Inter-Satellite Microwave Radiometer Calibration

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CFRSL

Outline

- Introduction and Objective
- Satellites and Collocation
- Radiative Transfer Model
- Taylor Series Expansion Prediction
- Results of Inter-Satellite Calibration
- Summary

Introduction of Topic

- Satellite Constellation
  - Short/long term environmental variation; numeric climate model
  - Environmental changes + instrument errors (design + aging)
  - T_b differences between instruments; lifetime calibration consistency of each sensor
- Radiometer Systematic Error Sources
  - Hot load: temperature unstable; change in emissivity
  - Cold load: main reflector spill over; earth interception; degradation of reflector surface
  - Antenna pattern correction algorithm
  - Radiometric noise from receiver
- Post-launch Cross Calibration (Objective: sub-Kelvin)
  - <u>Between normalized simultaneous and collocated measurements</u>
  - To ground based radiometers
  - To Radiative Transfer Model (RTM) simulations
  - On intermediate environmental retrievals, e.g. sea surface temperature

Inter Satellite Calibration Challenges

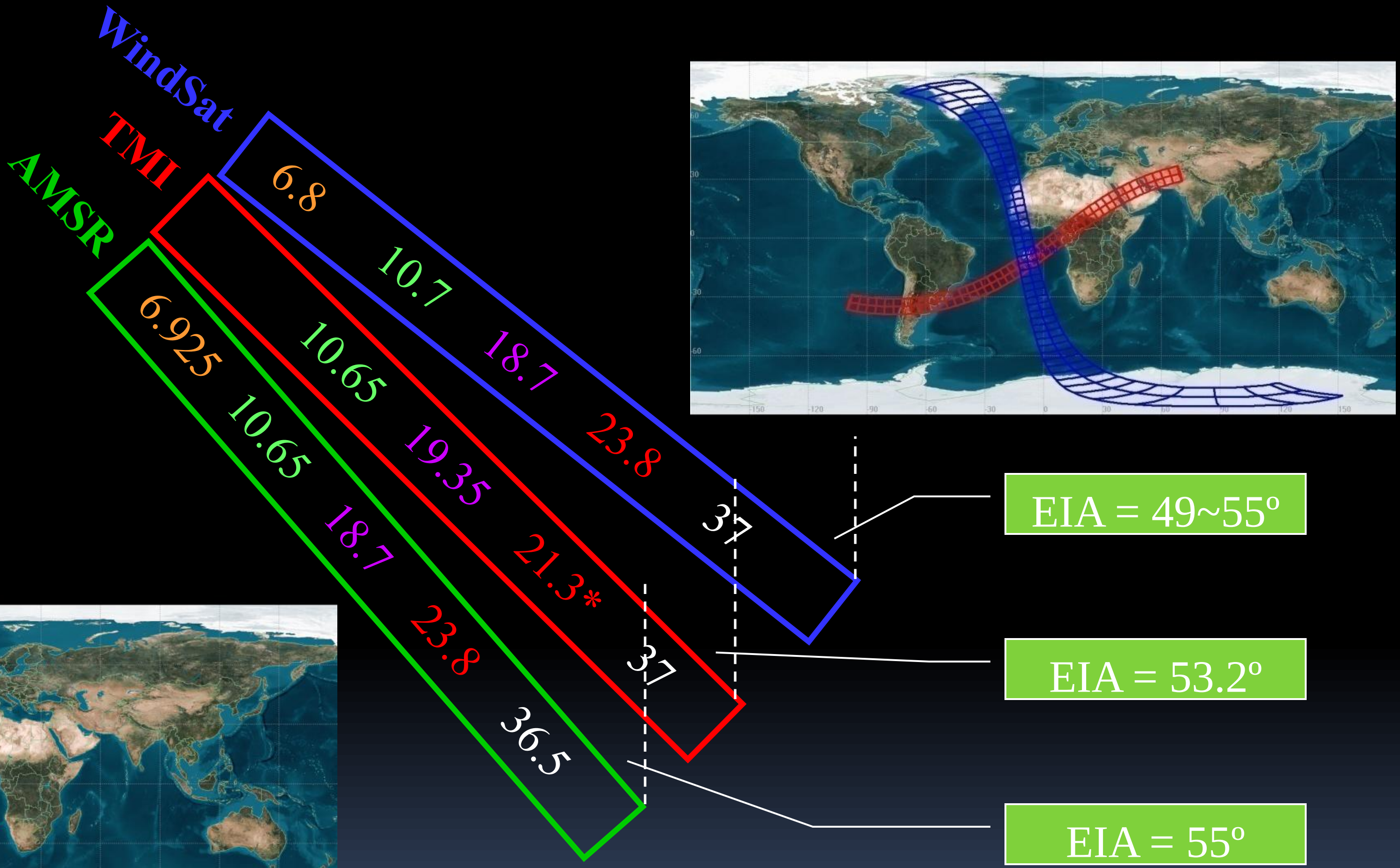
- Collocation
  - Constellation of satellites in both sun synch and non-sun synch orbits
  - Dynamic nature of atmosphere and ocean parameters restricts inter-comparison to time windows of a few minutes
    - Polar satellites + Polar satellites
      - No near-simultaneous pair-wise collocations over oceans
      - Simultaneous collocations only at the poles (non-ocean) scenes
    - Non-polar satellites
      - Near-simultaneous ocean scene collocations, which vary in latitude and longitude on a daily basis
- T_b Comparison
  - Frequency & Viewing angle (azimuth and incidence) differences
  - Normalization
    - Spectral Ratio
    - Multi-channel regression
    - Taylor series expansion

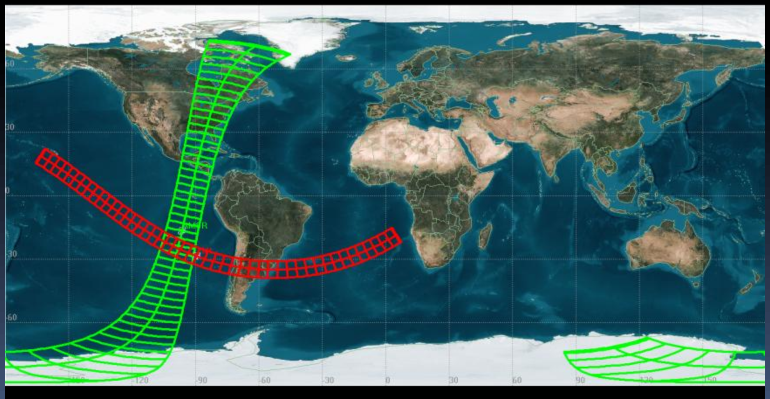
PMM Plan and Our Research

- NASA's PMM Plan
  - PMM Multi-satellite constellation calibrations
    - Constellation of satellites in both sun synch and non-sun synch orbits
    - Minimize T_b differences between instruments by comparing simultaneous collocated ocean T_b measurements
  - Algorithm development
    - Use TMI (Calibrated to WindSat) as proxy for GMI
    - Satellite collocations with temporal and spatial tolerance
    - Freq. and incidence angle normalization
- **Our Research**
  - **Transfer WindSat calibration to TMI, then use it as a transfer standard for AMSR calibration**
  - **Taylor series expansion prediction to normalize T_b's for comparisons**
  - **Normalization equations built on RTM simulations**

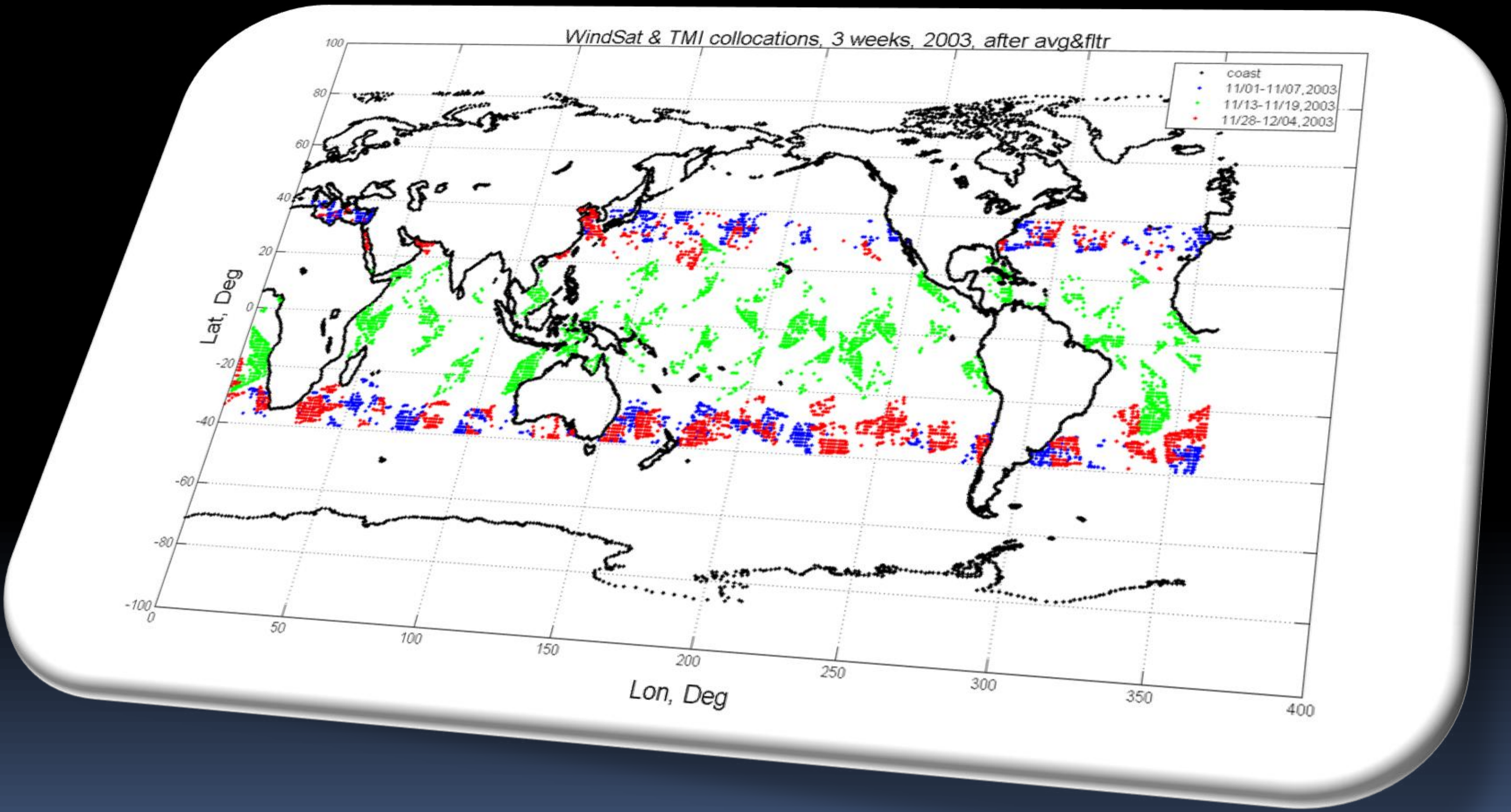
WindSat, TMI and AMSR

- WindSat & AMSR on sun-sync orbit
- TMI on low inclination orbit
- V & H –pol for all chan. Except for TMI 21.3GHz



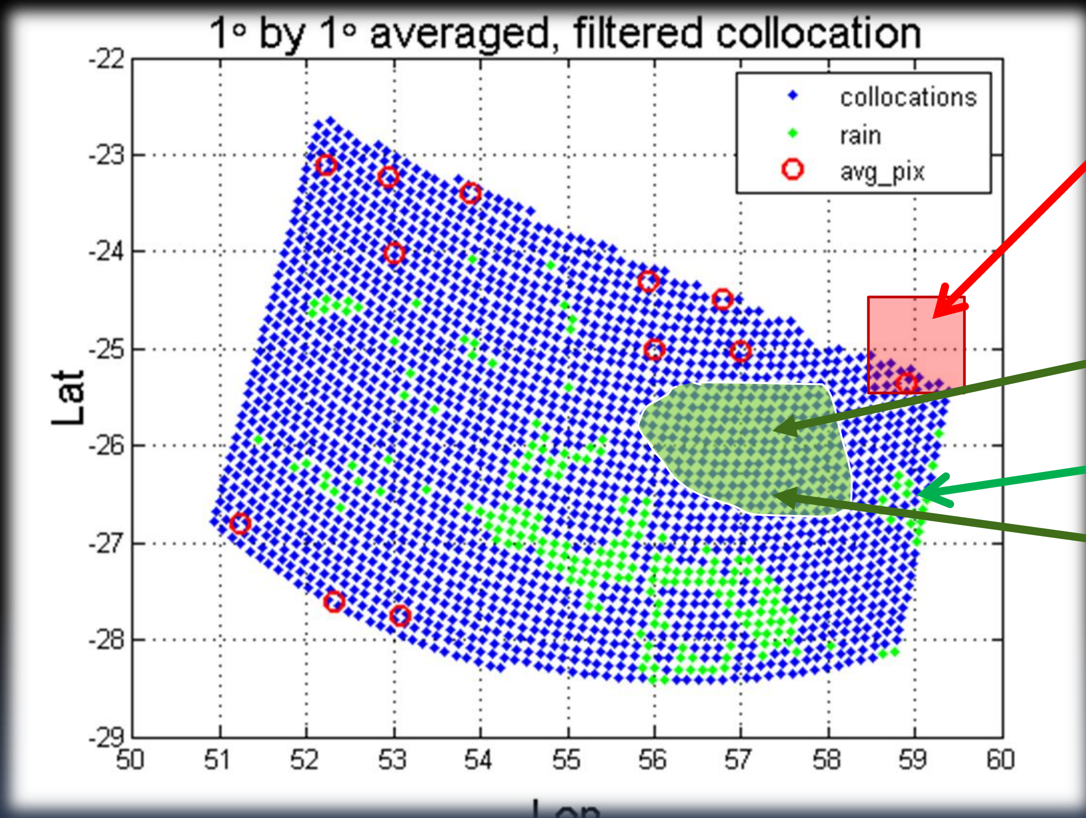


WindSat & TMI Collocations



Week1 data Week2 data Week3 data

Data Averaging and Filtering



- Data averaged over 1° by 1° box
- Box removed if
  - Std(V-pol) > 2K or std(H-pol) > 3K,
  - Any rainy pixel inside
  - Any pixel over upper limit of Tb's

WindSat, TMI and AMSR Collocation Pairs

Calib. Pair	Time Period	# of Cases
WindSat (SDR) & TMI (1B11)	06/01 - 06/30, 2003	5652
	11/01-07, 11/13-19, 11/28-12/04	4816
	One week each in 11/2003, 02/2004, 05/2004 and 08/2004	4397
TMI (1B11) & AMSR (L2A)	06/01 - 06/30, 2003	10783
	One week each month, 04/2003 - 10/2003	13001

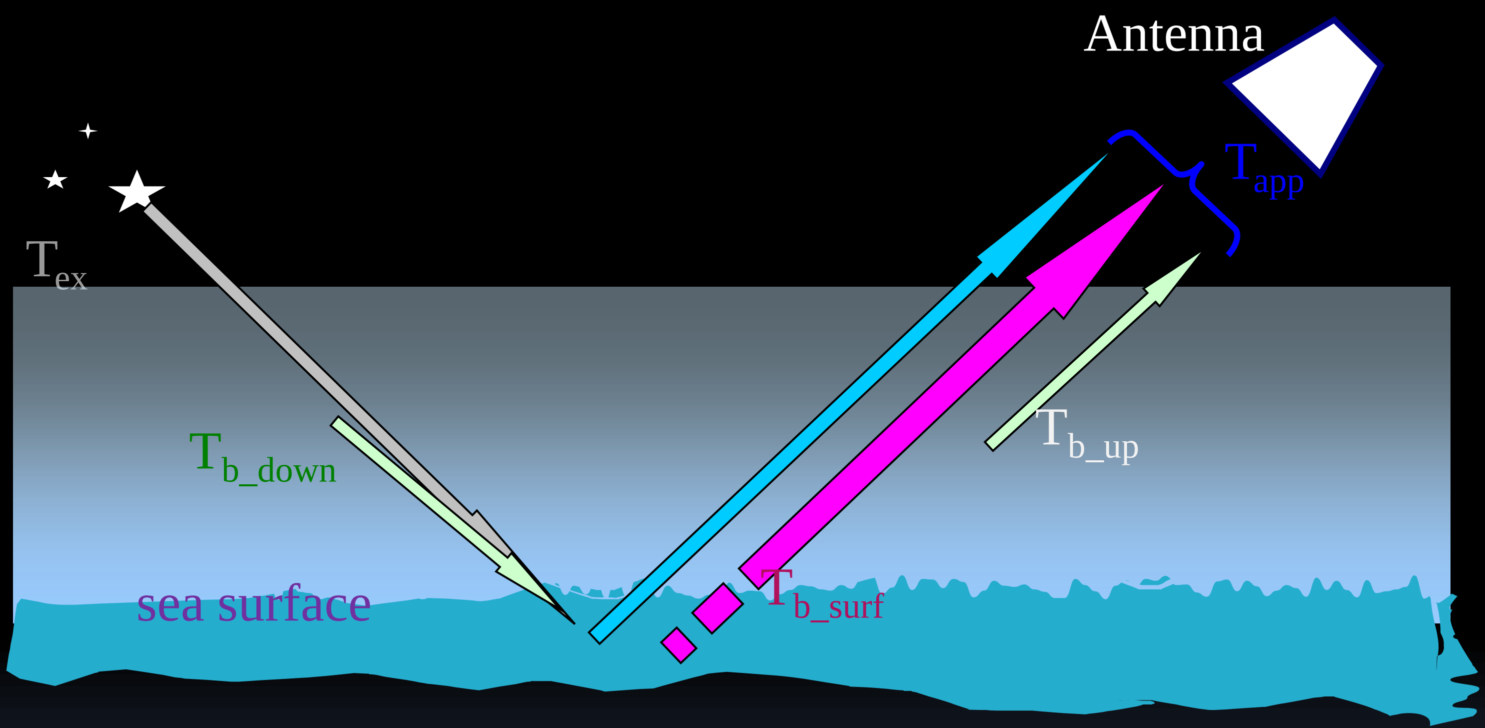
- Collocations of all periods of cover Lat. -40 deg~40 deg within all longitudes
- Temporal limit 15 min, spatial limit 25 km
- Cases are after 1° by 1° box averaging and filtering

Taylor Series Expansion Method Requires Valid RTM

- RadTb (CFRSL RTM) tuned to WindSat measurements under limited subset of geophysical conditions
- Validation of RadTb using WindSat measured T_b's over wide range of geophysical conditions
- Additional comparisons for RadTb simulations with AMSR and TMI T_b measurements
- Definition of geophysical condition levels

Level	WS (m/s)	WV (mm)	SST (C)	CLW (mm)
Low	≤4	≤20	≤10	≤0.1
Med	4-8	20 - 40	10 - 20	0.1 - 0.2
High	≥8	≥40	≥20	≥0.2

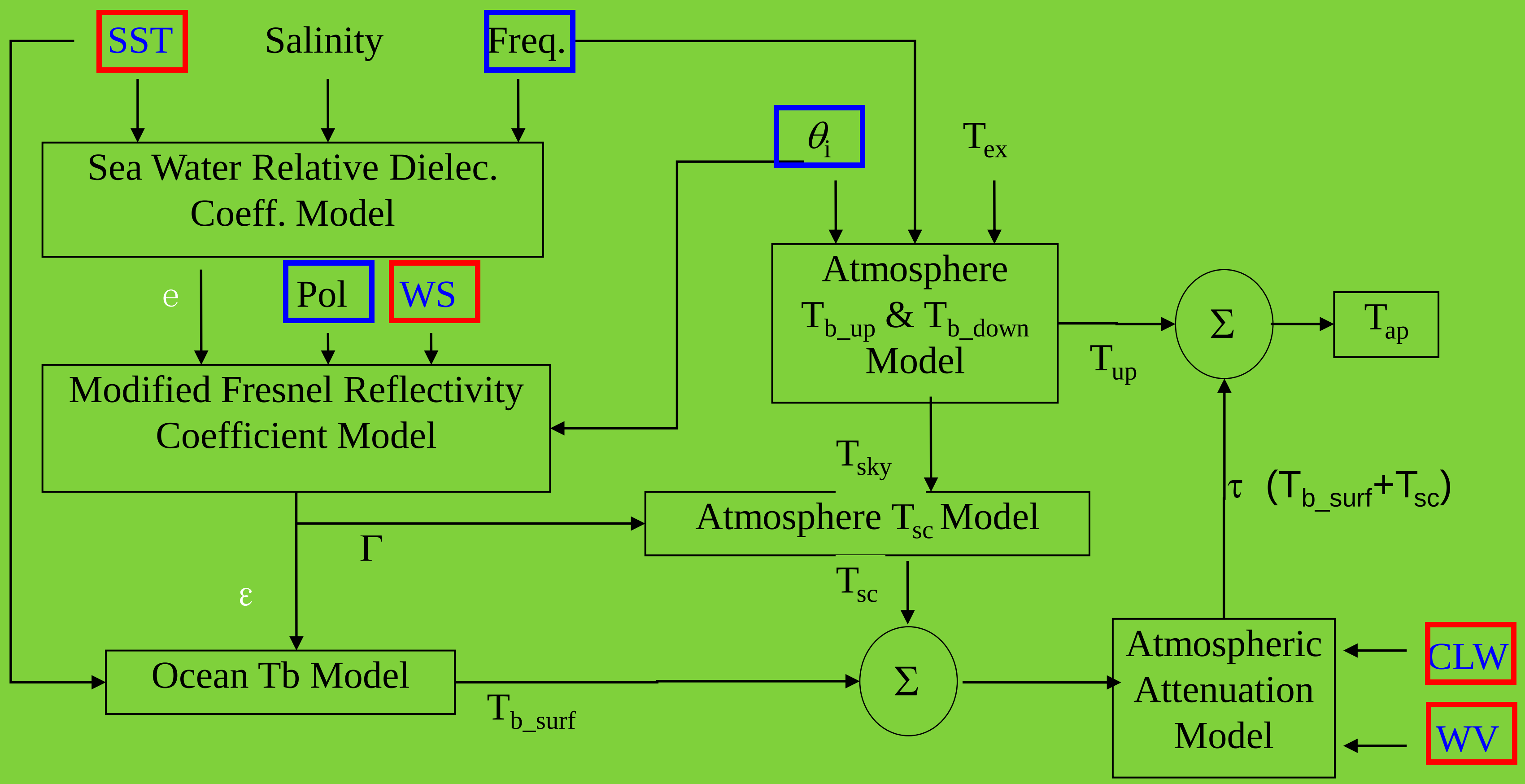
Radiative Transfer Theory



$$T_{refl} = (1-\varepsilon)(\tau T_{ex} + T_{b\_down})$$

$$T_{app} = T_{b\_up} + \tau(T_{b\_surf} + T_{sc})$$

CFRSL RTM (RadTb) Diagram



RadTb Tuning Inputs (4.7M Cases)

#	Input Item	Source
1,2,3	Mon, Lat, Lon	Sat. Data (SDR)
4,5,6,7, 13	Surface pressure, Surface air temperature, Lapse rate*, Surface absolute humidity*, Sea surface temperature	GDAS** >1º x 1º grid >3-D (21 pressure levels) >00, 06, 12, 18Z >Interpolate to WindSat Geolocations
8,10,11 ,12	Water vapor, Cloud liquid water, Rain rate, Wind speed	Sat. Data (EDR)
9	Mixing ratio	Const.
14	Salinity	WOA

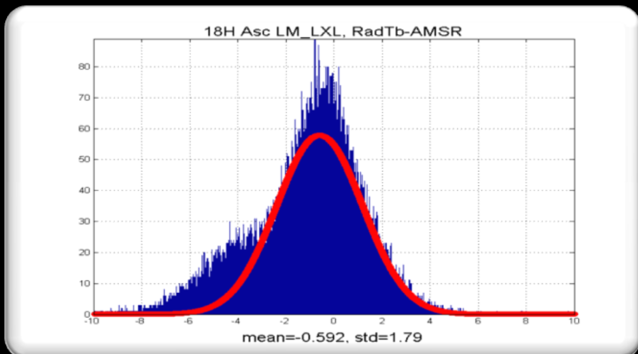
*Computed from source data, ** NWS/NCEP Global Data Assimilation System

RadTb Modules and Tuning

- Major Modules
  - Stogryn (1987) water vapor absorption model
  - Rosenkranz (1975) oxygen absorption model
  - Wentz (2000) dielectric constant and emissivity model
- **Tuning**
  - **Cloud Fraction**
  - **Sea Surface Emissivity Model**
  - **Sea Surface Emissivity Correction**
  - **Water Vapor Input Adjustment**

Cloud Fraction

Before Corr.

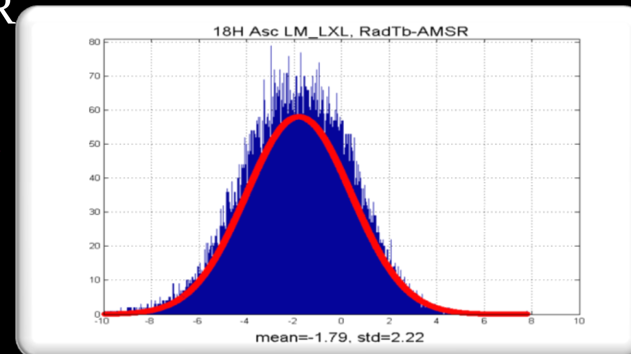


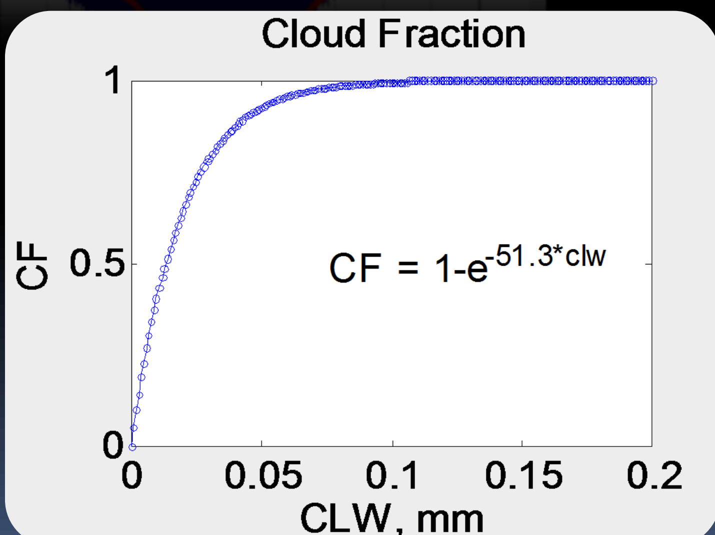
$\Delta Tb = RadTb - AMSR$

Cloud Fraction added

dual modes removed

After Corr.





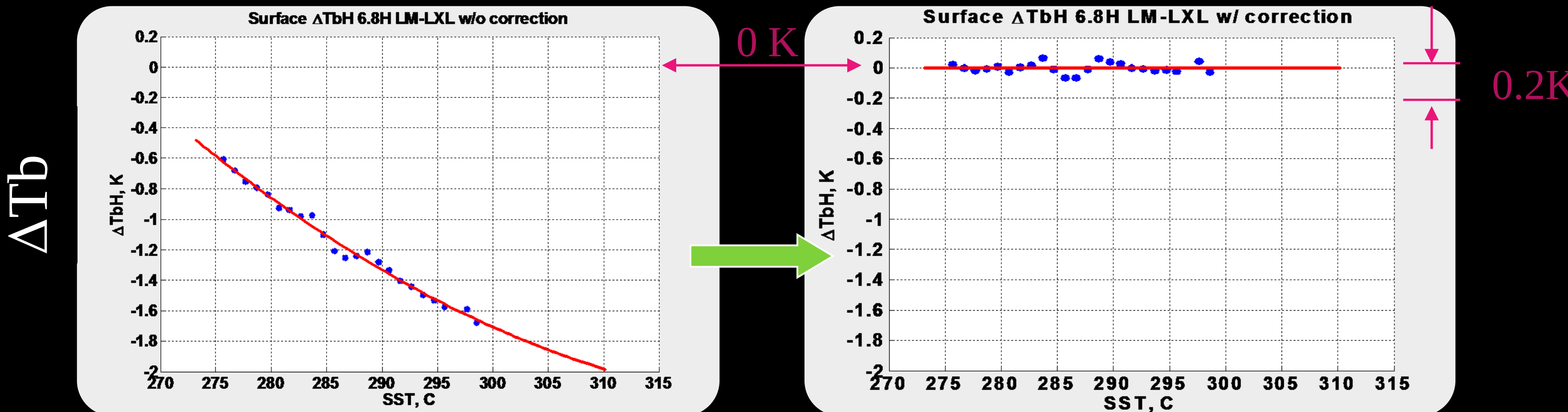
- Cloud Fraction (CF)
  - CF = F(CLW)
  - F(0.1) = 1
  - F(0.001) = 0.05
- $AH = AH_{noclw}(1-CF) + AH_{100\%sat}CF$
  - AH is the Absolute Humidity

Sea Surface Emissivity (WS Effect)

- Wentz's model works better on V-pol's for all frequencies especially when WS>10m/s
- Sample of 23.8 GHz V-pol, ΔTb = RadTb – WindSat

Sea Surface Emissivity (SST Effect)

Before Corr. **After Corr.**



$$T_{app\_model} = T_{up} + \tau\left(T_{surf\_model} + (1-\varepsilon)T_{sky}\right)$$

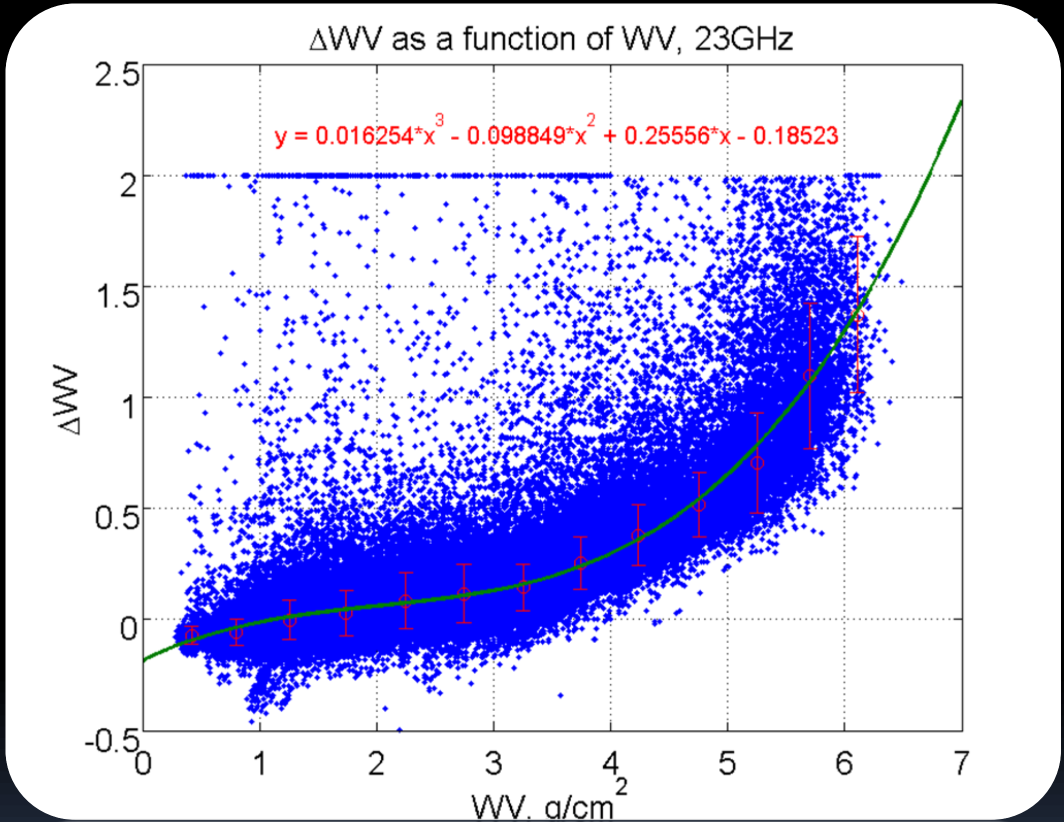
$$T_{app\_measure} = T_{up} + \tau\left(T_{surf\_measure} + (1-\varepsilon)T_{sky}\right)$$

$$T_{surf\_measure} - T_{surf\_model} = F(SST)$$

$$T_{app\_measure} = T_{up} + \tau\left(T_{surf\_model} + \boxed{F(SST)} + (1-\varepsilon)T_{sky}\right)$$

- F(SST) is a 2nd polynomial of SST
- Tuning under LM_LXL (650k cases)

Water Vapor Input to RadTb



Water vapor for RadTb input

- $WV_{new} = WV_{orig} + \Delta WV$
- ΔWV = 3rd degree polynomial of WV

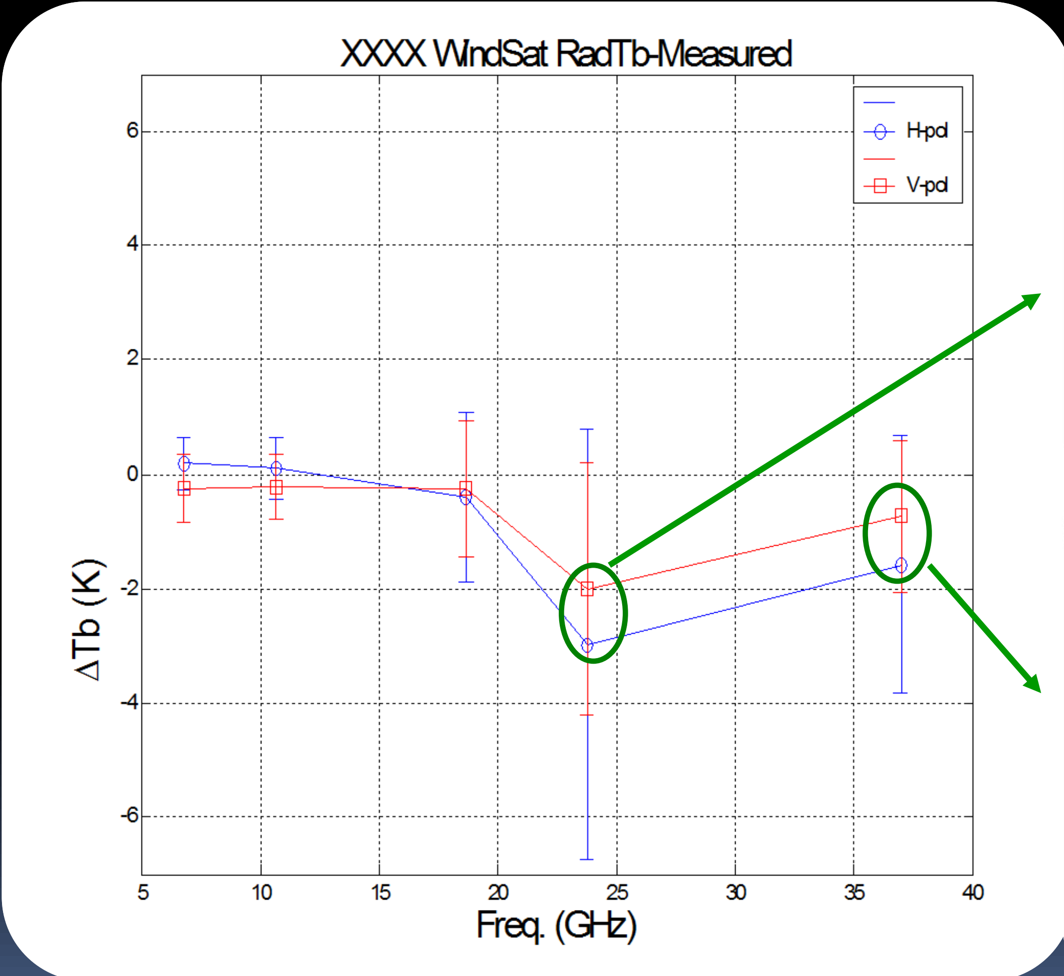
ΔWV Tuning

- Data set: LM_XXL, 50k cases
- ΔWV = -0.5 to +2.0, step size=0.01
- Varying ΔWV to get $\min(\Delta T_b)$

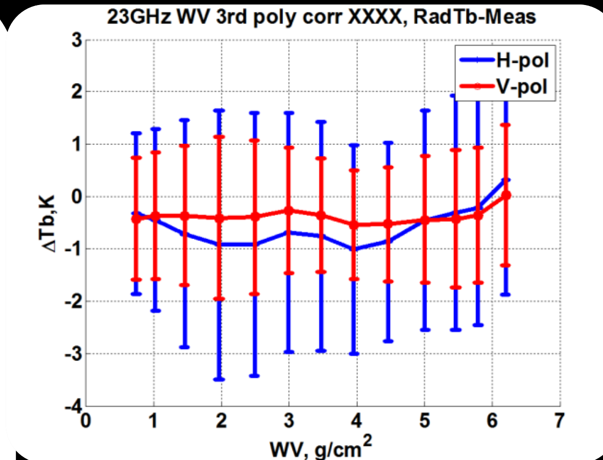
Applied to Freq. > 20GHz

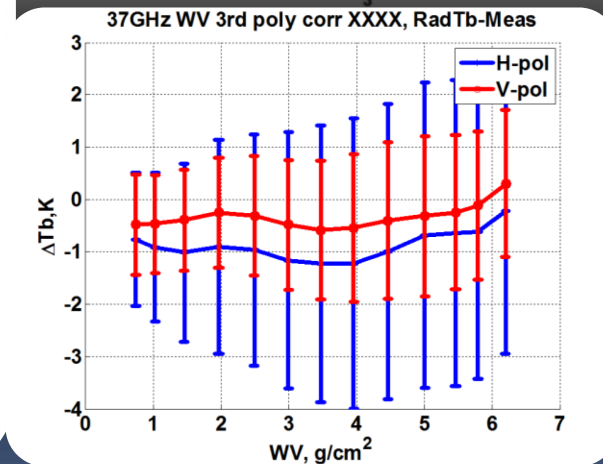
23.8 & 37GHz WV Correction

Before WV Corr.



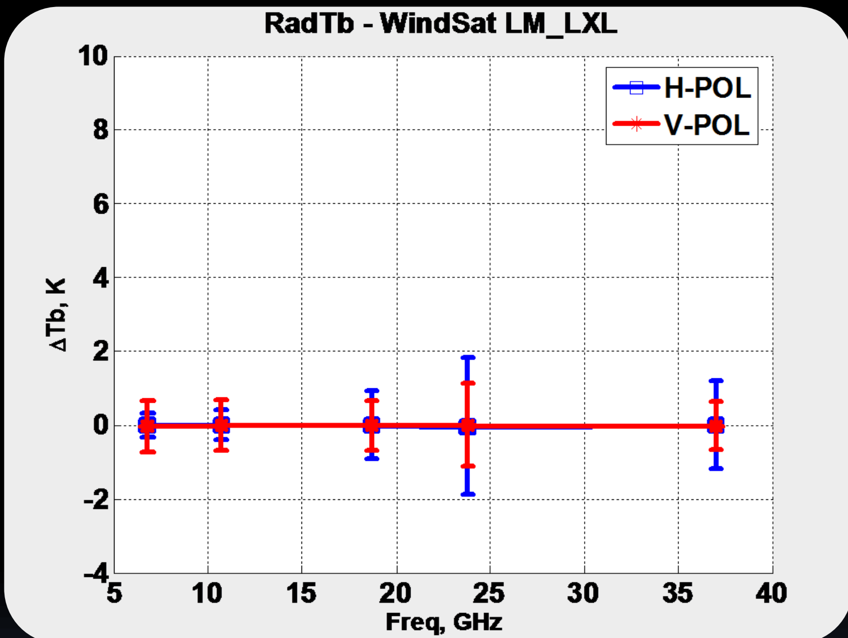
After WV Corr.





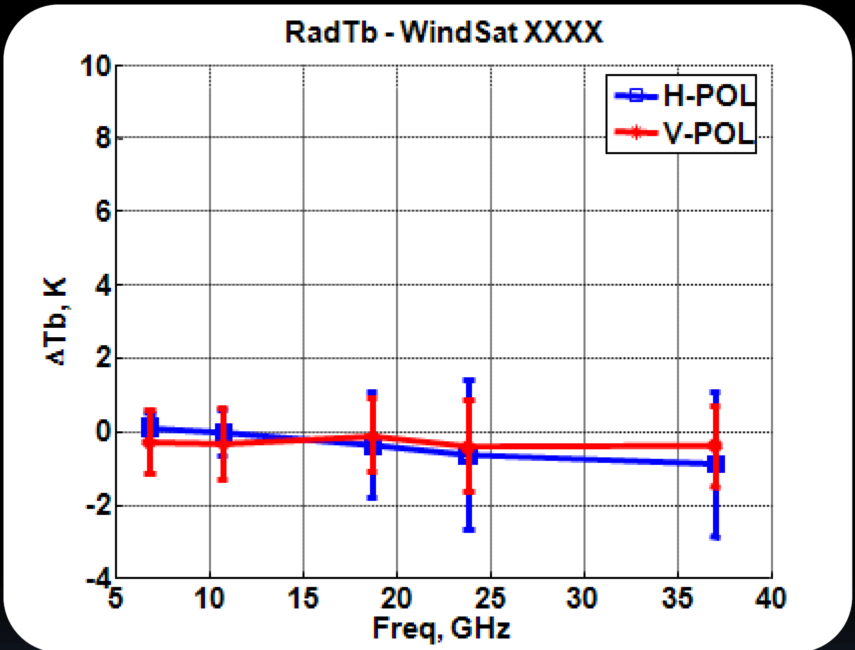
RadTb Simulation Compared with WindSat T_b's

650K cases



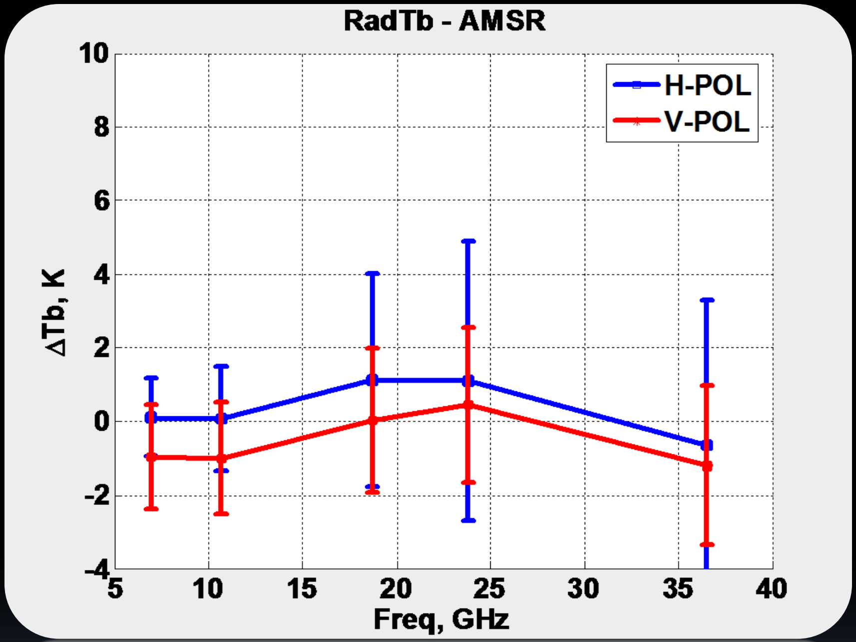
Wind speed ≤ 8m/s
Water vapor ≤ 20mm
Cloud liquid water ≤ 0.1mm

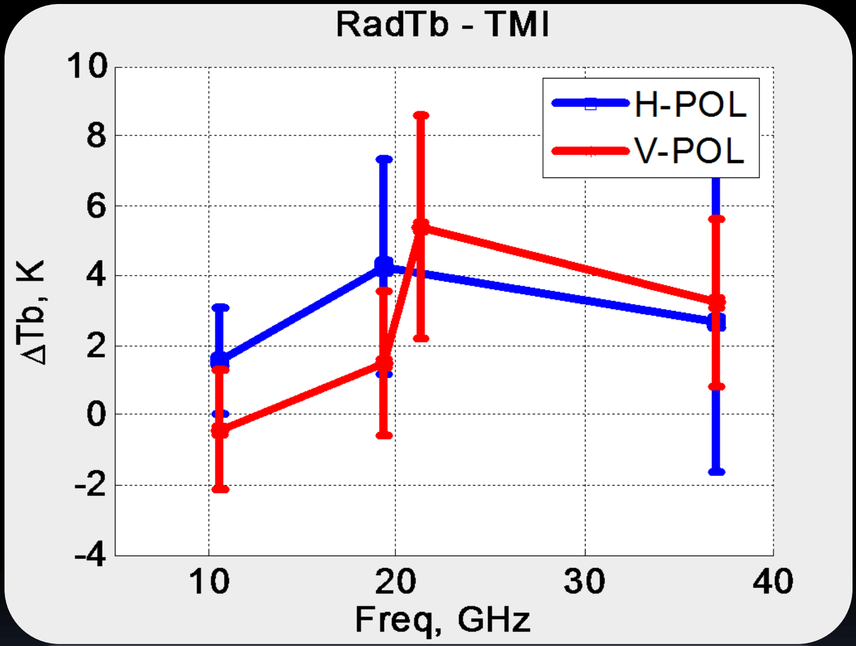
4.7M cases



Full range of geophysical conditions observed

RadTb Simulation Compared with AMSR & TMI Collocations





Taylor Series Expansion, Frequency Normalization

- Calc. Taylor series expansion coefficients

$$T_b(f_1) = T_b(f_0) + T_b^{'}(f_0) \times (f_1 - f_0) + T_b^{''}(f_0) \times \frac{(f_1 - f_0)^2}{2!} +$$

$$T_b^{(3)}(f_0) \times \frac{(f_1 - f_0)^3}{3!} + \ldots + T_b^{(n)}(f_0) \times \frac{(f_1 - f_0)^n}{n!}$$

  - f_o is the source freq., and f_1 is the target freq.
  - $T_b(f)$ based on RadTb simulations
  - Varies with different geophysical conditions and polarizations

Taylor Series Generation

- Combination of Wind Speed, Water Vapor, Sea Surface Temp. and Cloud Liquid Water levels define geophysical categories, 81 in total
- T_b simulations grouped under different geophysical condition categories
- Taylor series expansion derived from high (6^{th}) order polynomial of T_b Spectrum

T_b Spectrum

Calib. TMI with WindSat

* 37GHz is a common freq.

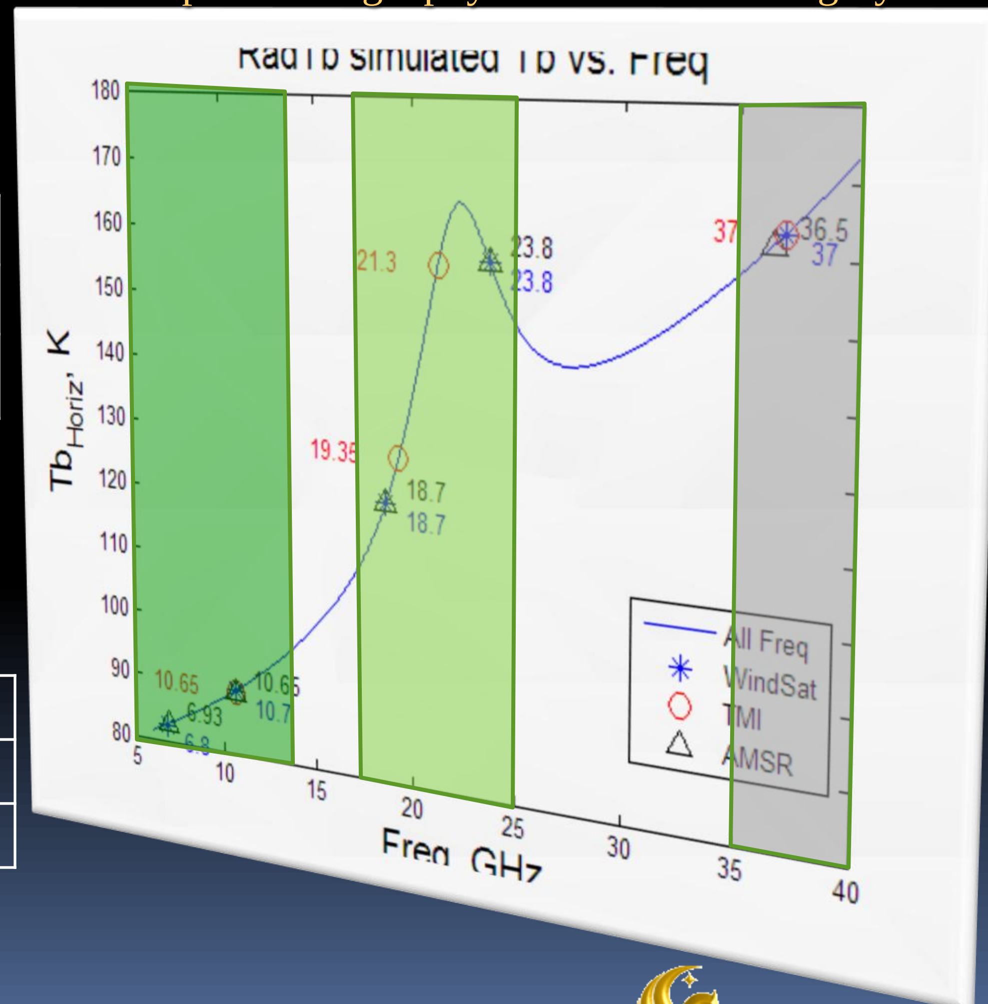
f_1:TMI (GHz)		10.65	19.35	21.3
H	f_0: WindSat (GHz)	10.7	18.7	N/A
V		10.7	18.7	18.7

Calib. AMSR with TMI

* 10.65GHz is a common freq.

f_1:AMSR (GHz)		6.925	18.7	23.8	36.5
H	f_0: TMI (GHz)	10.65	19.35	37	37
V		10.65	19.35	21.3	37

Example in one geophysical condition category



Taylor Series Expansion, EIA Normalization

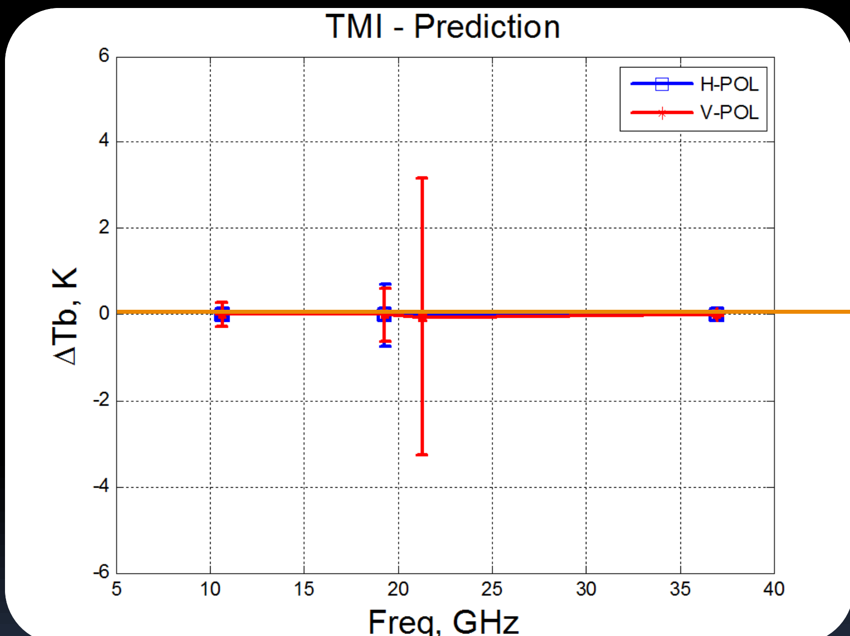
- For EIA transfer,

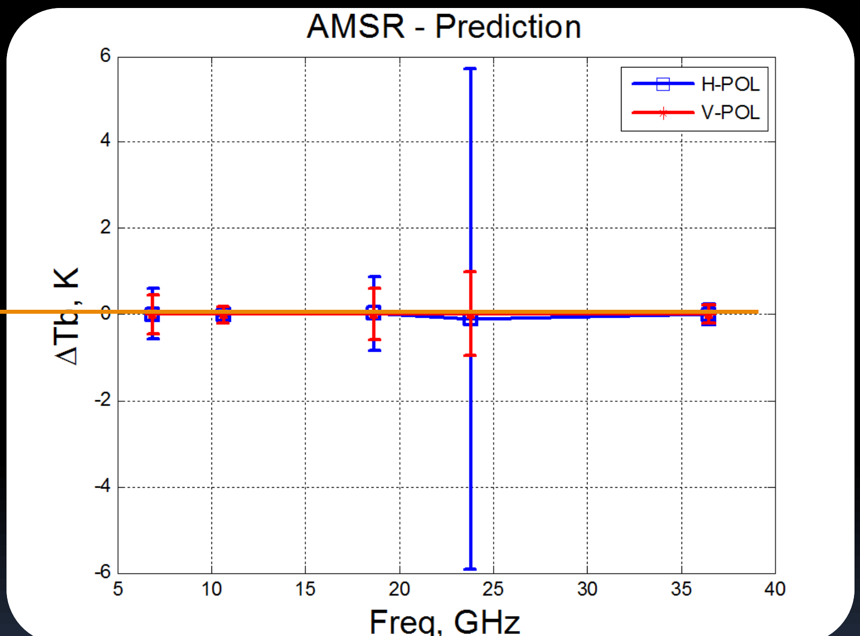
$$T_b(\theta_1) = T_b(\theta_0) + \frac{\partial T_b}{\partial \theta} \times (\theta_1 - \theta_0)$$

  - θ_o is EIA of source channel and and θ_1 is EIA of target channel
- For identical Freq's, only EIA transfer is applied

Simulated Tb vs. Prediction

- 5000 randomly selected cases
- Less than 0.05K errors in prediction of all channels





Multi-channel Regression

- To predict the desired channel theoretical T_b
  - Inputs: selected T_b observations from all source channels
  - Retrieval matrix: from regression analysis with Radiative transfer model (RTM) simulated T_b's

$$L_{Tb\_obj} = \sum \left(c_i T_b + c_{L\_i} L_{Tb\_source} \right) + C$$

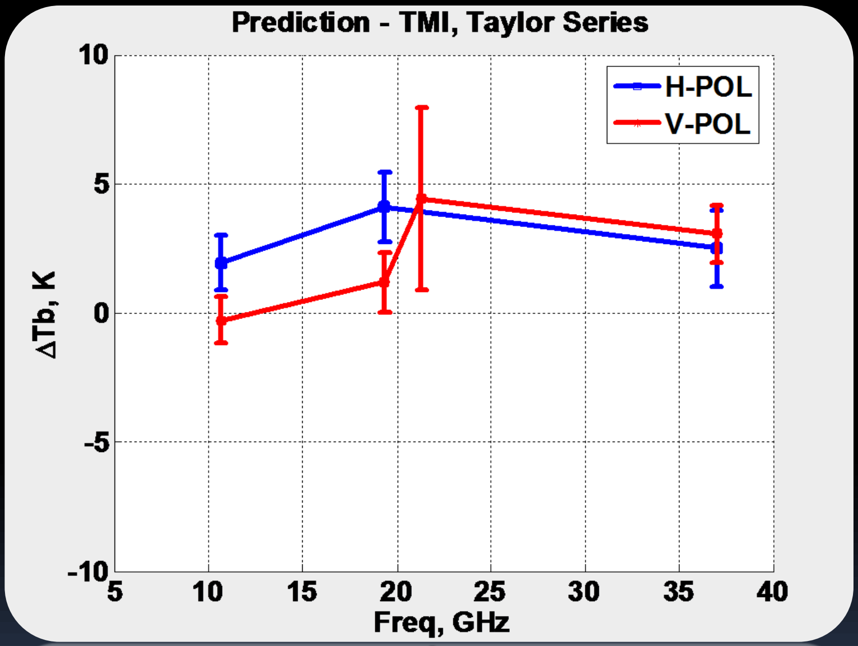
- Transformation to accommodate nonlinearity

$$L = \ln\left(285 - T_b\right)$$

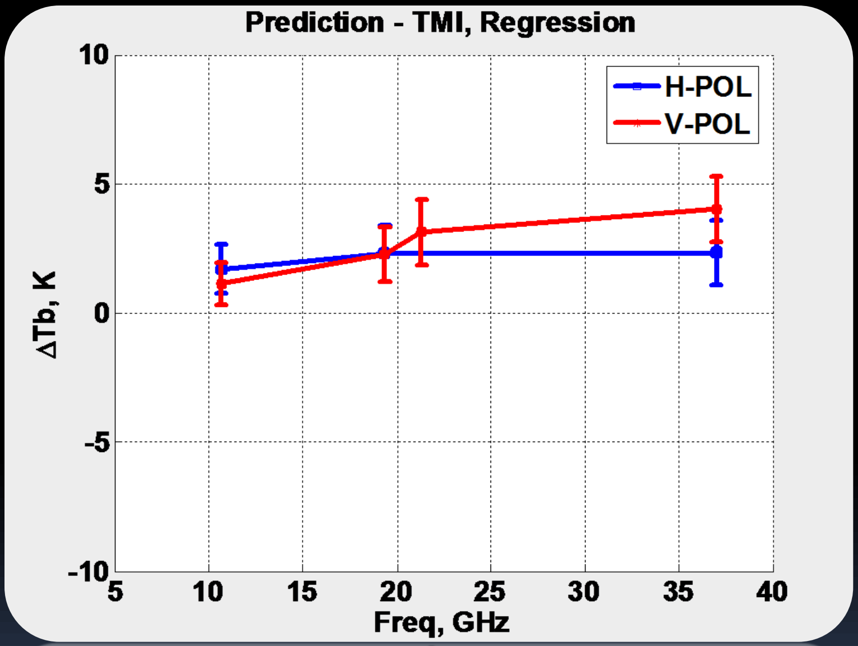
WindSat to TMI

ΔTb = WindSat – TMI (14865 cases)

Taylor Series Expansion

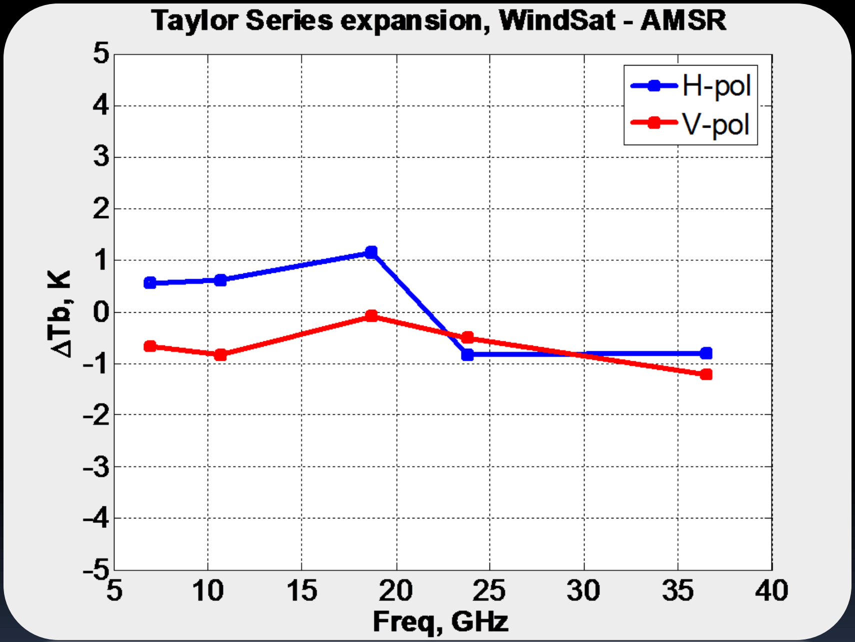


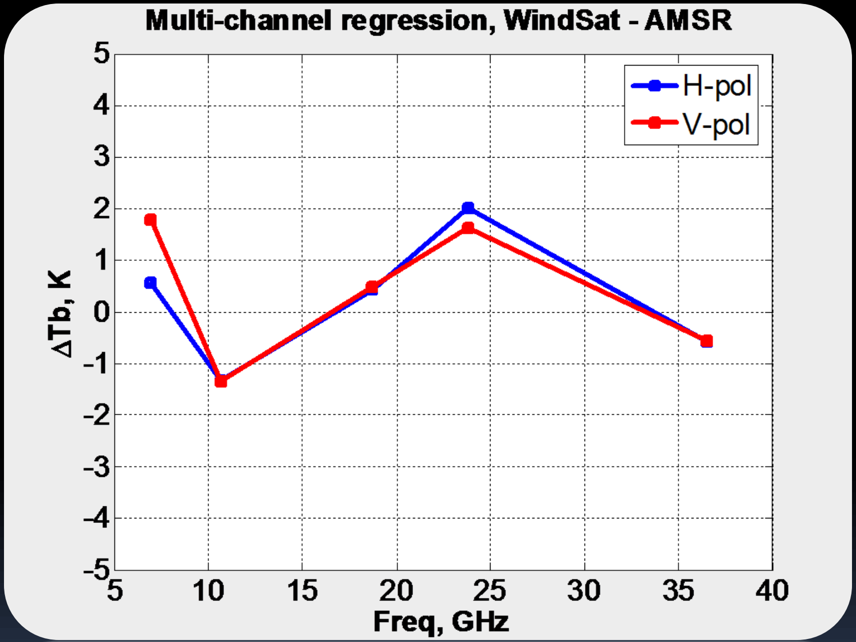
Multi-Channel Regression



WindSat to AMSR

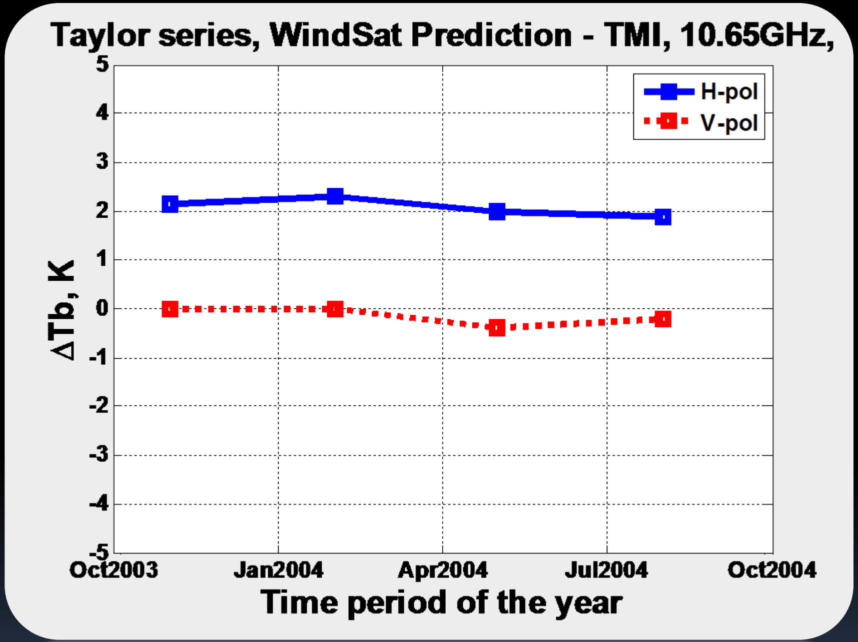
- Combined all time periods
- TMI calibrated with WindSat, then AMSR calibrated with TMI



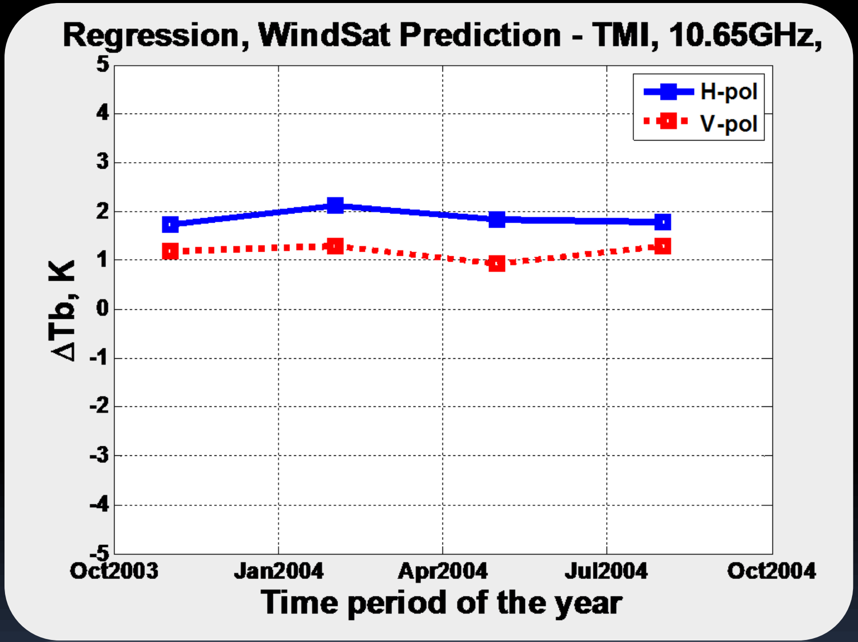


TMI vs. WindSat, Temporal Dependence Analysis

Taylor Series Expansion



Multi-Channel Regression



Inter-satellite Calibration Summary

- Taylor series expansion prediction presents an effective way for inter-sat calibration
  - Pros: Fast, generalized prediction, linear calibration transfer
  - Cons: Channel and environmental parameter dependence

Inter-satellite Calibration Summary continued

- Calibration results of WindSat, TMI and AMSR
  - Consistent results from both Taylor's series and multi-channel regression methods
  - WindSat and AMSR T_b's in general agreement
  - TMI T_b's lower than WindSat and AMSR, Significant biases ≤ 4 K, agreeing with WindSat and TMI 37GHz channel direct comparison sanity check
  - RadTb agrees with AMSR measurements better than TMI (consistant with calibration results)
  - No evident asc/dsc discrepancy for AMSR calibrations
  - No evident temporal dependence of cross calibration

Inter-satellite Calibration Summary continued

- Possible error sources
  - RadTb modeling of water vapor line Tb needs improvement
  - WindSat absolute radiometric calibration
  - Environmental data, especially GDAS model accuracy in water vapor profile
  - RadTb was tuned to WindSat under limited geophysical conditions
  - Real time EIA not equaling to nominal values
  - Viewing angle difference in collocations

Publications

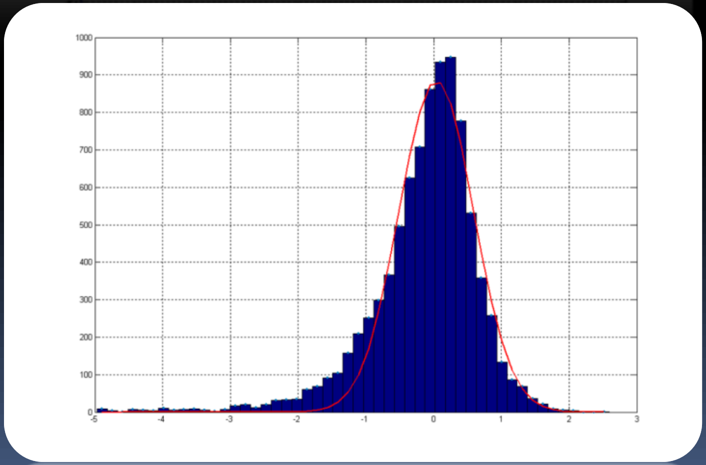
- **Liang Hong**, Linwood Jones, Thomas Wilheit, "Inter-Satellite Microwave Radiometer Calibration", to be submitted to *IEEE Trans. GeoSci. Rem. Sens*
- **Liang Hong**, Linwood Jones, Thomas Wilheit, "Inter-Satellite Radiometer Calibrations between WindSat, TMI and AMSR", *IEEE Internat GeoSci Rem Sens Symp IGARSS 2007*, July 23-27, Barcelona, Spain
- Guillermo Gonzalez, Rafik Hanna, **Liang Hong**, W. Linwood Jones, "HF Communications Analysis for Varying Solar and Seasonal Conditions", *IEEE SoutheastCon 2007*, March 22-25, Richmond, VA
- **Liang Hong,** Linwood Jones, and Thomas Wilheit, "Inter-Satellite Microwave Radiometer Calibration Between AMSR and TMI", *Proc IEEE Internat GeoSci Rem Sens Symp IGARSS 2006*, Denver, CO, July 31 – Aug. 4, 2006.
- Nishant Patel, **Liang Hong**, W. Linwood Jones, and Santhosh Vasudevan, "Evaluation of the Amazon Rain Forrest as a Distributed Target for Satellite Microwave Radiometer Calibration", will be presented in IGARSS 2006.
- W. Linwood Jones, Jun D. Park, Seubson Soisuvarn, **Liang Hong**, Peter Gaiser and Karen St. Germain, "Deep-Space Calibration of WindSat Radiometer", *IEEE Trans. GeoSci. Rem. Sens Volume 44, Issue 3, March 2006 Pages: 476-495.*
- **Hong, L.,** B. A. Lail, and L. Jones, "Near Real-Time Ionospheric HF Propagation Modeling and Prediction", *Proc 2004 IEEE AP-S International Symposium and USNC/URSI National Radio Science Meeting*, Monterey, CA, June 20-26, 2004

Questions?

Backup

Gaussian Distribution Fit

- Bin width (W) selection affects total number of bins→ histogram→Gaussian distribution fit
- $W = c * 2\ (IQR)\ N^{-1/3}$
  - Where c = 1/30
- Works well with large amount of cases (e.g. > 1000)



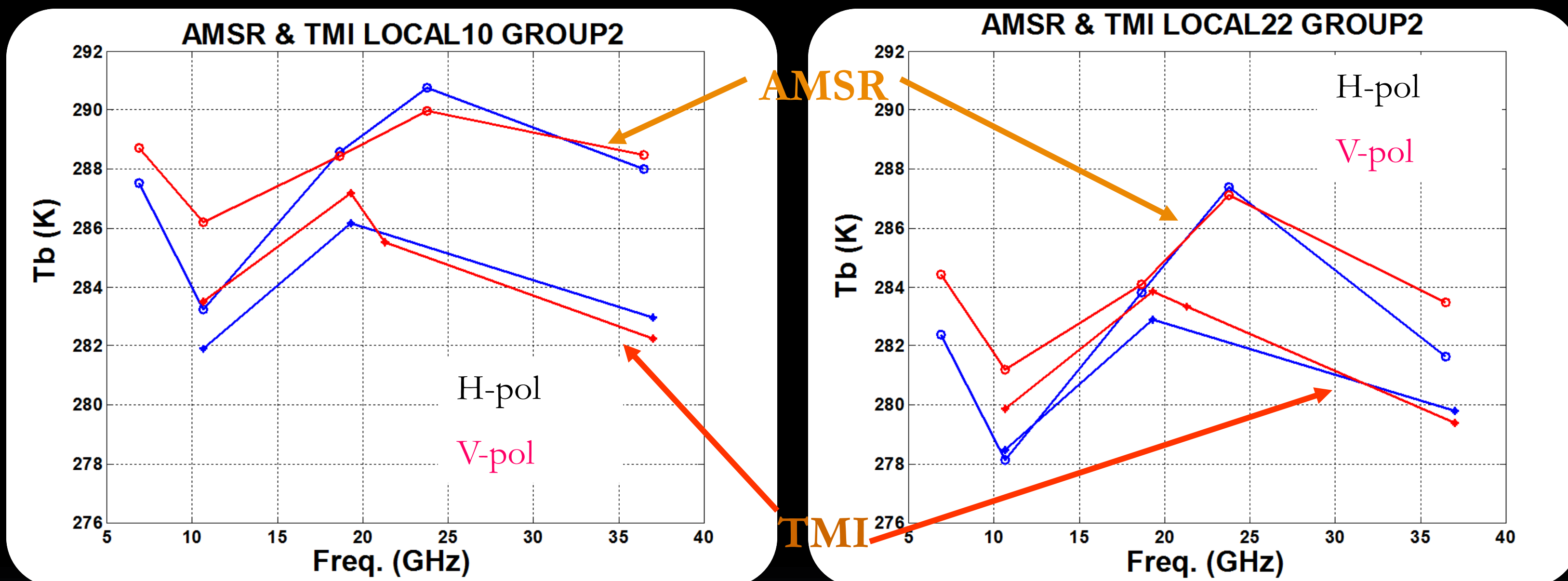
Future Works

- Amazon forest for hot calibration point
- Greenland glacial ice for cold calibration point
- Other T_b prediction approaches
  - Artificial Neural Networks
    - Generalized Regression Neural Network (GRNN)

Amazon Forest

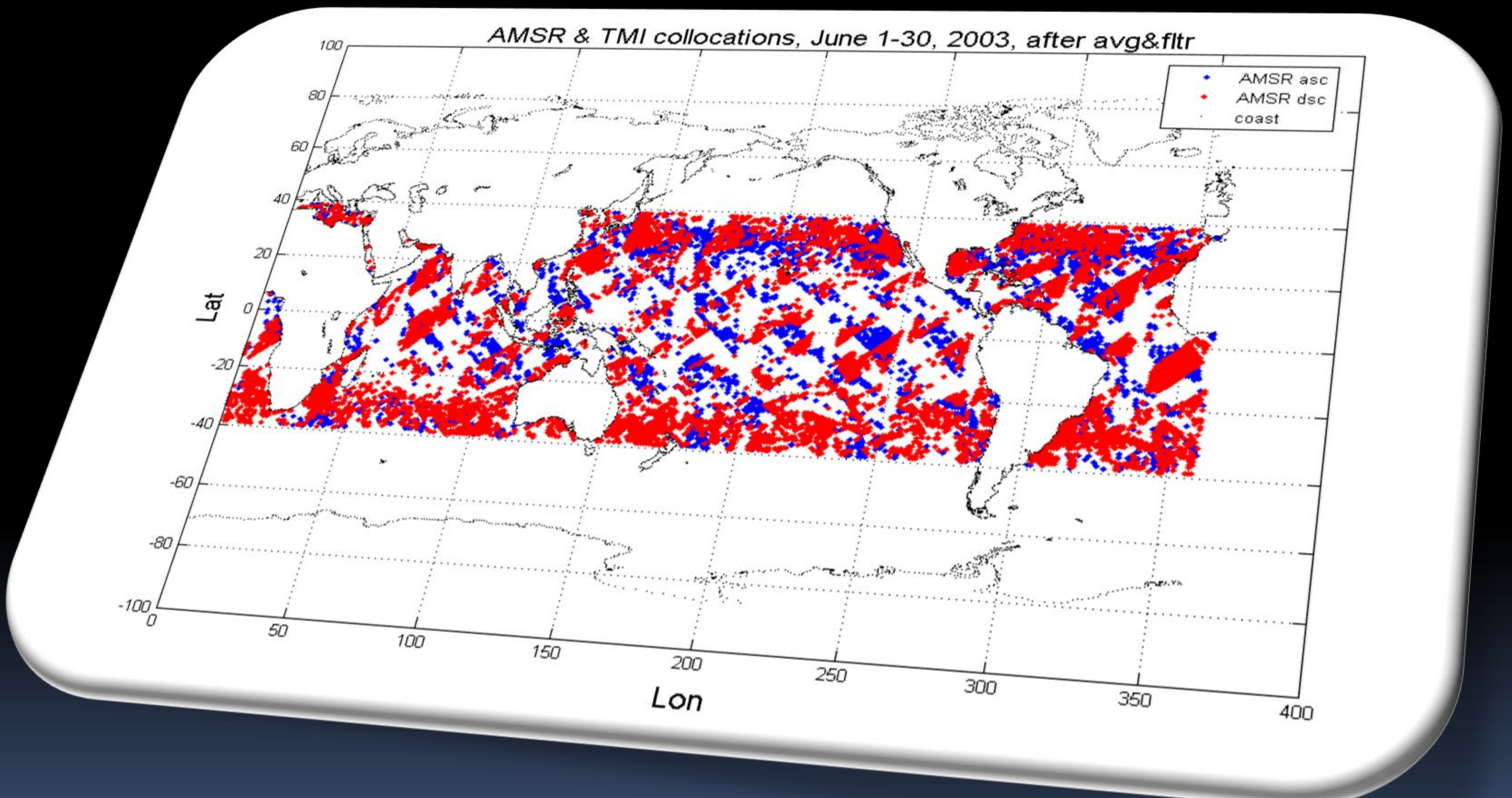
- Amazon area for hot calibration points
  - Large geographic area covered with a dense leaf canopy of tropical rain forest vegetation
  - Random collection of diffuse microwave scatterers and emitters
  - Located at the equator - provides insensivity to seasonal changes
  - Current radiative transfer model doesn't apply
  - Homogeneity analysis
    - Spatial: most Tb's fall within $\pm$ 1.5 K
    - Temporal: diurnal dependence
- Works to do
  - Characterize Amazon for other frequencies
  - Refine measurements of effective Amazon physical temp
  - Refine Amazon surface Tb calculation
  - Refine surface emissivity

AMSR & TMI Tb's Over Amazon



- AMSR Asc @ 22:00LST, Dsc @10:00LST, June 2003
- Three groups of geographical locations
  - Small standard deviations in each group
  - Similar patterns

AMSR & TMI Collocations

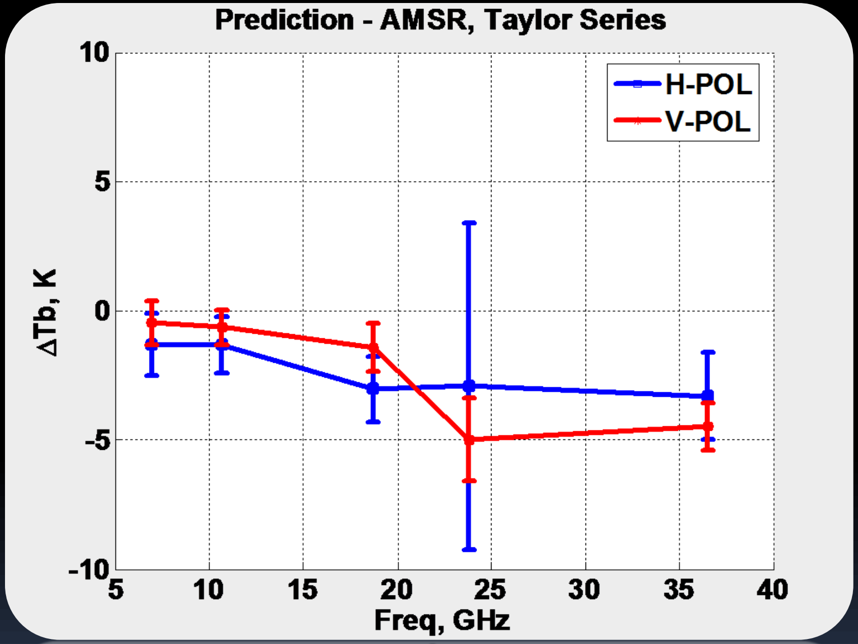


AMSR Ascending data AMSR Descending data

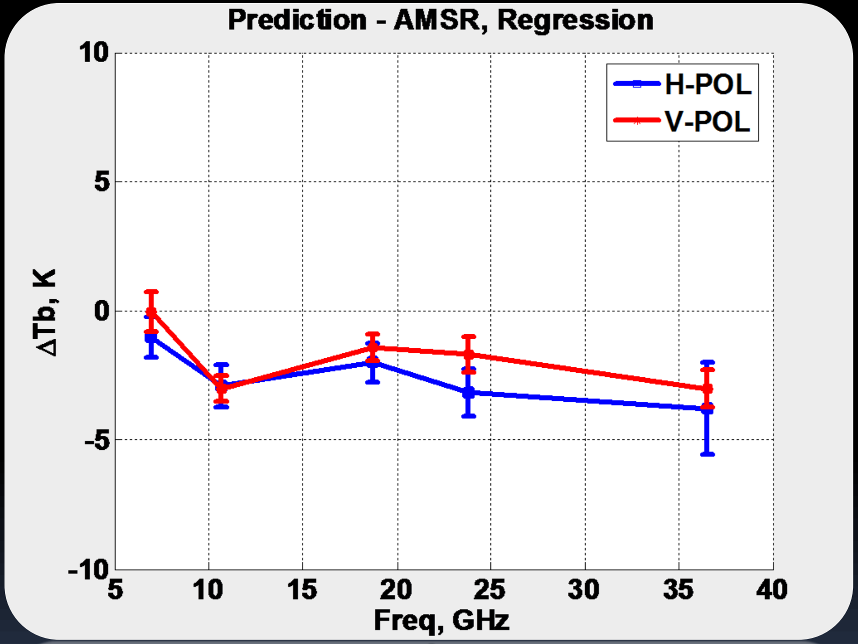
AMSR vs. TMI

ΔTb = TMI – AMSR (23784 cases)

Taylor Series Expansion

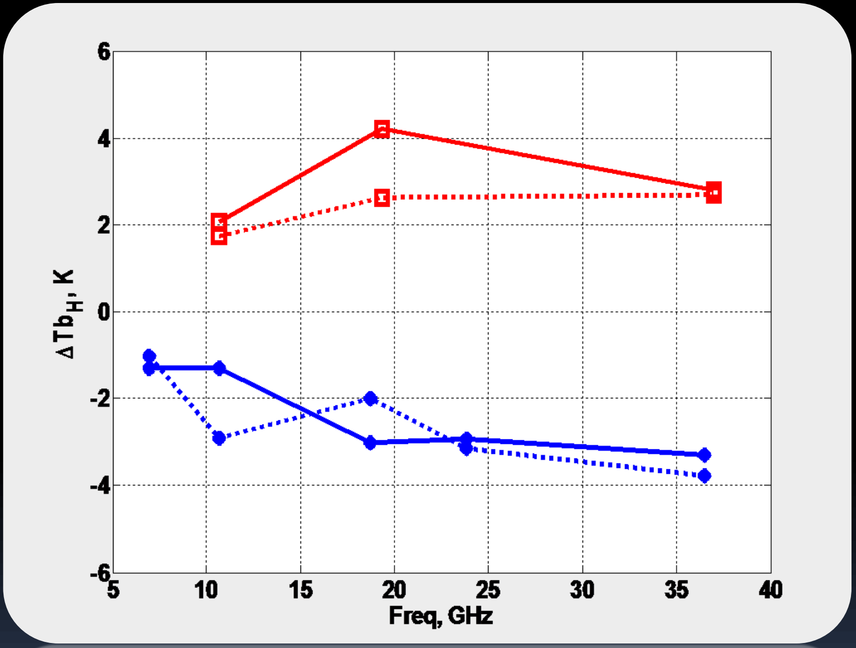


Multi-Channel Regression

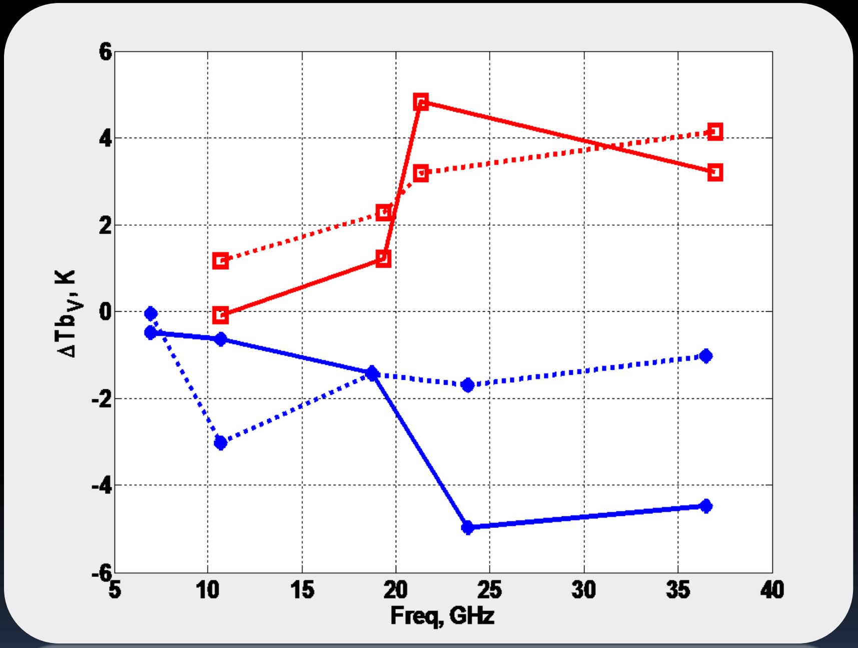


Composite Plots, June 1-30, 2003

Horizontal Polarization



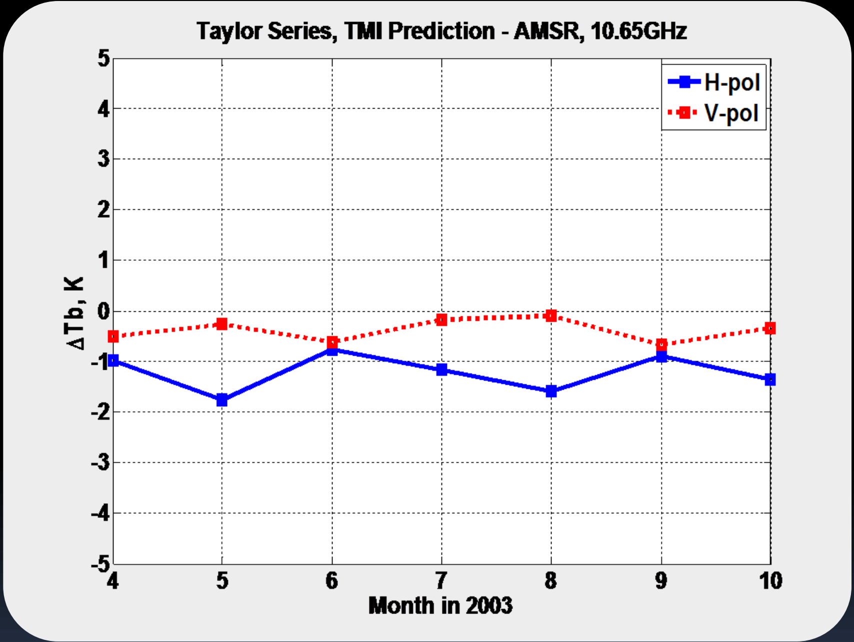
Vertical Polarization



WindSat->TMI, Taylor
WindSat->TMI, Regression
TMI->AMSR, Taylor
TMI->AMSR, Regression

AMSR vs. TMI, Temporal Dependence Analysis

Taylor Series Expansion



Multi-Channel Regression