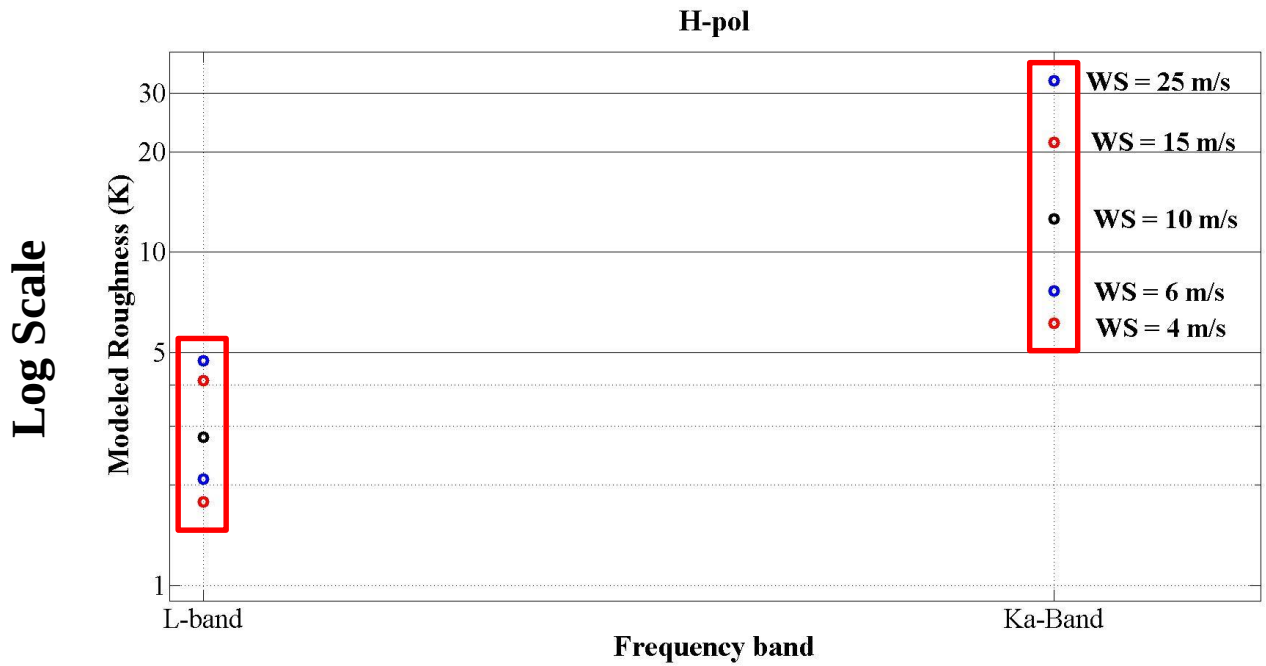
AQ Baseline Ocean Roughness Correction

- AQ uses scatterometer to provide radiometric roughness correction (*ΔTb*)
  - Empirical cross-correlation relationship between radar backscatter with excess ocean emissivity



MWR Ocean Roughness Correction

- Measured MWR Tb at Ka-band used to calculate ΔTb_{Ka} and RTM used to translate to ΔTb_L
  - Ka-band Tb is more ***sensitive*** to changes in wind speed
  - Provides the opportunity for an alternative roughness correction using the simultaneous MWR measurements
  - MWR IFOV provides > Nyquist spatial sampling



Previous CFRSL Ocean Surface Emissivity Model (El-Nimri, 2010)

- RTM combined many published radiometer data sets from different instruments to develop ocean surface emissivity model
  - Primary emphasis was
    - C-band (4 – 8 GHz)
    - Wide incidence angle range (EIA = 0° – 70°)
    - High wind speed values > 15 m/s
- Model was later extrapolated to model lower and higher ranges frequencies
  - L-band (1 GHz) and Ka-band (40 GHz)
  - However, model accuracy at L- and Ka-bands were compromised because of limited experimental data
- Now AQ and MWR measurements provide sufficient and accurate data for tuning CFRSL model at these frequencies

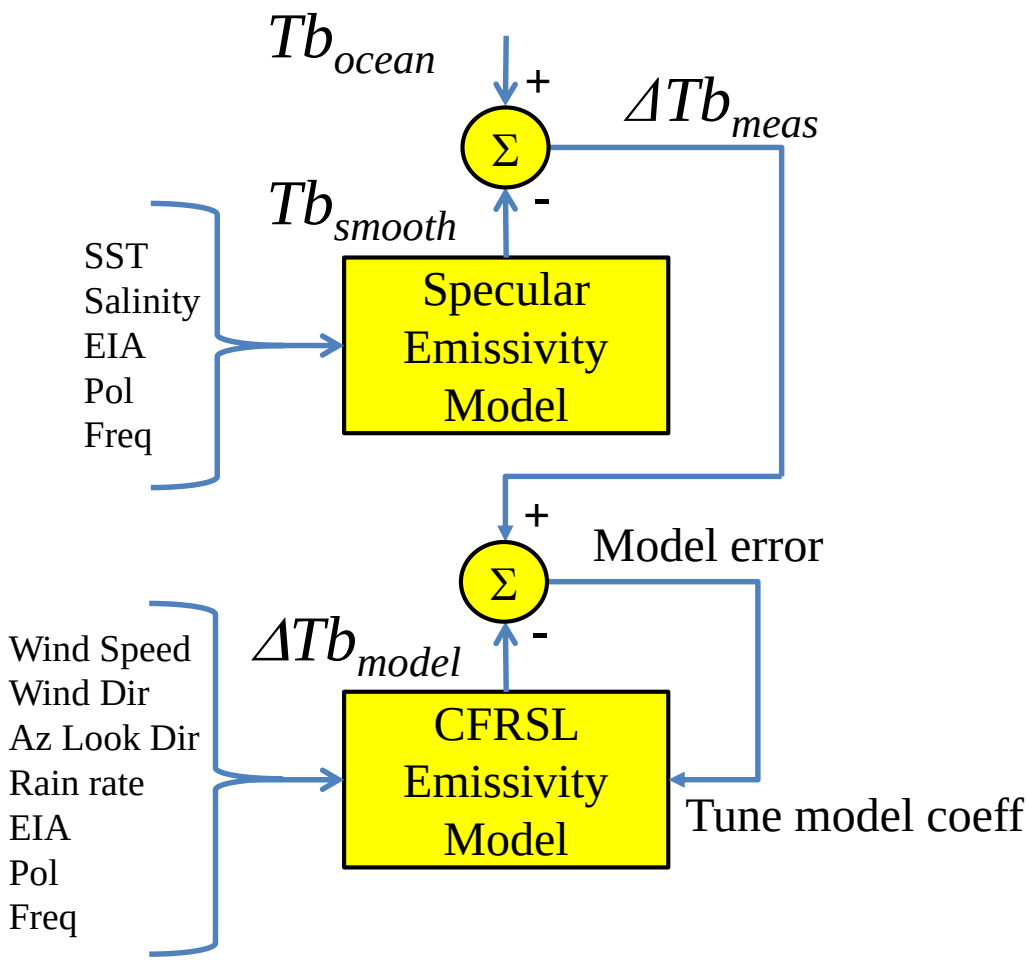
MWR Approach for AQ Roughness Correction

- This dissertation provides an alternative approach to calculate roughness correction for AQ that uses collocated:
  - MWR Tb at 36.5 GHz V- & H-pol
  - Numerical Weather Model/ Ocean Wind Vector
  - WindSat and SSMIS retrieved environmental parameters
- Incorporates a refined CFRSL Ocean Surface Emissivity Model (RTM)
  - Tuned to on-orbit AQ and MWR Tb measurements
- Calculates an AQ (L-band) roughness correction due to wind speed (WS) and wind direction (WD)

CFRSL RTM Tuning using Match-up Dataset

- Wind speed and wind direction effects were analyzed using ~ 1 year of AQ & MWR data
  - MWR Tb V7.0
    - Two incidence angles: 52°, 58°
    - ~ 6,000,000 data points
  - AQ L-2 V3.0
    - Three incidence angles: 29°, 35°, 46°
    - ~ 16,000,000 data points
  - These data sets were filtered to remove points where rain exists
  - MWR data Averaged over the AQ Instantaneous Field of View (IFOV)
- Measured isotropic roughness correction at Ka-band was cross-correlated with corresponding roughness correction at L-band
  - Empirical relationship was found for use in the Roughness Correction Algorithm

CFRSL Model Empirical Tuning Procedure, L-band

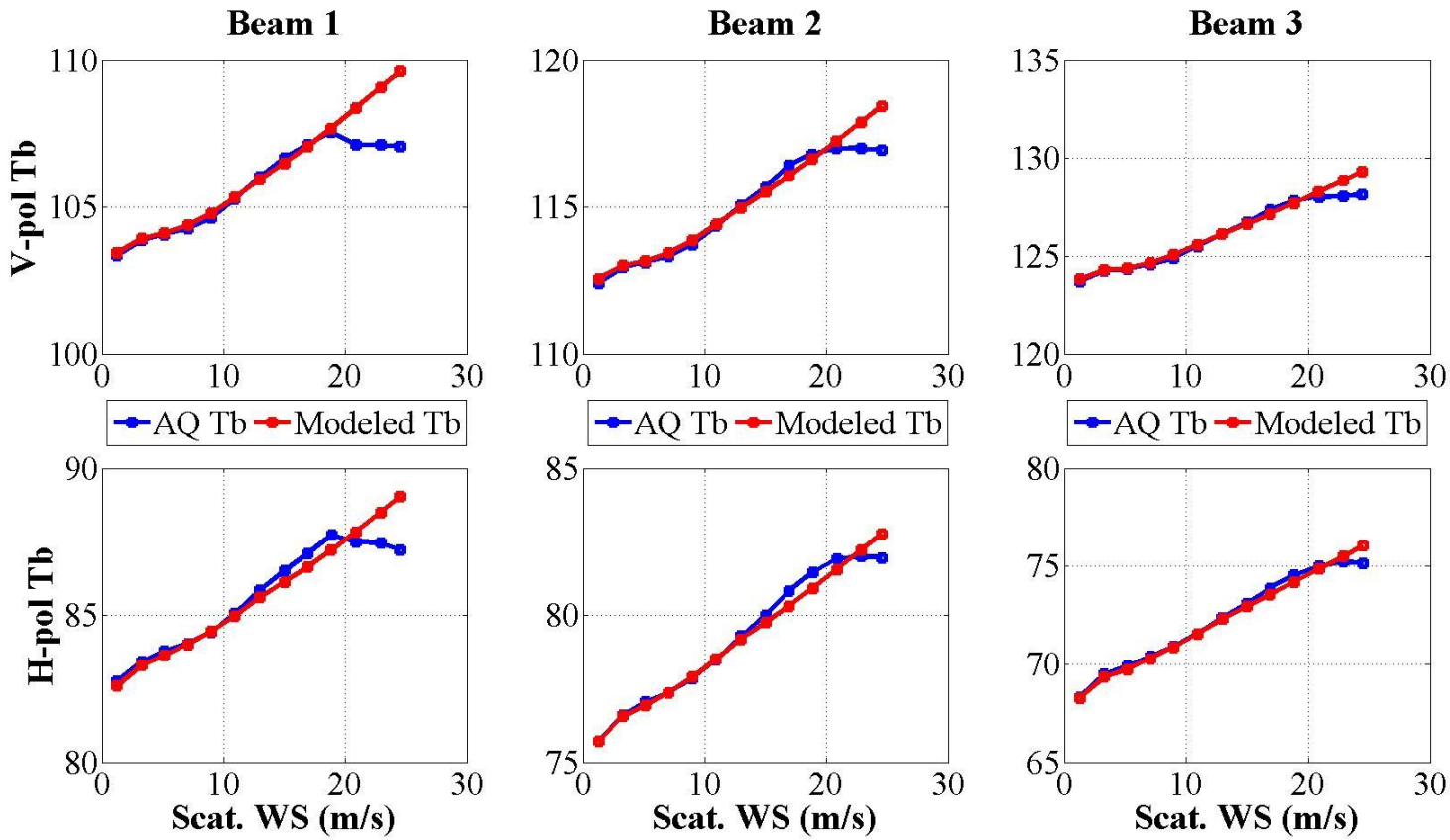


Tuning CFRSL Model for L-Band

- Aquarius dataset used (Level-2 Version 3.0)
  - One year of data: 2012
- Aquarius processing system provides:
  - Ocean Surface Tb_{ocean}
  - Collocated ancillary data
    - NCEP surface wind speed and wind direction
    - Scatterometer wind speed
    - Reynolds Sea Surface Temp (SST)
    - HYCOM Salinity (SSS)
  - Quality flags are provided with the data product
    - Instrumental and calibration flags

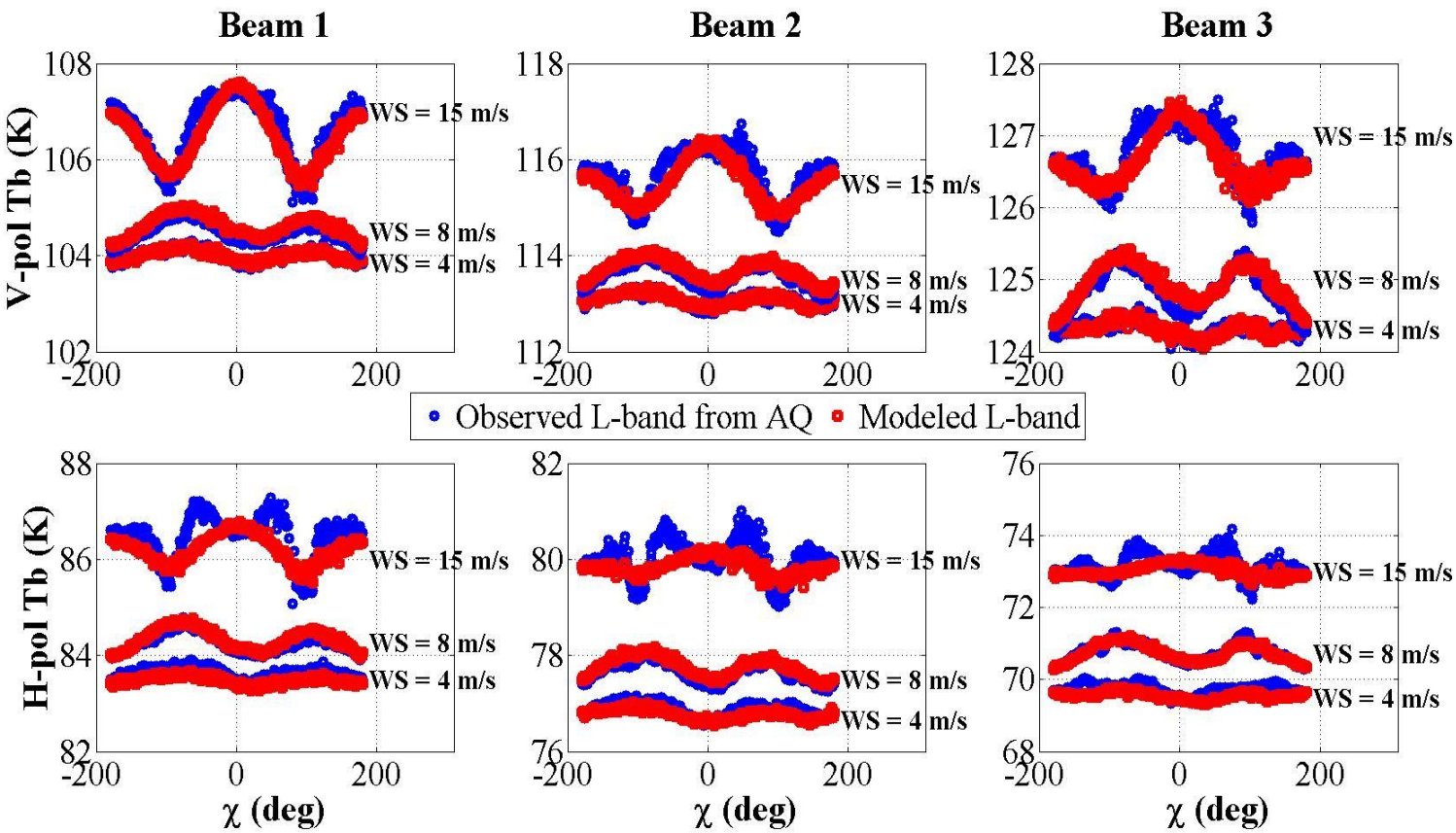
Tuning the RTM for ***WS*** @ L-band

$$Tb_{ocean} = Tb_{smooth} + Tb_{isotropic(WS)} + Tb_{anisotropic(WD)}$$



Tuning the RTM for ***WD*** @ L-band

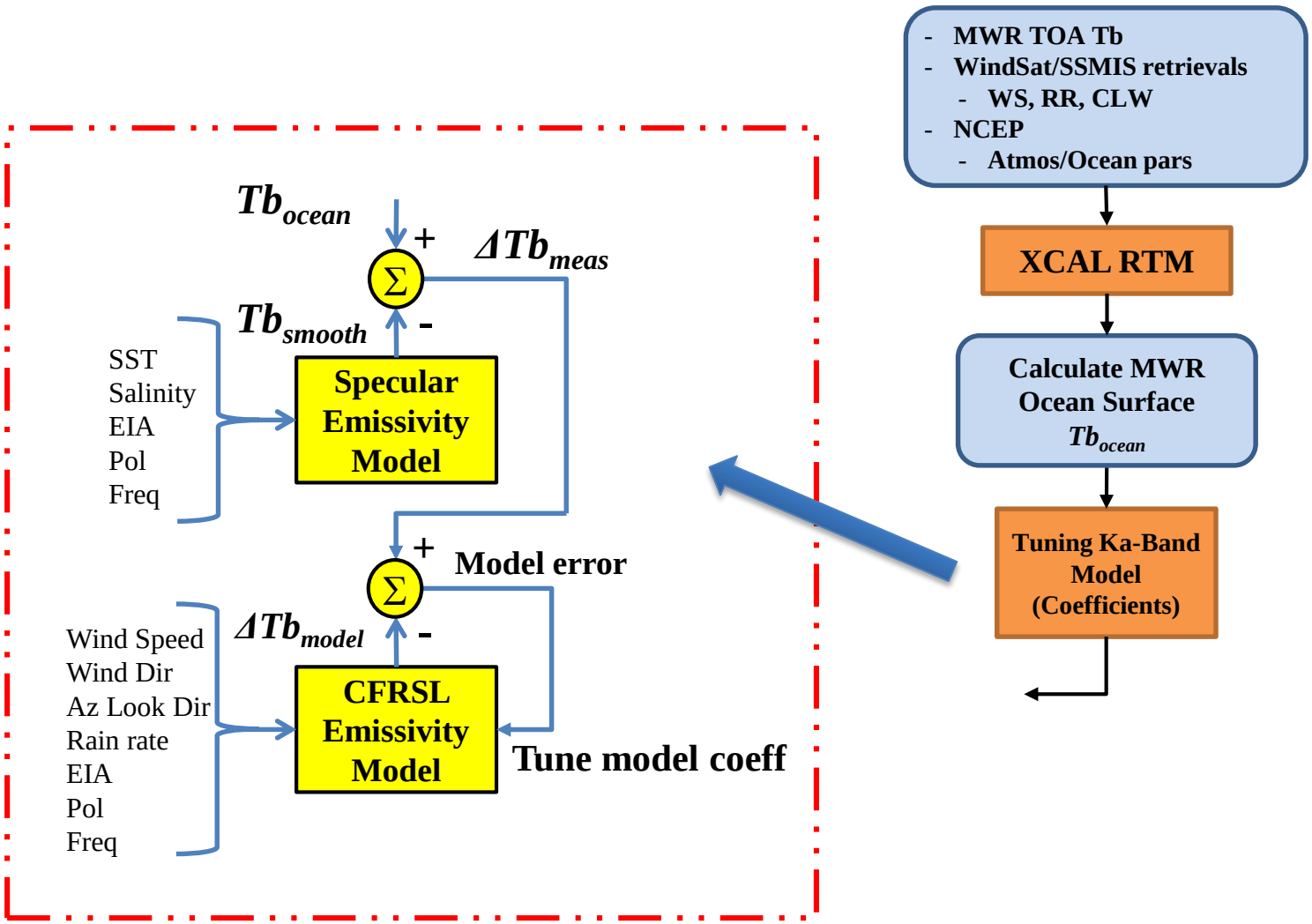
$$Tb_{anisotropic(WD)} = \beta_1 \cos(\chi) + \beta_2 \cos(2\chi)$$



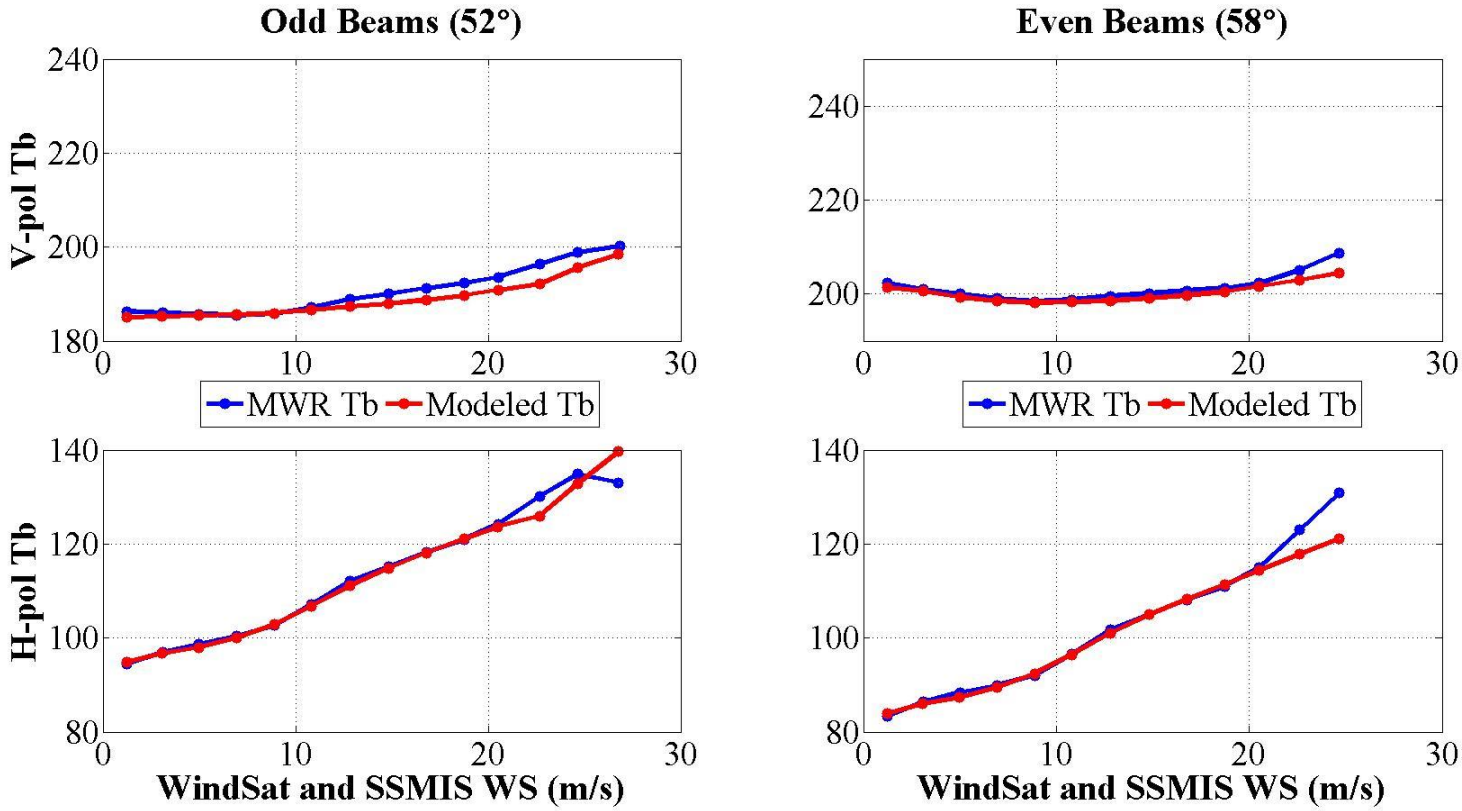
Tuning Model for Ka-Band

- MWR dataset used (Level-1B Version 7.0)
  - 6 months of 2012
- MWR provides Top-of-Atmosphere Tb (Tb TOA)
  - Further processing is required to calculate ***Surface Tb***
  - Further processing is required to provide wind speed and wind direction values

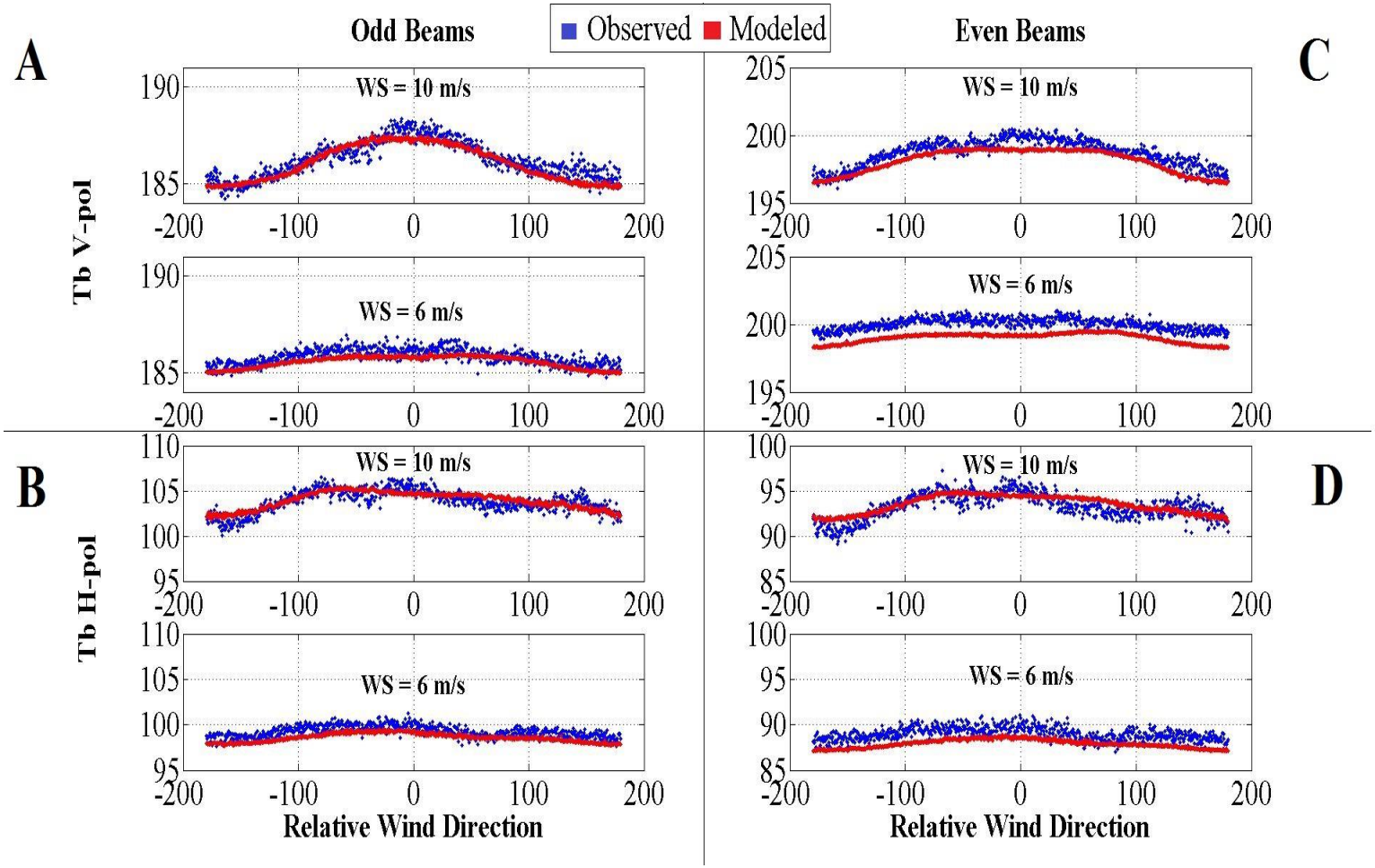
CFRSL RTM Isotropic Tuning Procedure, Ka-band



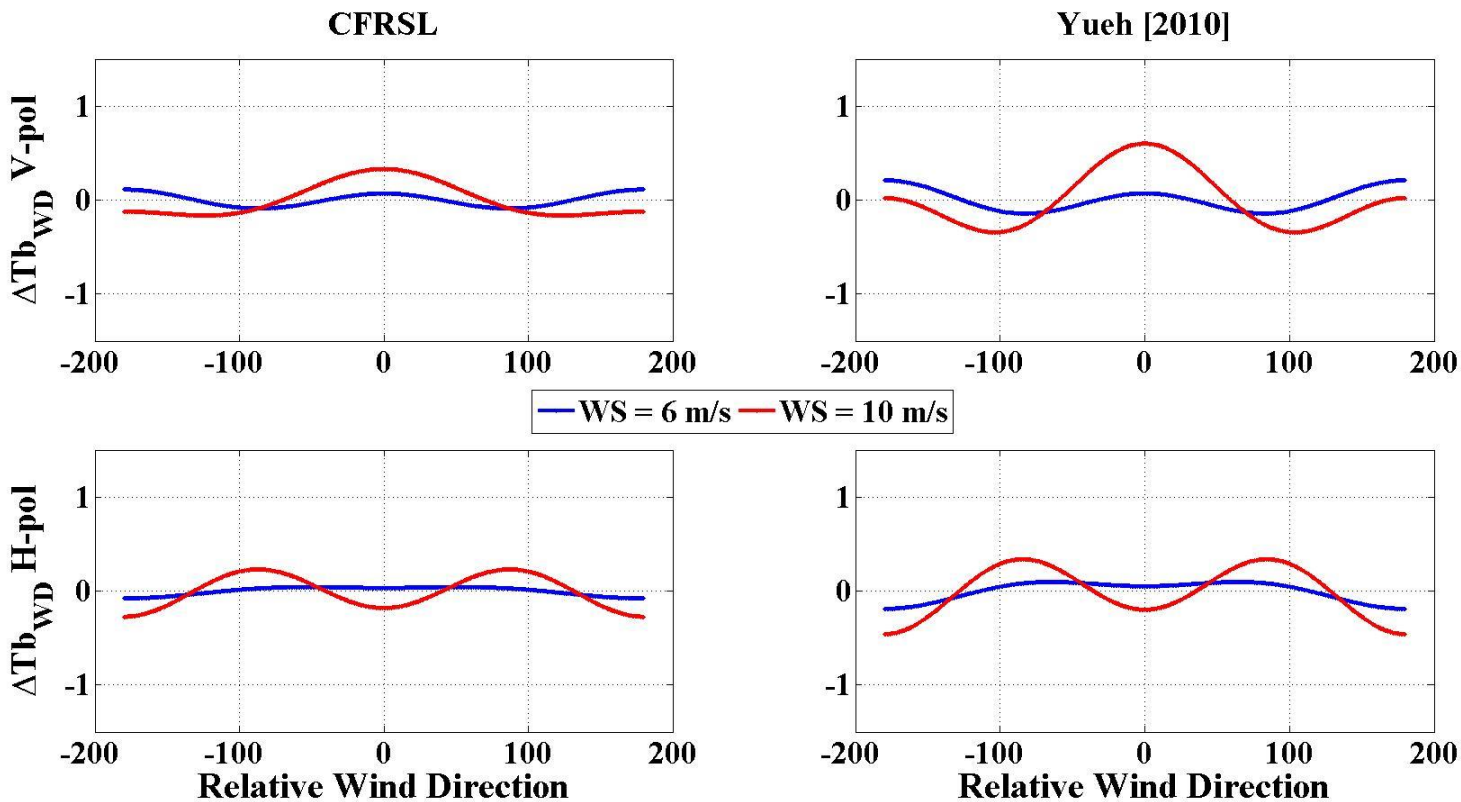
Tuning the RTM for ***WS*** @ Ka-band



Tuning the RTM for ***WD*** @ Ka-band

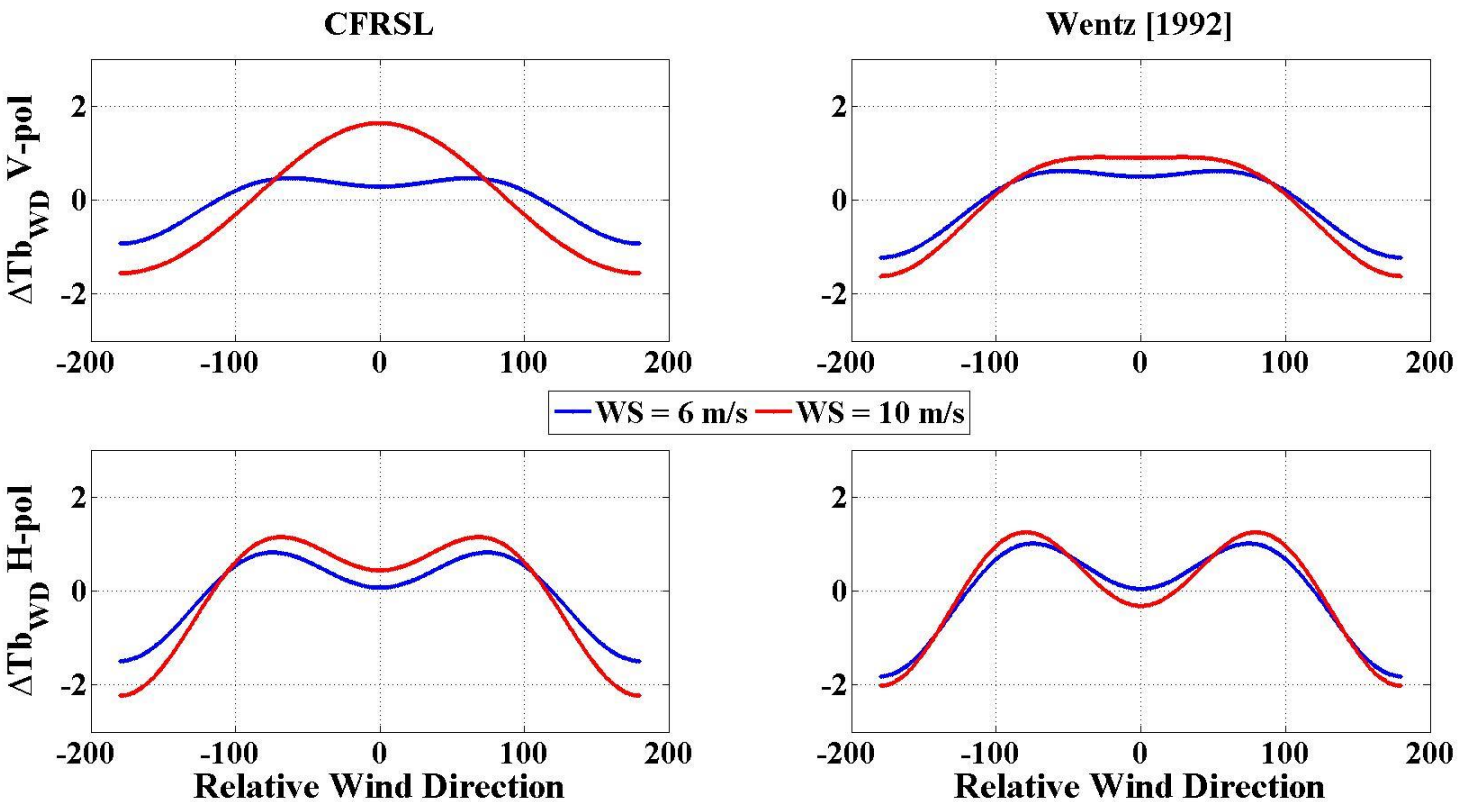


Comparison of Wind Direction Model @ L-band



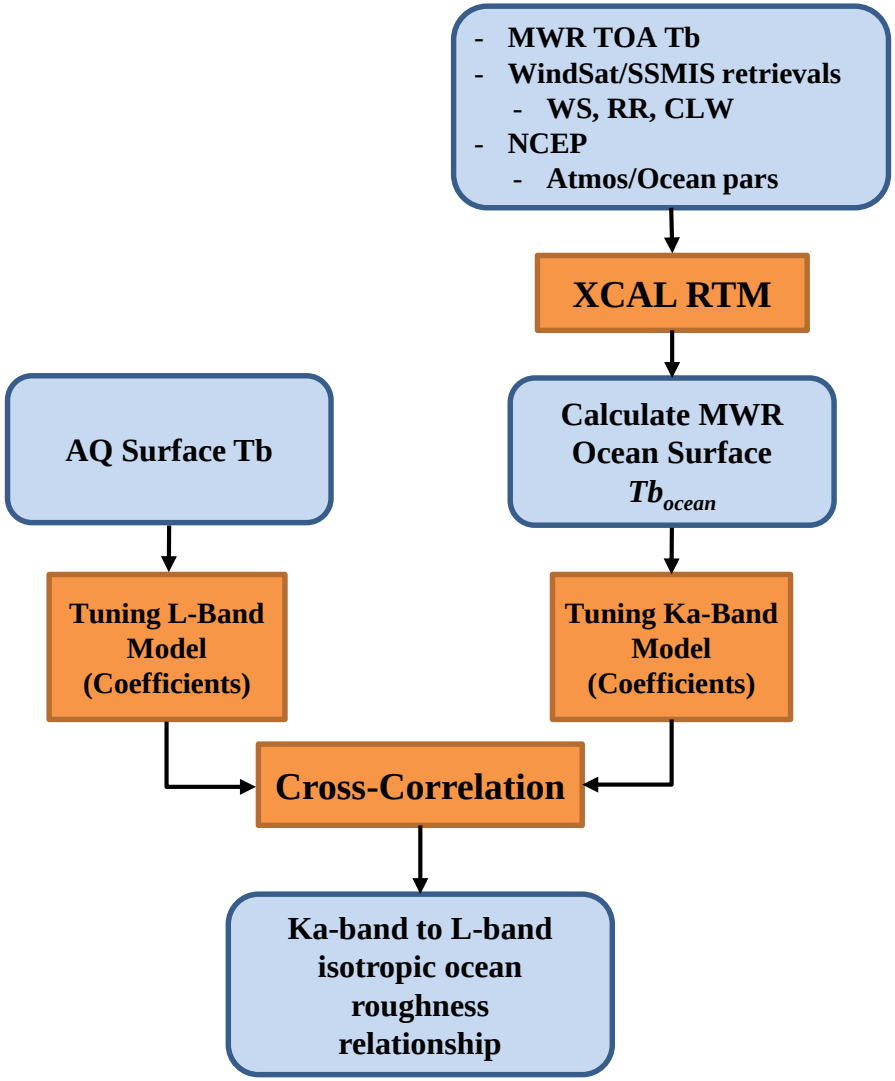
Yueh, S.H., Dinardo, S.J., Fore, A.G., and Fuk, K.L.: 'Passive and Active L-Band Microwave Observations and Modeling of Ocean Surface Winds', Geoscience and Remote Sensing, IEEE Transactions on, 2010, 48, (8), pp. 3087-3100

Comparison of Wind Direction Model @ Ka-band

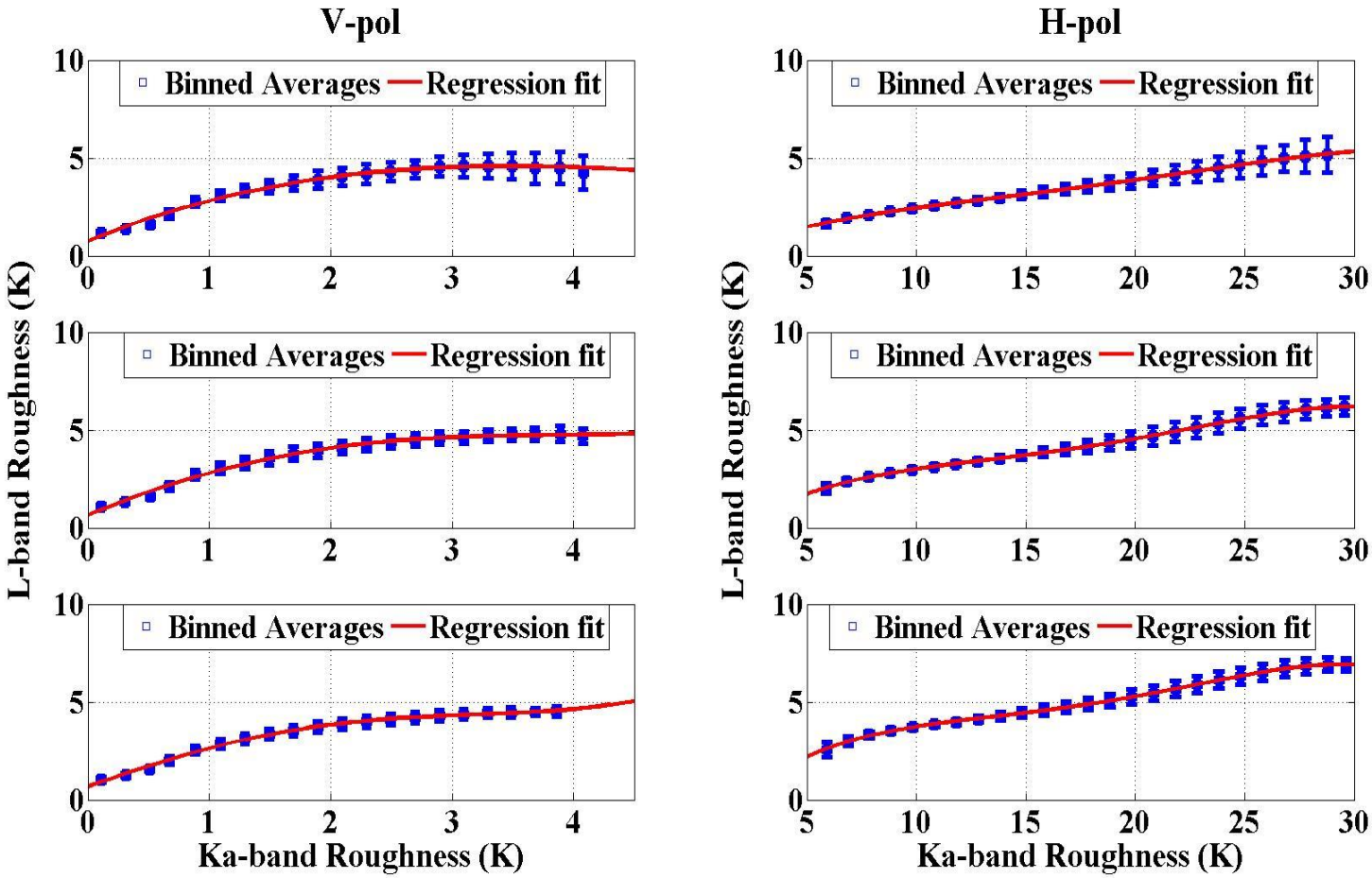


Wentz, F.J.: 'Measurement of oceanic wind vector using satellite microwave radiometers', Geoscience and Remote Sensing, IEEE Transactions on, 1992, 30, (5), pp. 960-972

MWR Isotropic Roughness Correction Procedure



Correlation Between L-Band and Ka-Band Roughness

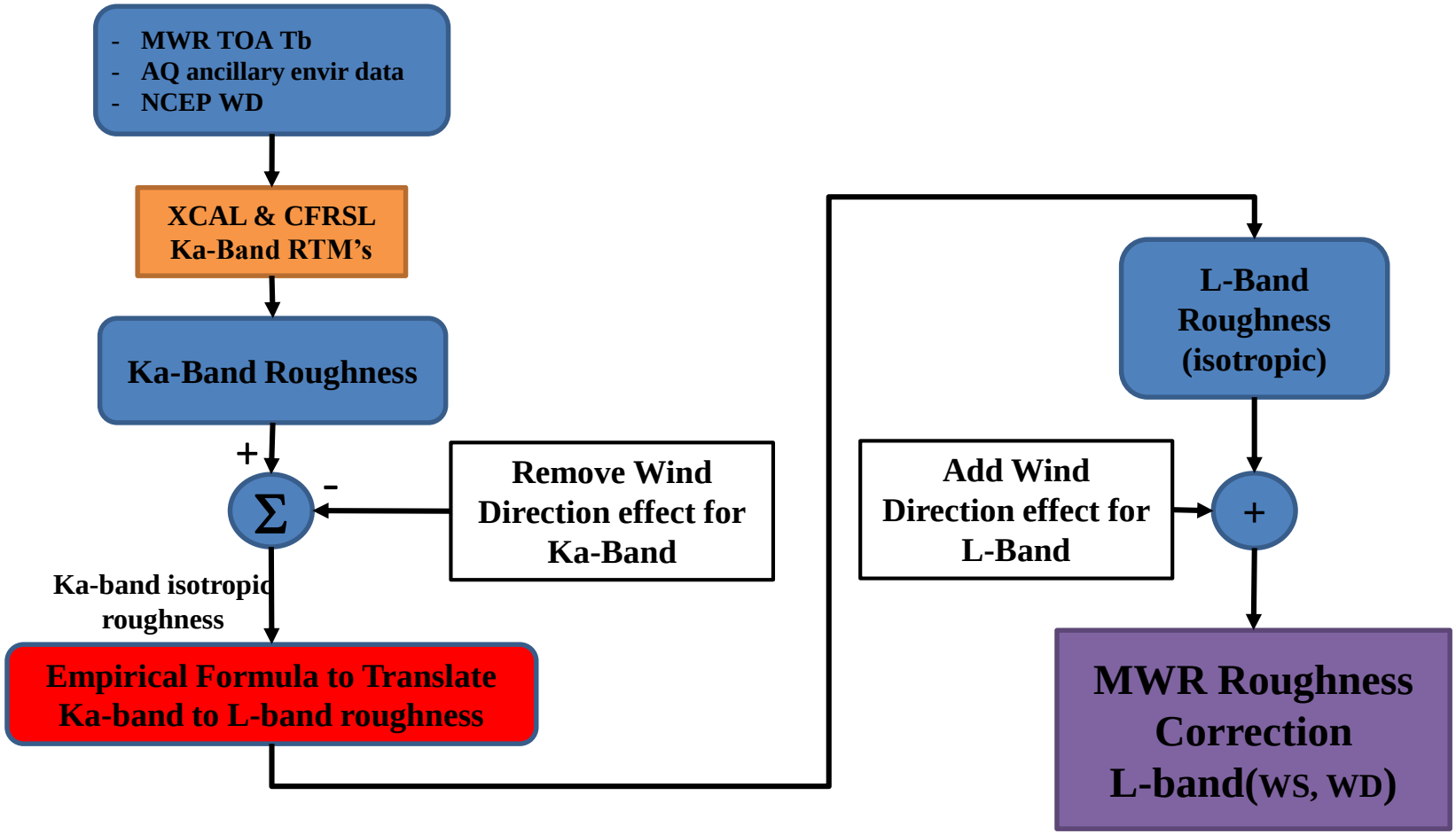


Correlation Between L-Band and Ka-Band Roughness – Incorporating L-band WD Effect

- The Wind Direction effect then is added given the relative wind direction value of the AQ point

$$\Delta Tb_{WS,total} = \Delta Tb_{WS,isotropic} + \Delta Tb_{WD}$$

MWR Roughness Correction Algorithm Flow Chart



Salinity Retrieval Algorithm

- The roughness correction is applied by simply subtracting modeled roughness fro measured surface Tb

$$Tb_{smooth} = Tb_{surf,measured} - \Delta Tb_{WS,WD}$$

- $\boldsymbol{Tb_{smooth}}$ is a function of SSS and SST at a given frequency, polarization and incidence angle
- Salinity is retrieved using the salinity retrieval algorithm used by the AQ team
  - No algorithmic differences

SSS Retrieval Validation

- For AQ validation, salinity retrievals using both ocean roughness correction techniques were compared to HYCOM
  - US Navy/NOAA global ocean salinity model output produced every 24 hours
    - Ingests In-Situ salinity measurements from around the globe
    - Incorporates ocean circulation physics to model the 3D salinity profiles cover the entire globe.
  - The HYCOM global mean salinity provides the reference for salinity
    - AQ will provide improve ocean salinity by higher spatial sampling to improve the HYCOM model

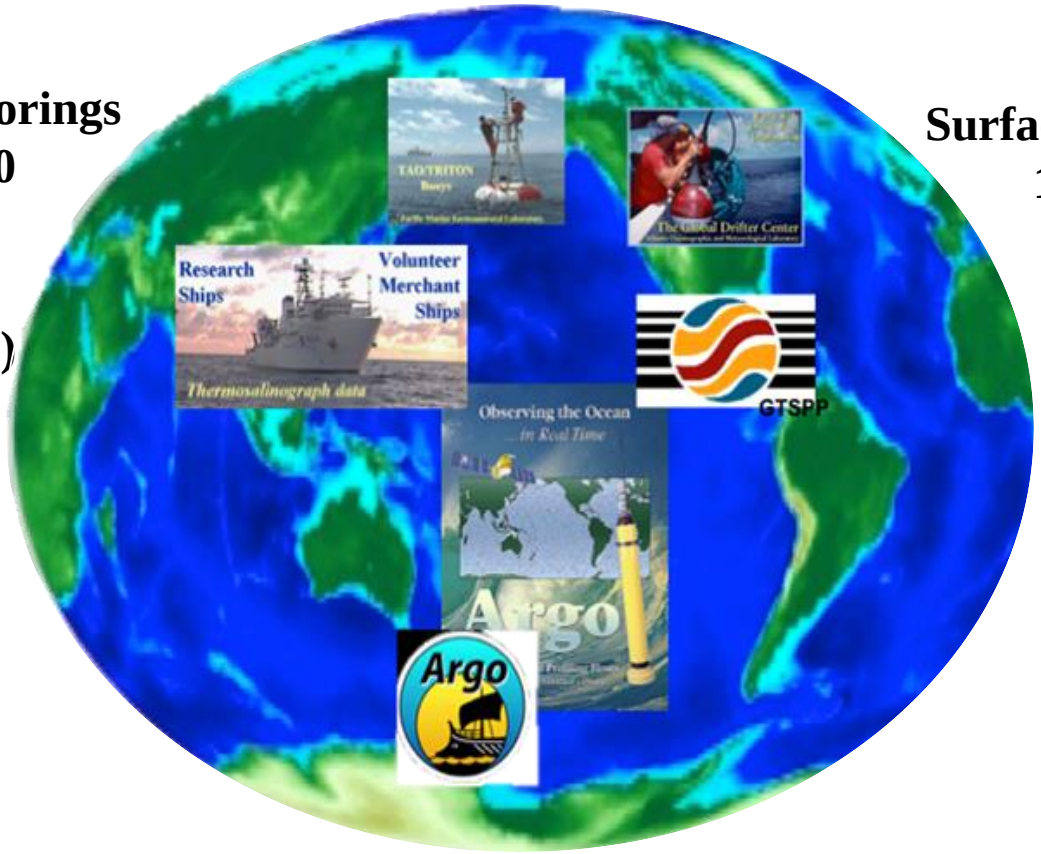
In Situ Data Sources
(Aquarius Validation Data System)

Fixed moorings
1,500

Surface drifters
1,500

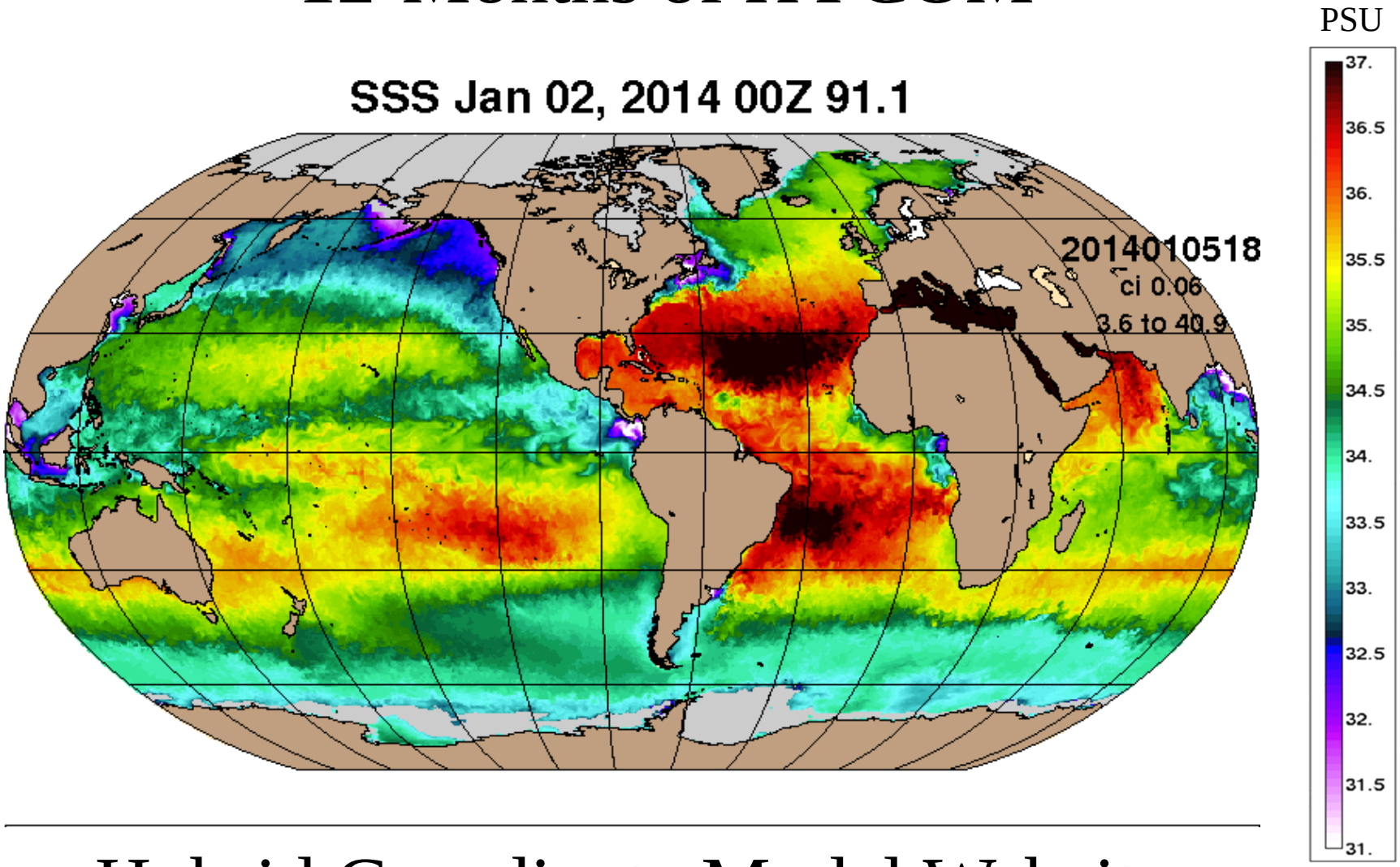
Research ships (TSG)

CTD profiles



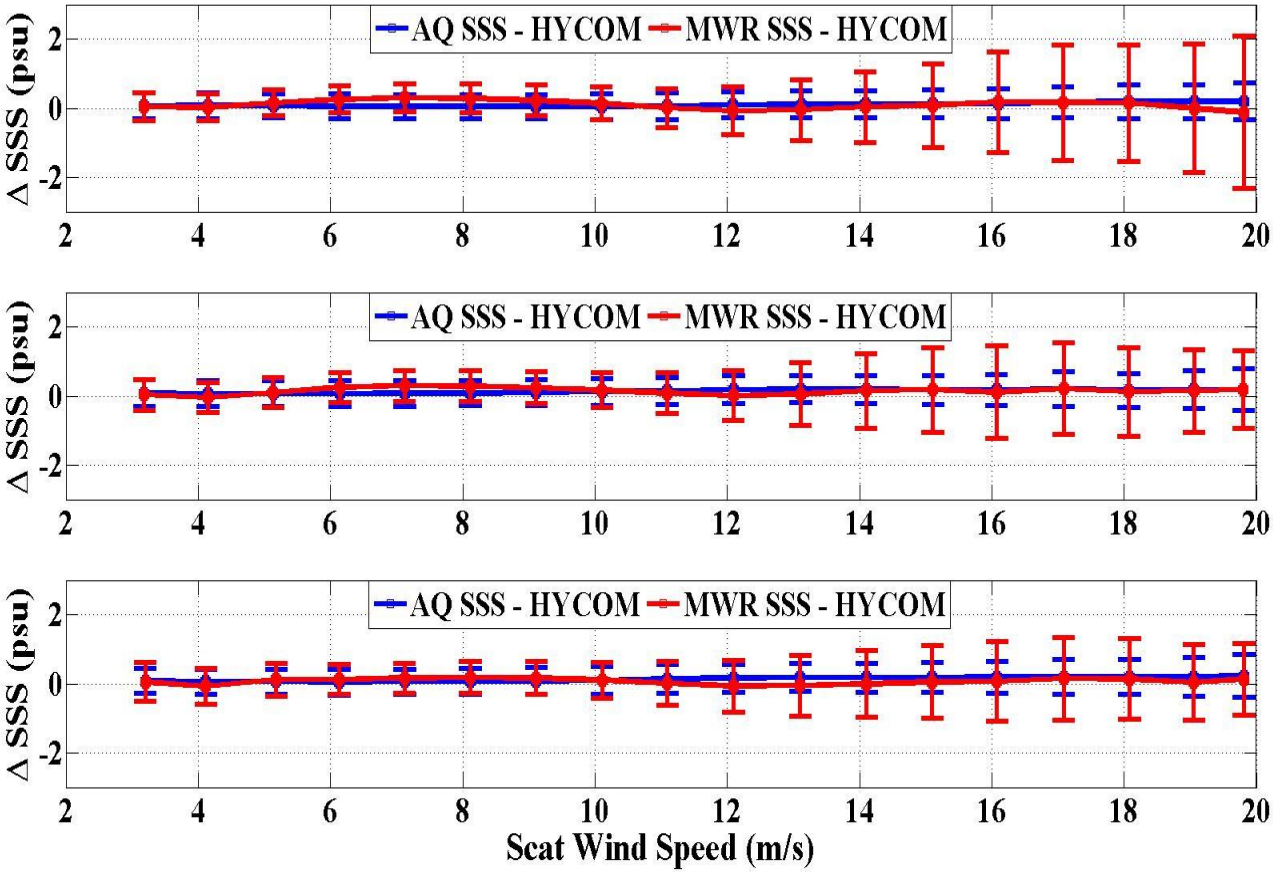
ARGO profile floats
3,000

12-Months of HYCOM



Hybrid Coordinate Model Website

ΔSSS for AQ and MWR Salinity Retrievals

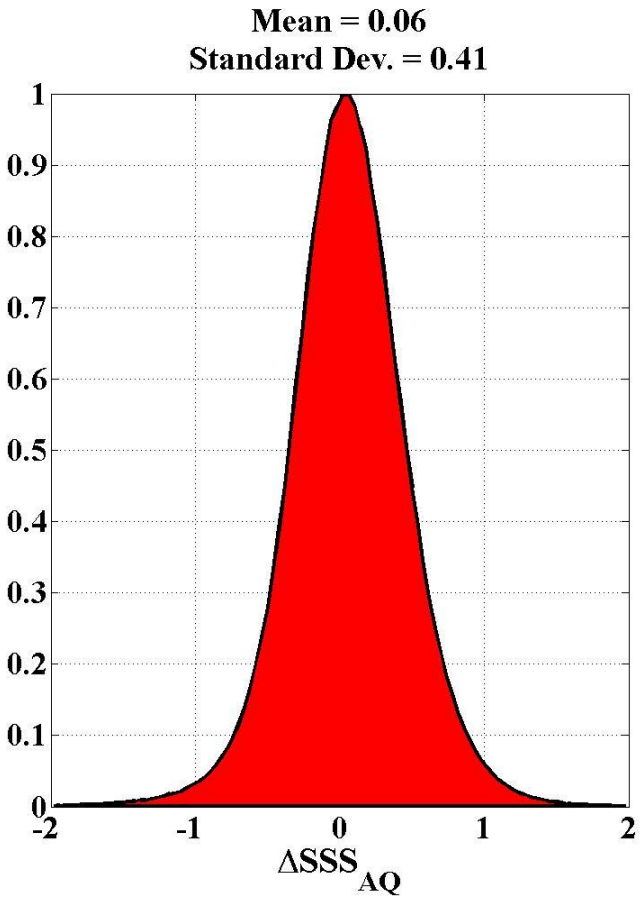


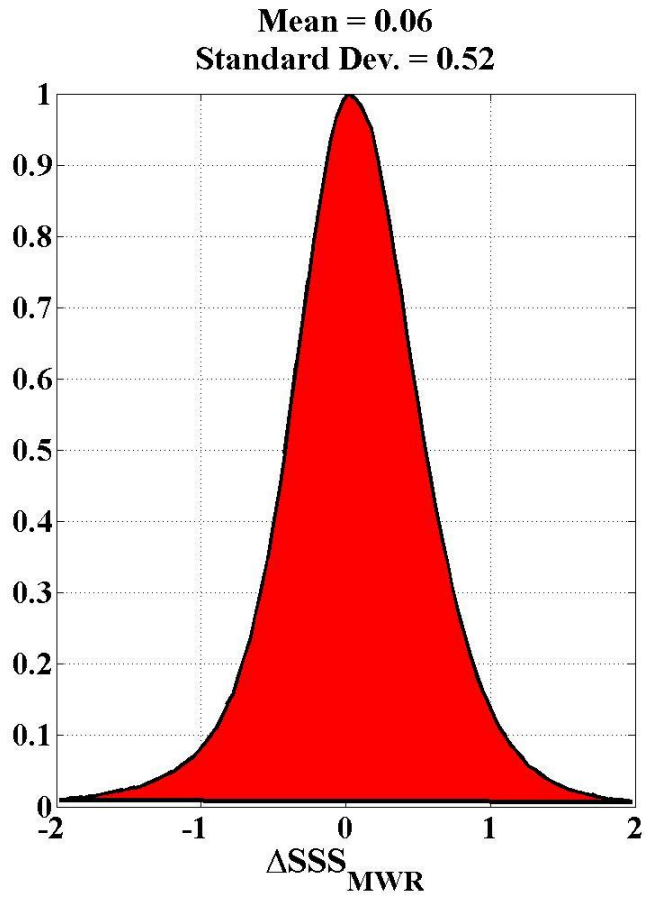
Beam 1

Beam 2

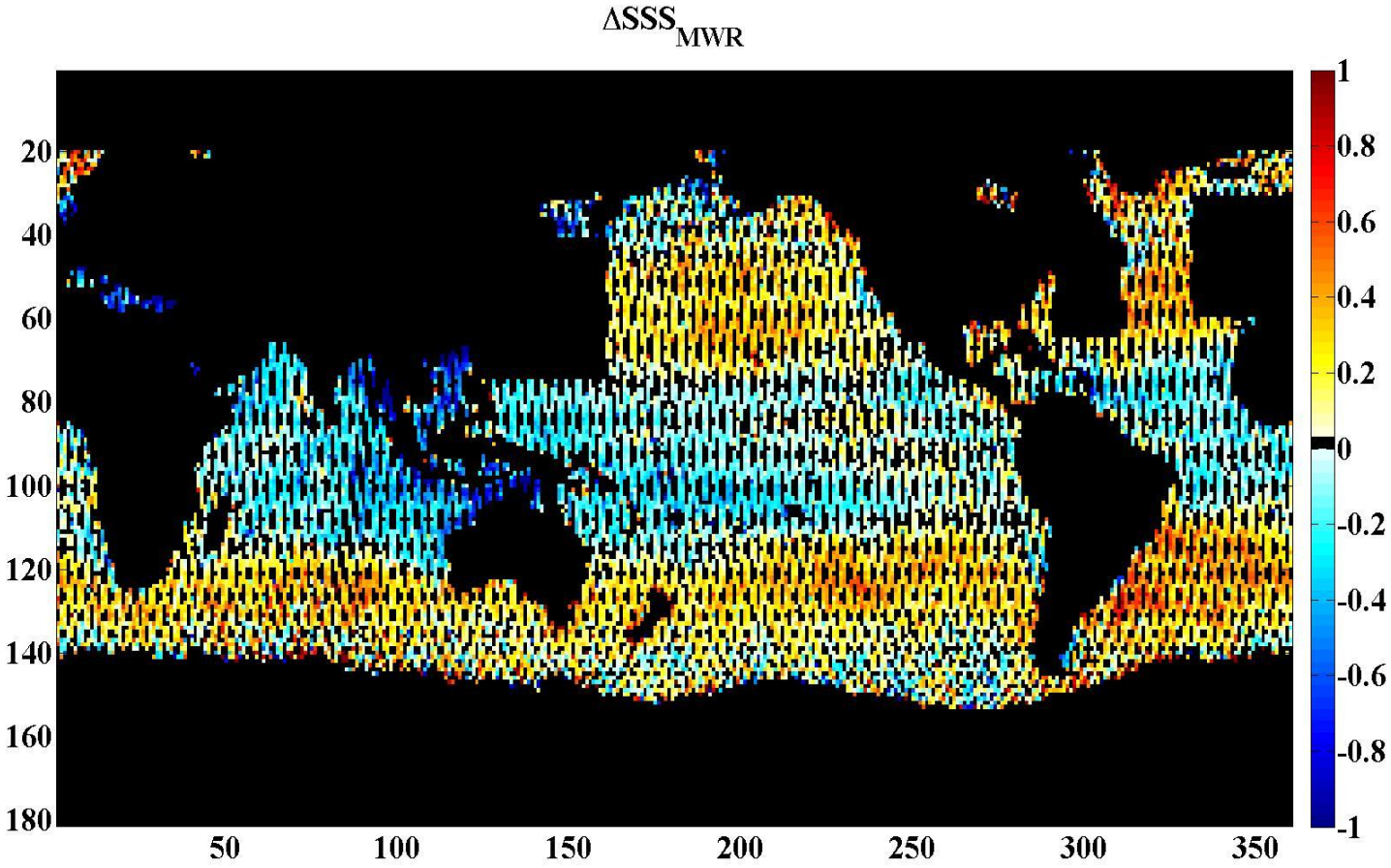
Beam 3

ΔSSS for AQ and MWR Salinity Retrievals (Beam 1)

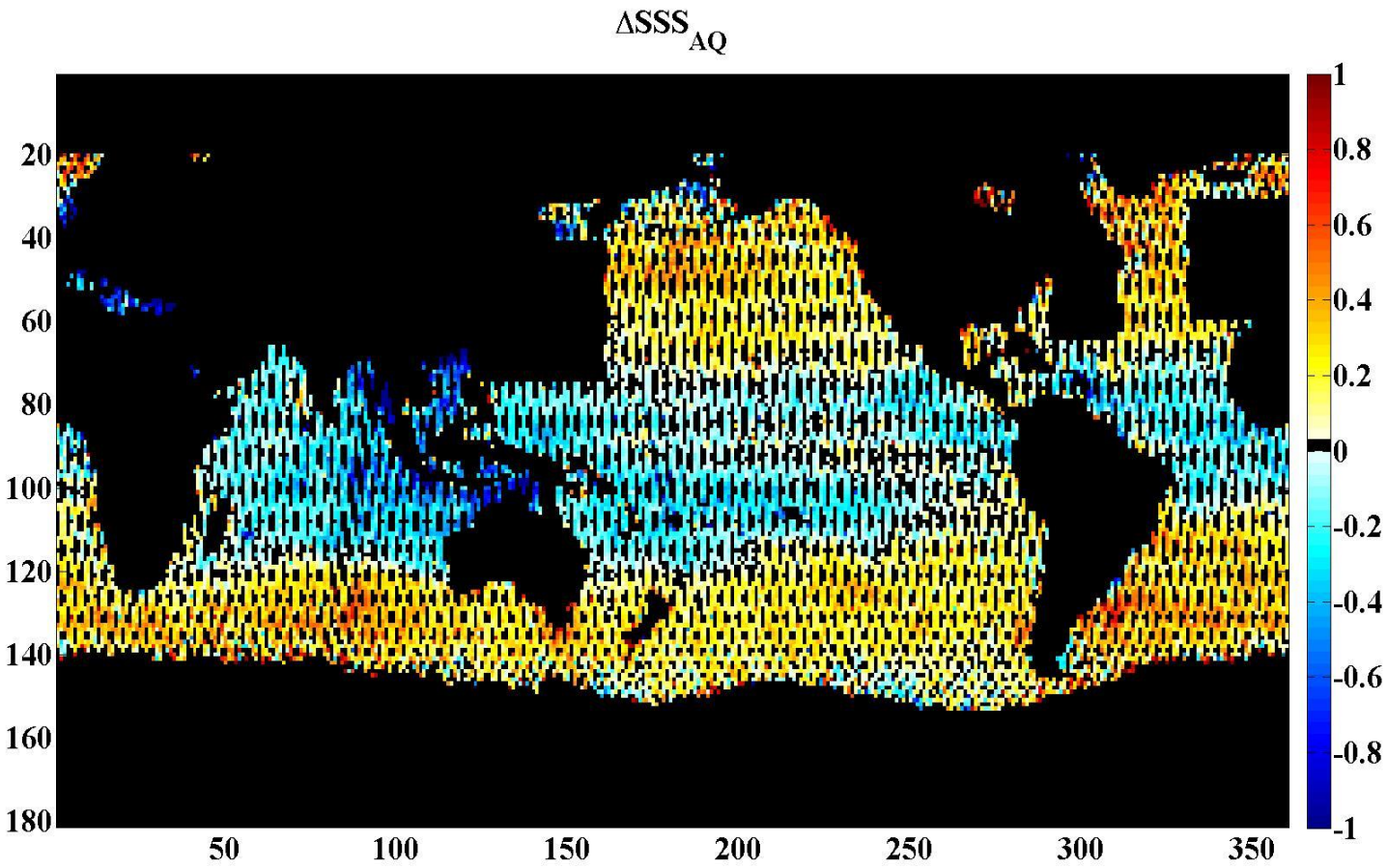




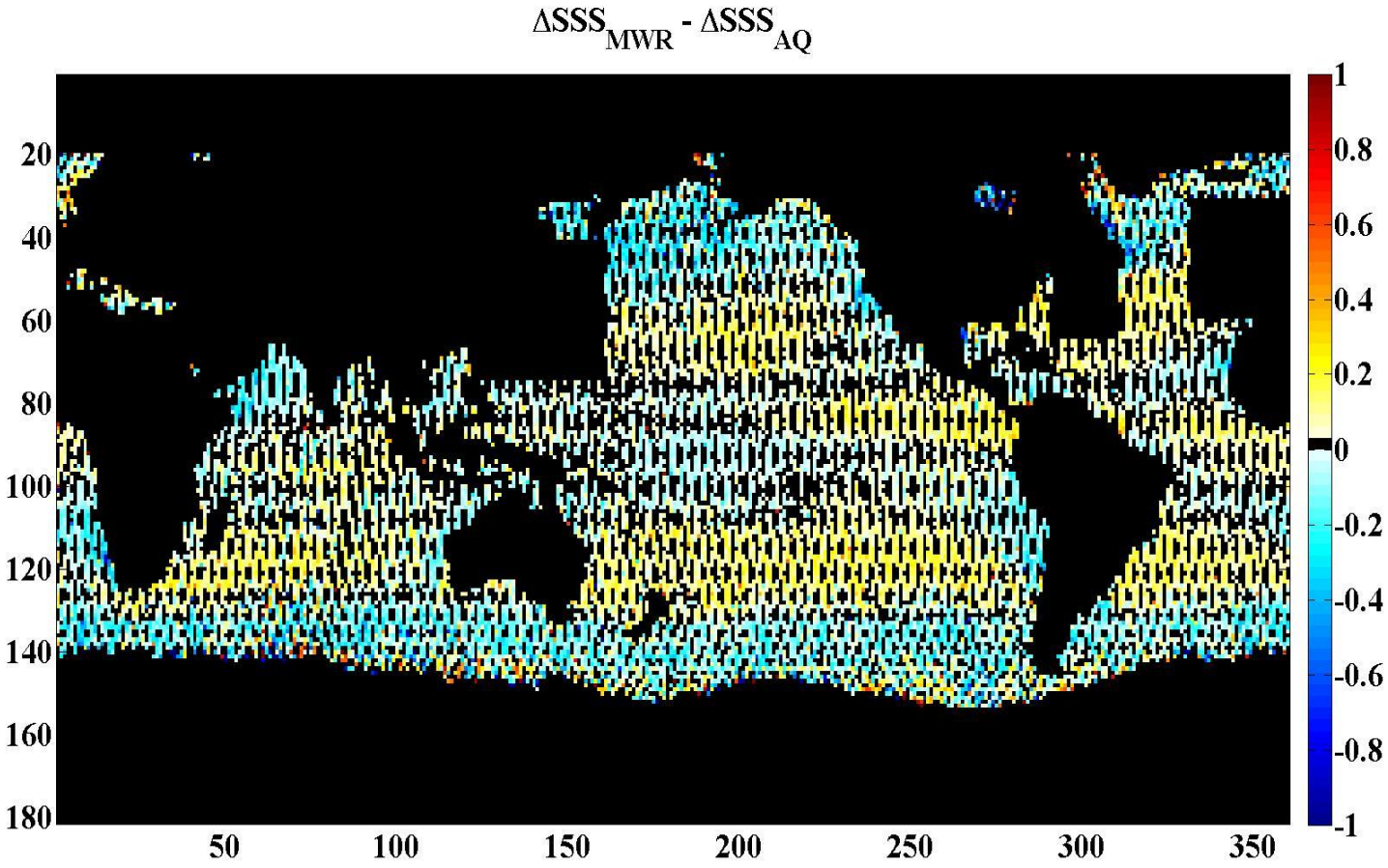
ΔSSS_{MWR} Global Map



ΔSSS_{AQ} Global Map



Double Difference



Standard Deviation = 0.37 psu

Conclusion

- Ocean Surface Emissivity Model was developed using on-orbit data from Aquarius and MicroWave Radiometer instruments
  - Wind Speed
  - Wind Direction
  - Statistical differences between model and observed data are reduced to ~±0.5 K
- Collocated data set was produced
  - Weighted averaging of MWR beams with Aquarius IFOV
- Roughness Correction was used to calculated smooth surface Tb
  - Retrieve Sea Surface Salinity
- Results were compared to baseline roughness
  - No wind speed dependence
  - Results are highly comparable for wind speeds between 0-15 m/s

Future Work

- Since two techniques are independent, future combination between the two will be analyzed
  - Reducing Standard Deviation
- Provided CONAE and the science team with data product
  - Approximately 3 years of MWR data (Roughness)
- Include tuning of the Foam Emissivity part of CFRSL Model

Conference Papers

1. **Hejazin, Y**.; Jones, W.L.; El-Nimri, S., "A roughness correction algorithm for aquarius using MWR," Microwave Radiometry and Remote Sensing of the Environment (MicroRad), 2014 13th Specialist Meeting on , vol., no., pp.44,48, 24-27 March 2014
2. Santos-Garcia, A.; Ebrahimi, H.; **Hejazin, Y**.; Jacob, M.M.; Jones, L.; Asher, W.E., "Application of the AQ rain accumulation product for investigation of rain effects on AQ Sea Surface Salinity measurements," Microwave Radiometry and Remote Sensing of the Environment (MicroRad), 2014 13th Specialist Meeting on , vol., no., pp.72,77, 24-27 March 2014
3. **Hejazin, Y**.; Aslebagh, S.; Jones, W.L., "Aquarius/SAC-D MicroWave Radiometer ocean wind speed measurements," Oceans, 2012 , vol., no., pp.1,4, 14-19 Oct. 2012
4. **Hejazin, Y**.; Jones, W.L.; El-Nimri, S., "An ocean roughness correction algorithm for retrieving salinity on Aquarius," Oceans, 2012 , vol., no., pp.1,3, 14-19 Oct. 2012
5. Aslebagh, S.; **Hejazin, Y**.; Jones, W.L.; May, C.; Gonzalez, R., "An oceanic rain flag for Aquarius," Oceans, 2012 , vol., no., pp.1,4, 14-19 Oct. 2012
6. Jones, W.L.; **Hejazin, Y**.; El-Nimri, S., "Sea surface salinity roughness correction at L-band for Aquarius instrument," Geoscience and Remote Sensing Symposium (IGARSS), 2013 IEEE International , vol., no., pp.660,663, 21-26 July 2013
7. Ghazi, Z.; Biswas, S.; Jones, L.; **Hejazin, Y**.; Jacob, M.M., "On-orbit signal processing procedure for determining Microwave Radiometer non-linearity," Southeastcon, 2013 Proceedings of IEEE , vol., no., pp.1,5, 4-7 April 2013
8. **Hejazin Y**., Jones L. El-Nimri S., "Development of a L-band ocean emissivity electromagnetic model using observations from the Aquarius Radiometer", AGU Fall Meeting, 2012
9. Jones L., **Hejazin Y**., Rabolli M., "Improved Sea Surface Salinity Retrievals using Ancillary data for Aquarius Ocean Roughness Correction", AGU Fall Meeting, 2012
10. Tauro C., Etala P., Echevarría P., **Hejazin Y**., Jacob M. M., Jones L., "Results and validation of marine surface wind speed obtained from SAC-D/Aquarius MWR", AGU Fall Meeting , 2012
11. Jones L. Gallo J., Rocca D., Rabolli M., Madero F., Kuba J., Masuelli S., Heredia S. D., Biswas S. K., **Hejazin Y**., "First Results from the Microwave Radiometer (MWR) on Aquarius/SAC-D", AGU Fall Meeting, 2011
12. Heredia, S. D., Jones L., **Hejazin Y**., Masuelli S., Jacob M. M., "Water Vapor and Rain Rate Retrievals Algorithms – Validation", AGU Fall Meeting, 2012

Journals

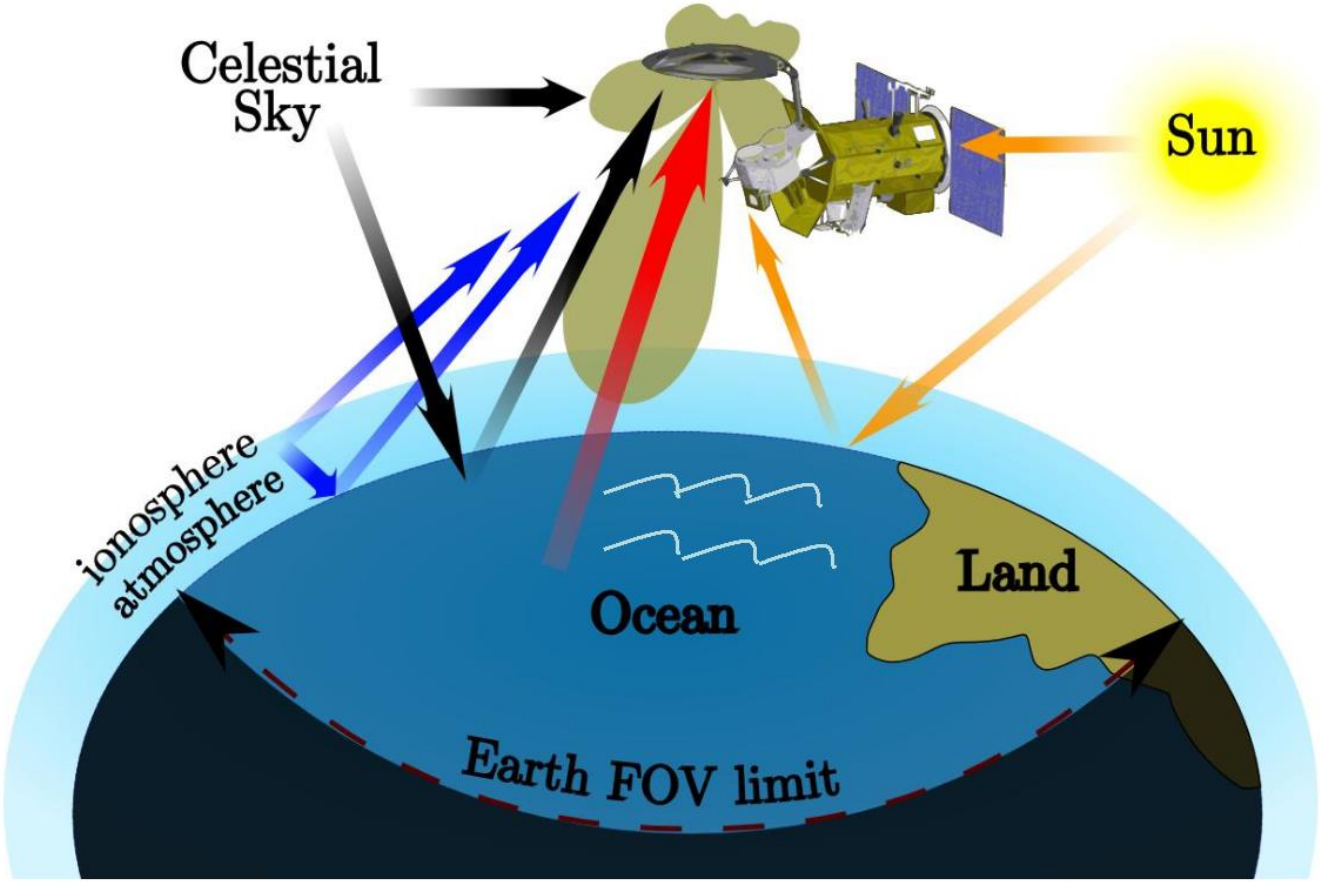
- **<u>Published</u>**
  - Santos-Garcia, A., M. M. Jacob, W. L. Jones, W. E. Asher, **Y. Hejazin**, H. Ebrahimi, and M. Rabolli (2014), Investigation of rain effects on Aquarius Sea Surface Salinity measurements, J. Geophys. Res. Oceans, 119
- **<u>Accepted with Reviews</u>**
  - **Hejazin, Y**.; Jones, W. L.; Santos-Garcia, A.; Jacob, M.M.; El-Nimri, S., "A roughness correction for Aquarius using the CONAE MicroWave Radiometer, " Geoscience and Remote Sensing, *IEEE* Transactions, Accepted January 2015
- **<u>Submitted and Pending</u>**
  - Tauro, C.; **Hejazin, Y**.; Jacob, M.M.; Jones, W.L., "An algorithm for sea surface wind speed from SAC-D/Aquarius MicroWave Radiometer, " Geoscience and Remote Sensing, *IEEE* Transactions, Submitted January 2015

Thank You

Bckup Slides

Major Sources of Tb Error

- There are 12 major sources of Tb measurement error
  - 6 must be corrected using auxiliary data

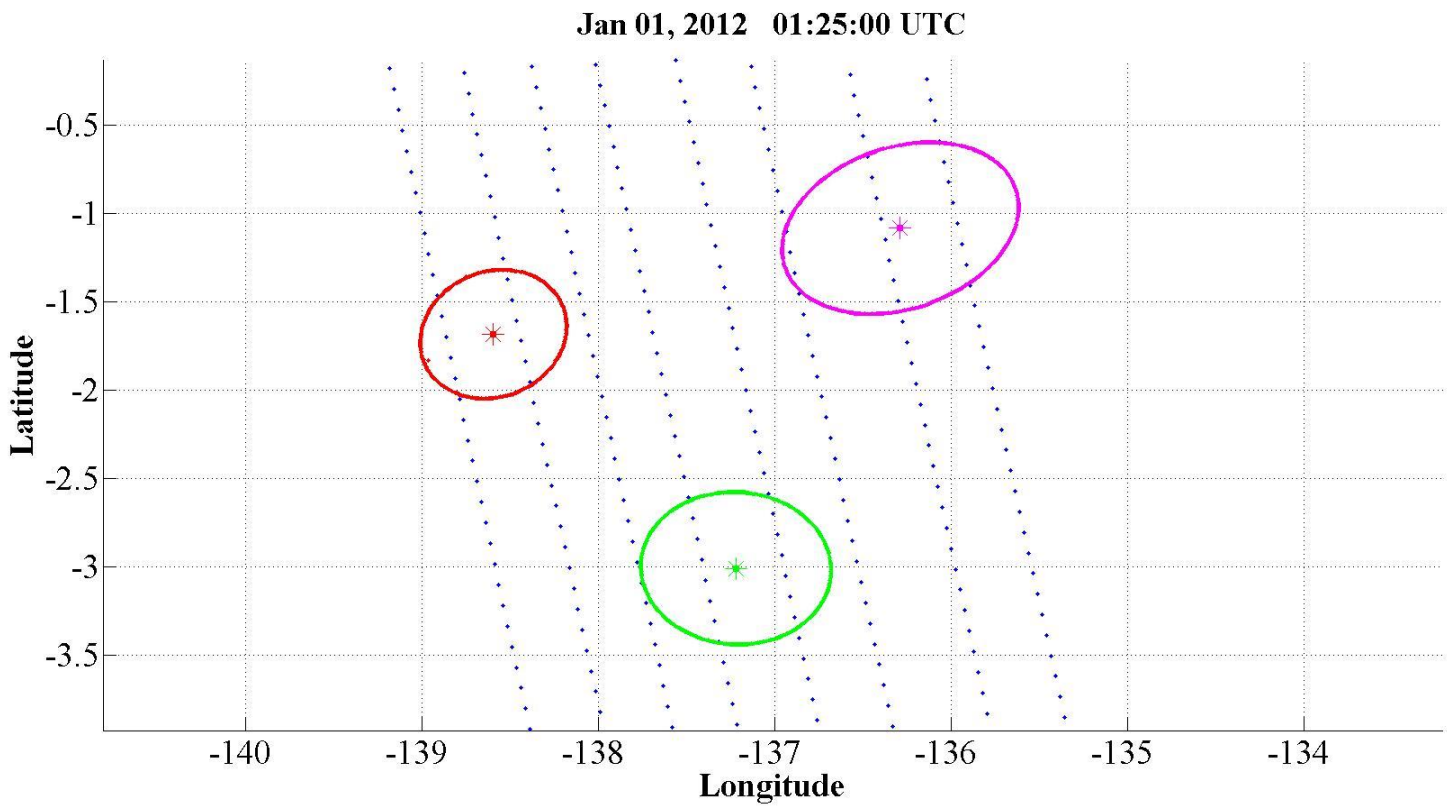


Error Sources

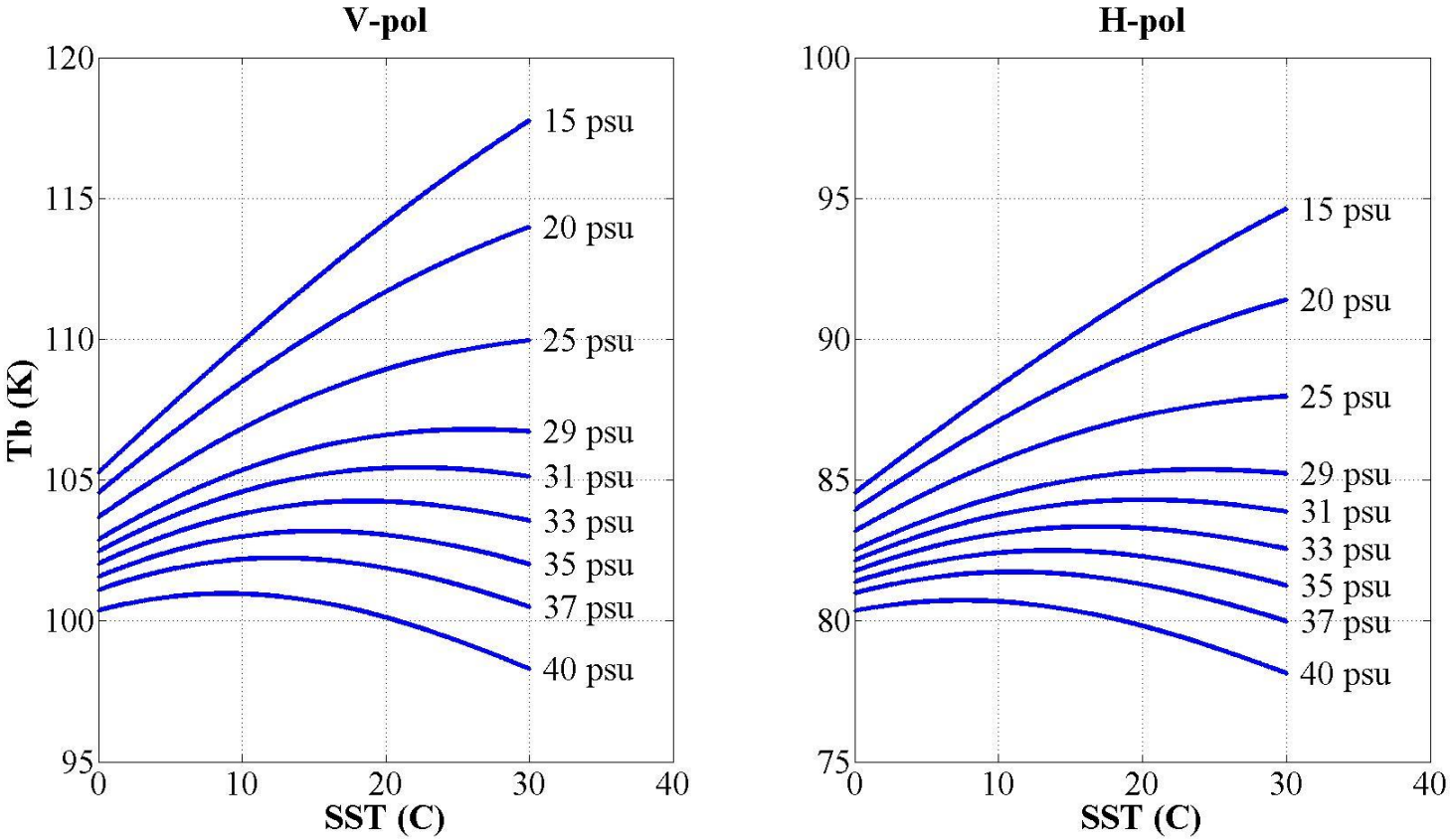
Mission CDR July 2008

Error Sources	3 Beam RMS	
	Allocation	CBE
Radiometer	0.15	0.11
Antenna	0.08	0.01
System Pointing	0.05	0.02
Roughness	0.28	0.12
Solar	0.05	0.02
Galactic	0.05	0.04
Rain (Total Liquid Water)	0.02	0.01
Ionosphere	0.06	0.05
Atmosphere - other	0.05	0.02
SST	0.10	0.07
Antenna gain near land & ice	0.10	0.10
Model Function	0.08	0.07
Brighness Temperature Error per Observation	Baseline Mission	
	Allocation	CBE
Total RSS (K)	0.38	0.23

Averaging MWR in AQ IFOV



Specular Emissivity



Tuning the CFRSL RTM

- Adding relative wind direction effect model

$$\Delta \boldsymbol{Tb_{WD}} = \boldsymbol{\beta_1} \times \mathbf{cos}(\boldsymbol{\chi}) + \boldsymbol{\beta_2} \times \mathbf{cos}(\mathbf{2}\boldsymbol{\chi})$$

- Changing the coefficients of the roughness model to reduce the RMS difference between modeled surface Tb and measured surface Tb

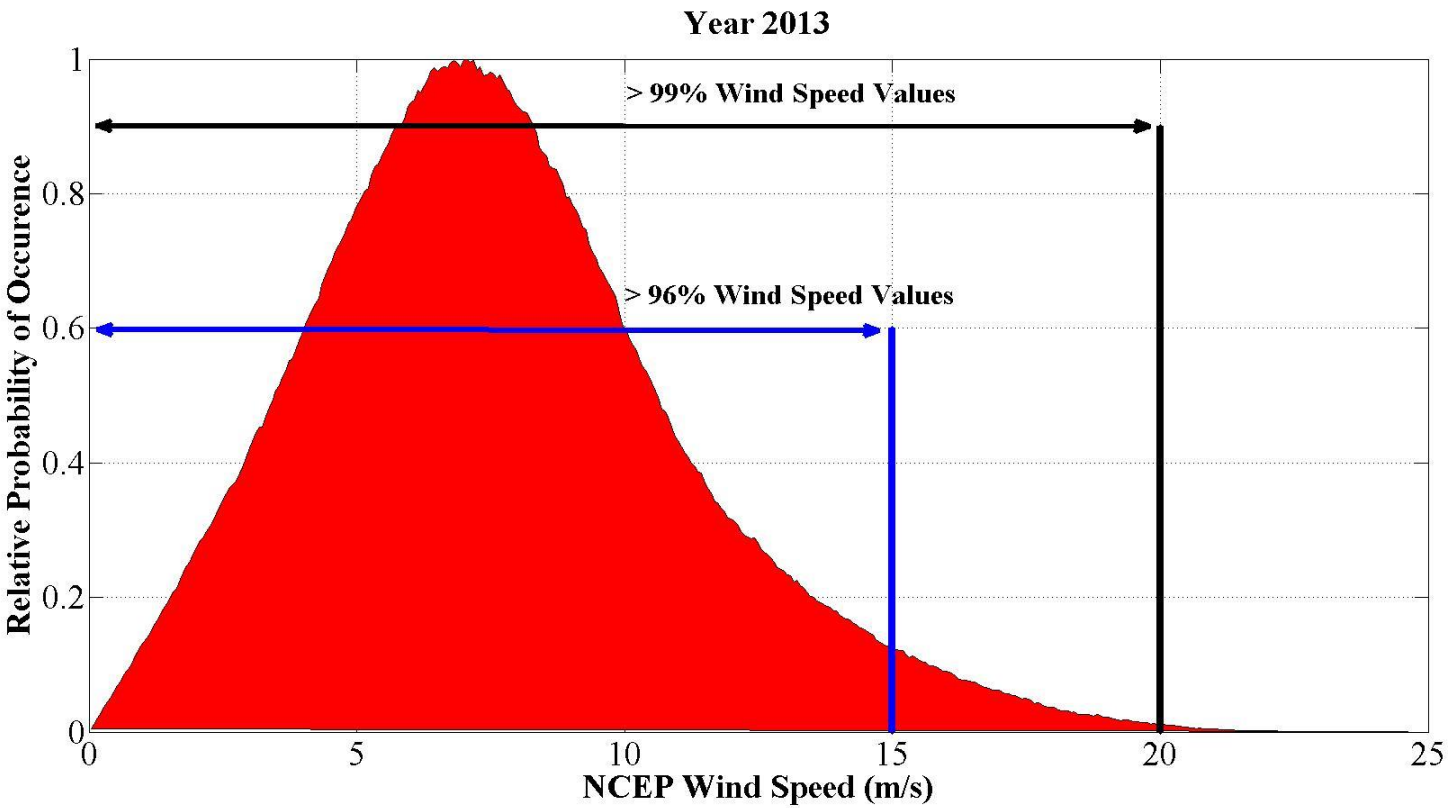
$$\boldsymbol{RMS} = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - \boldsymbol{y_i})^2}{\boldsymbol{n}}}$$

- Tuning done separately for L-band and Ka-band
  - Tuning was done using the statistical algorithm that works for the majority of points

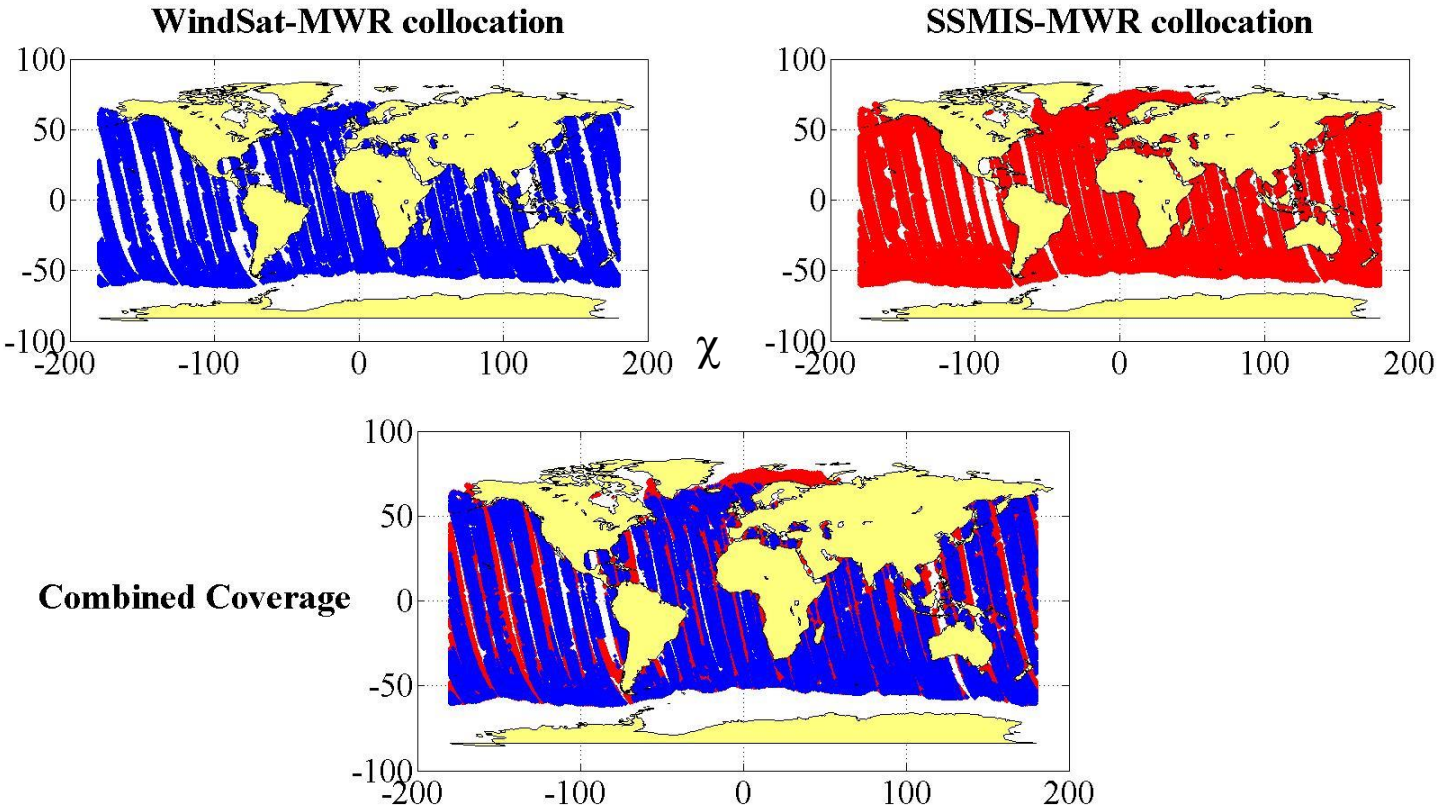
Tuning Model for Ka-Band – cont.

- MWR data is collocate with the environmental data from The National Centers for Environmental Prediction (NCEP)
  - Environmental data used to calculate T_{up}, T_{down} and atmospheric transmissivity (τ)
    - Previously developed X-CAL RTM [Sayak 2013]
- MWR data is collocated with two other satellite instruments to provide wind speed, wind direction and rain rate values
  - WindSat
  - Special Sensor Microwave Imager Sounder (SSMIS)

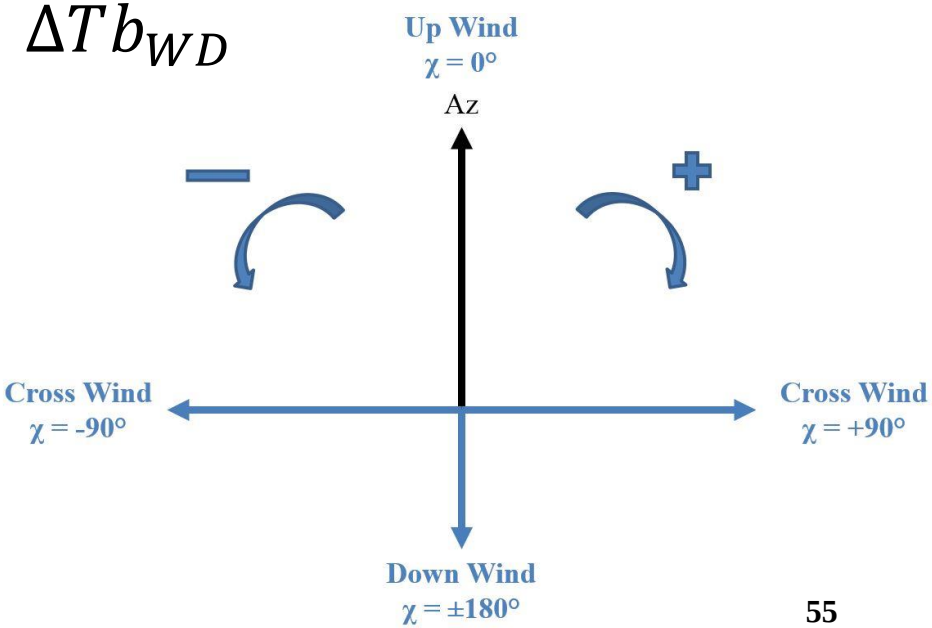
Histogram of Global Wind Speeds



MWR Collocated Data Set
(1 Week of Ascending Passes)



Collocating with two instruments for abundancy

Correlation Between L-Band Roughness and Ka-Band Roughness

- Due to difference in geometry, the wind direction affects each points differently depending on the azimuth angle of the beam
- This effect was subtracted from the model before find the correlation
- $Tb_{surf,isotrpic} = Tb_{surf} - \Delta Tb_{WD}$