Validation of QuikSCAT Radiometer (QRad) Microwave Brightness Temperature Measurements

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PhD Defense

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Dissertation Objective

- Validate the QuikSCAT Radiometer (QRad), microwave brightness temperature algorithm (JPL L2A product)
- Perform inter-satellite radiometric calibration with the WindSat microwave radiometer
  - Primary QRad Tb calibration over oceans during continuous sun-lighted orbits
    - Establish absolute Tb measurement accuracy
      - Mean Tb biases relative to WindSat (standard)
    - Establish radiometric precision
      - Measure noise equivalent delta-Tb (NEDT)
    - Evaluate calibration stability
      - Seasonal changes in QRad Tb biases
      - Changes during eclipse periods (thermal transient case)

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Dissertation Objective cont.

- Evaluate QRad Tb measurements over land
  - Effects of radar echo subtraction
- Evaluate antenna pattern effects
  - Sidelobe spill-over near land
  - Land mask for ocean Tb

- Relate systematic Tb calibration biases to problems within the QRad Tb algorithm and recommend future improvements

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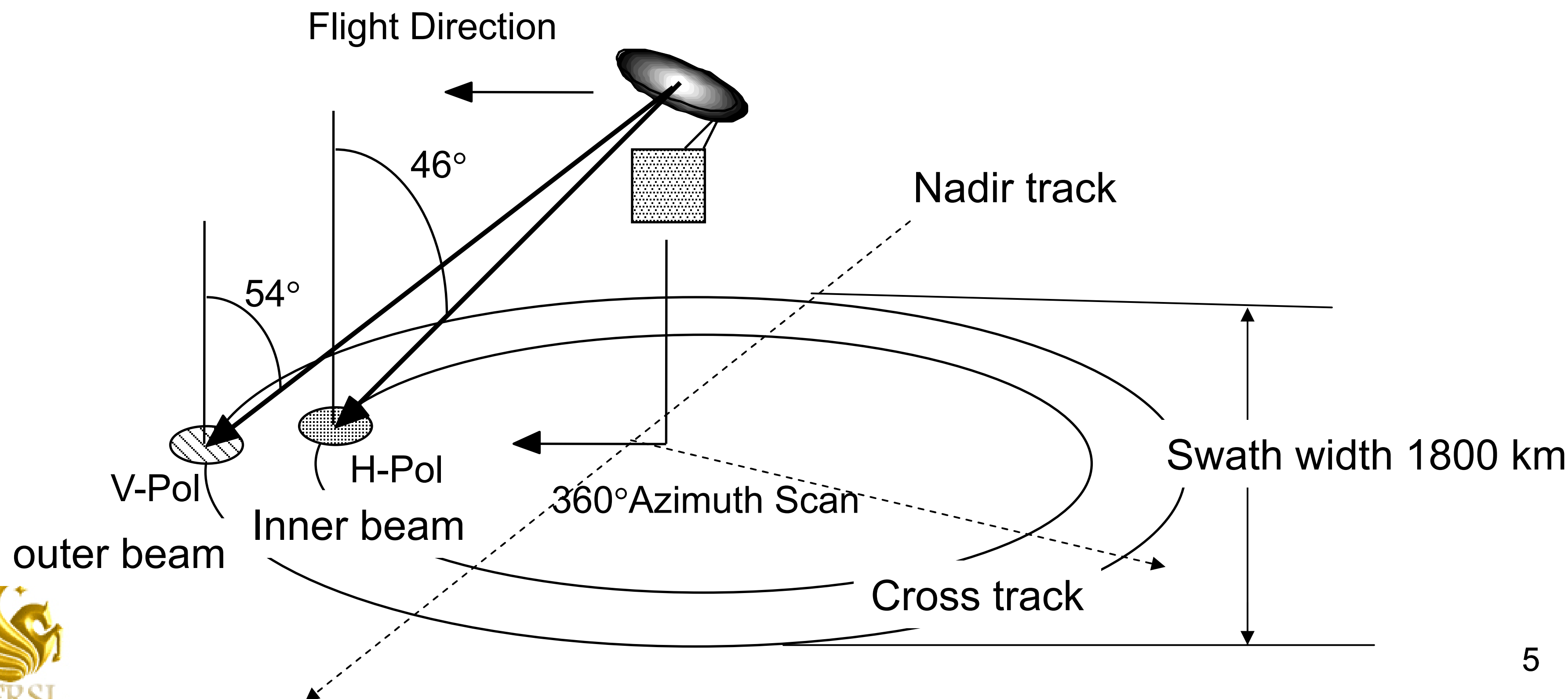
SeaWinds on QuikSCAT

- SeaWinds is a satellite-borne radar scatterometer used to remotely sense oceanic surface winds
  - Launched June 1999 on the Quick Scatterometer (QuikSCAT) satellite
  - Low Earth Polar Orbit:
    - Sun-synchronous
    - 98.6° inclination orbit
    - Operating Freq. 13.4 GHz
    - Incidence angles:
      - 46° H-pol & 54° V-pol

Microwave Scatterometry Geometry

- Scatterometer measurements are collected over 360° of aziumth
  - 25 km “wind vector cells” within overlapping swath
  - Radar measurements at 4 azimuth looks



QuikSCAT Radiometer (QRad) Apparent Brightness Temperature Algorithm

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QRad Brightness Temperature (Tb) Measurement

- SeaWinds is a radar scatterometer, which employs signal processing similar to a total power radiometer
- Post-launch, SeaWinds measurements were expanded to include T_b and an oceanic rain flag
  - Algorithm developed by CFRSL and implemented by JPL in science data processing

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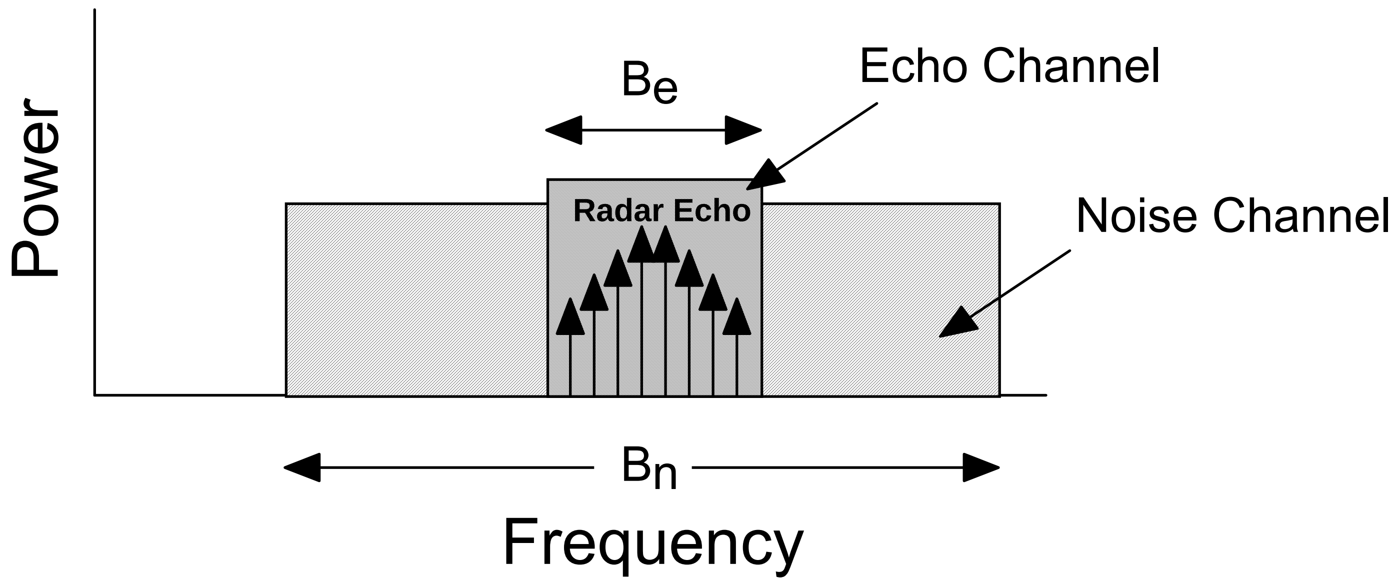
Scatterometer Measurement

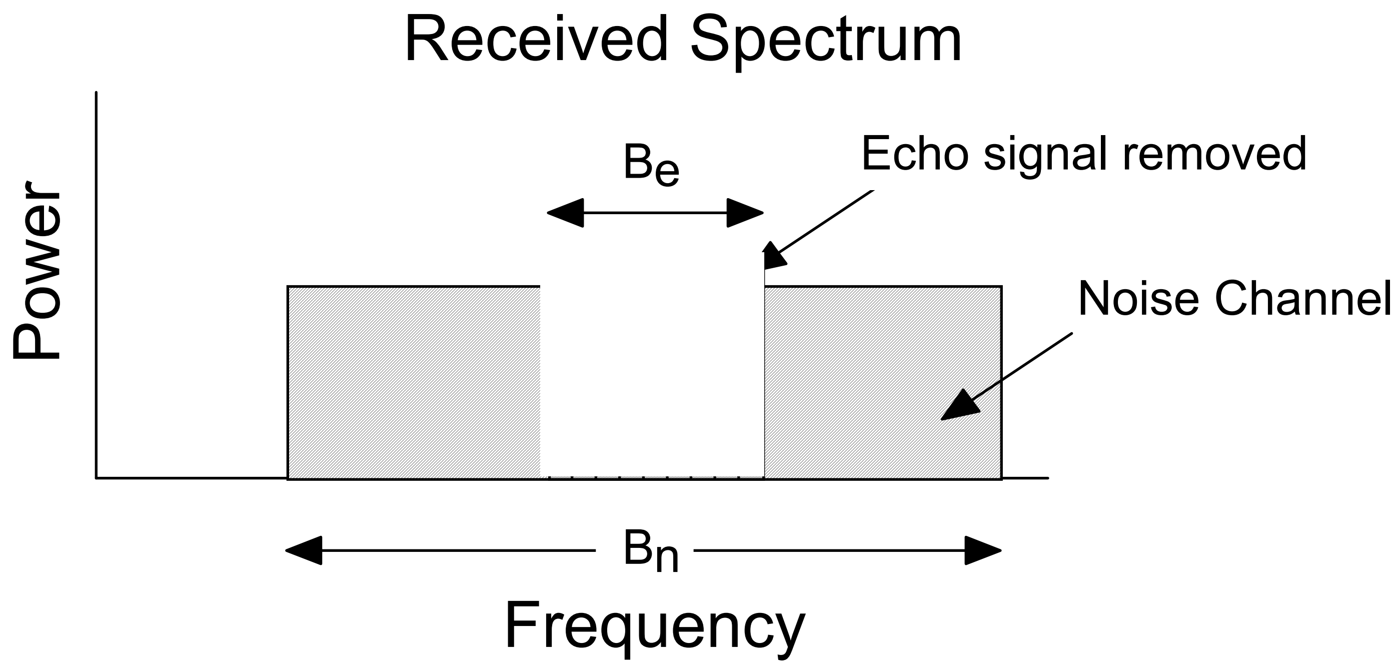
- Signal power (radar echo) measured in "echo" channel (high S/N)
- Noise power measured in parallel "noise" channel (low S/N)
- Noise chan subtracted from echo chan to yield the signal (surface backscatter power)

Received Spectrum

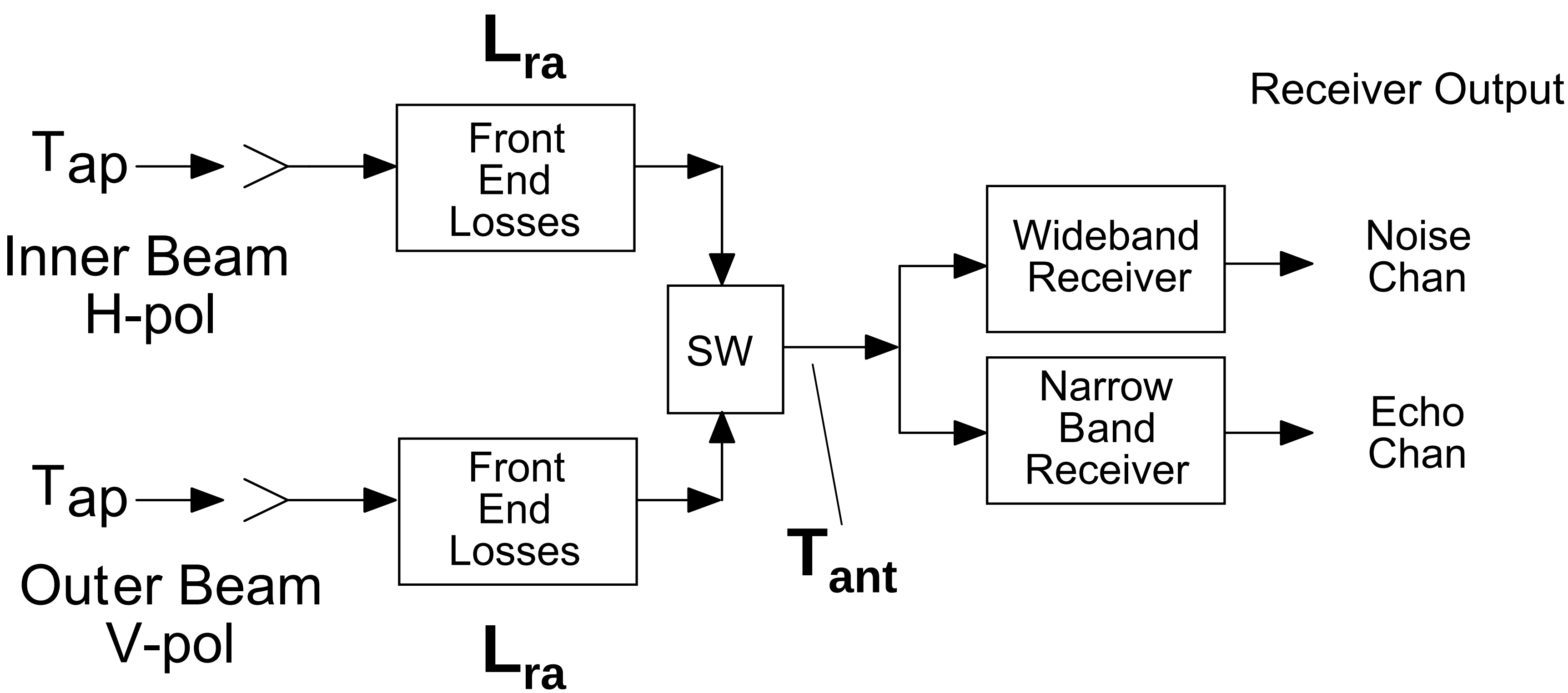


Antenna Excess Noise Measurement

- Echo channel is subtracted from noise channel to yield the differential antenna noise (Excess Noise)
  - Channel subtraction removes radar echo power



SeaWinds Receiver (Radiometer) Simplified Block Diagram



Effect of Losses on T_b

- Antenna temperature is the input to the radiometer receiver that includes:
  - Surface brightness temperature collected by the antenna (T_{ap})
  - Noise emitted transmission line losses (front-end losses, L_{ra})

$$T_{ant} = Tap\ L_{ra} + (1- L_{ra})T_{phy}$$

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Radiometer Transfer Function

- The measured radiometer output noise temperature equals the product of input (system noise temp) x (receiver gain)

$$T_{sys} = T_{ant} + T_{recvr}$$

$$T_{meas} = T_{sys} * \text{Gain}$$

Solving for

$$T_{ant} = (T_{meas} / \text{Gain}) - T_{recv}$$

$$Tap = [T_{ant} - (1 - l_{ra})\, T_{phy}] / l_{ra}$$

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Integrated Excess Noise Power

Excess Noise (N_{xi}) energy is the weighted difference between the noise channel and echo channel integrated output power

$$E_n = \int_0^{\tau} p_n dt$$

$$N_{xi} \approx \left(E_{ni} - \beta * E_{ei}\right)$$

- *p = noise or echo chan output power*
- E_{ni} = noise channel energy,
- E_{ei} = echo channel energy
- i = "h" (inner beam) and = "v" (outer beam)
- β = gain ratio = G_{noise}/G_{echo}

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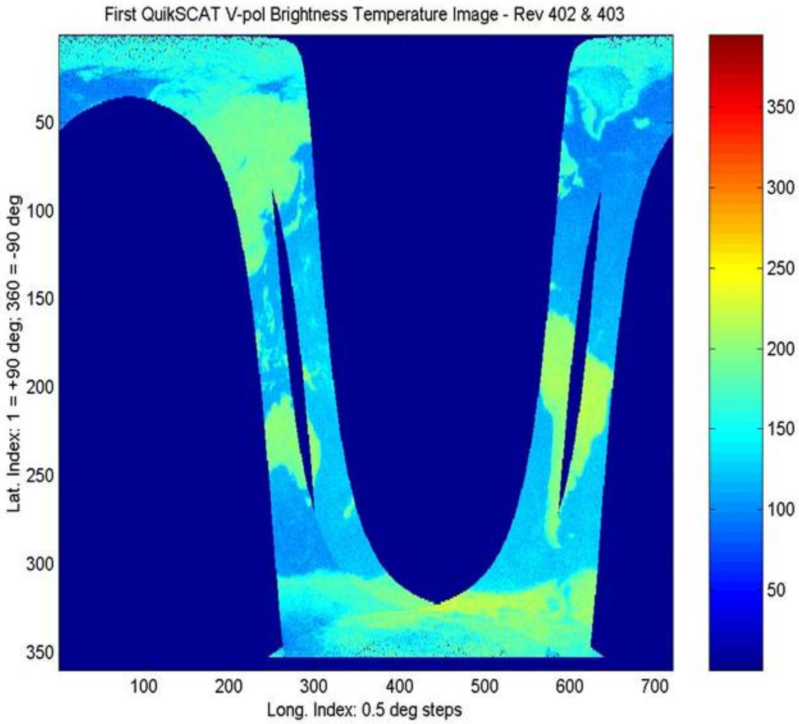
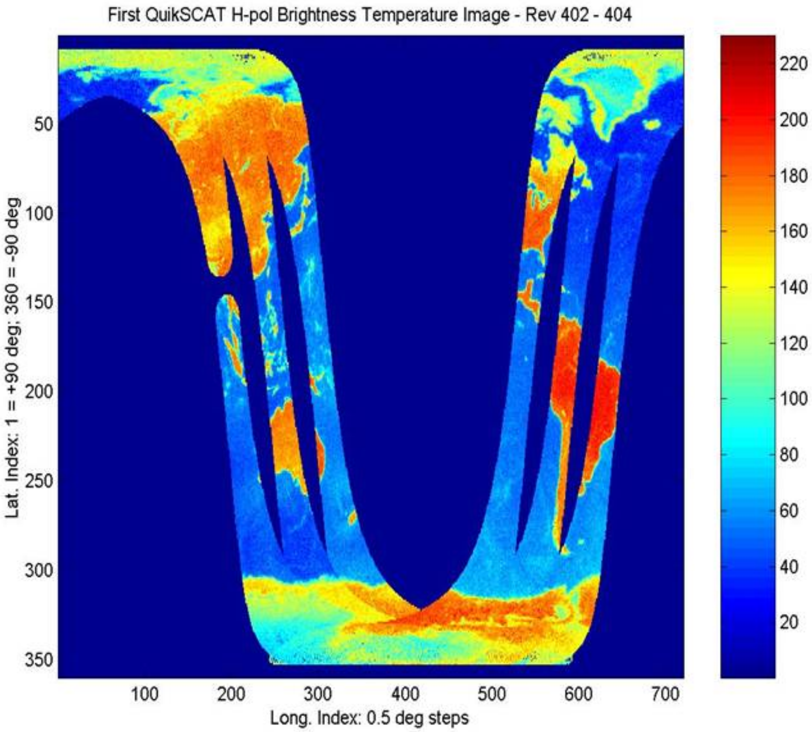
QRad First Tb Images

V-pol T_{bap}
at 54 deg incidence



H-pol T_{bap}
at 46 deg incidence



Inter-satellite Radiometric Calibration

QRad Inter-satellite Radiometric Calibration

- QRad Tb Validation History
  - TMI Tb Comparisons
- WindSat Tb Comparisons
  - QRad Tb Biases during continuous Sun-Lighted Orbits

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QRad Tb Measurement Performance is not well Validated!

- QRad L2A Tb product quality is not well validated
  - Algorithm tuning was preformed in 1999 using simultaneous ocean Tb comparisons with the TRMM Microwave Imager
  - Semi-annual QRad/TMI comparisons from Sept, 1999 - April, 2003
- QRad Tb algorithm performed poorly when applied to SeaWinds on ADEOS-2 in an orbit with ~ 50% day/night operation
  - Large Tb Biases (~ 10 K) were observed in the night-side of the orbit
  - Reason for algorithm failure was not determined

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My Dissertation Contributions

- Investigation of ADEOS-II QRad algorithm failure
- Development of MatLab version of QRad Tb algorithm
- Conduct of intensive QRad Tb validation
  - Absolute accuracy
  - Radiometric precision
  - Calibration stability
  - Land Tb evaluation

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Inter-satellite Radiometric Calibration (ocean)

- Performed to assess the quality of QRad radiometric (brightness temperature) L2A product
- Comparison of near-simultaneous ocean brightness temperature (Tb) between QRad and WindSat

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Inter-satellite Radiometric Calibration March-ups

- WindSat and QRad Tb's match-ups
  - 1° (lat x lng) boxes on monthly basis
- Primary calibration during continuous sun-lighted orbits
  - Aug 2005 and Feb 2006
- Secondary calibration during eclipse periods
  - Nov 14, 2005 - Jan 30, 2006

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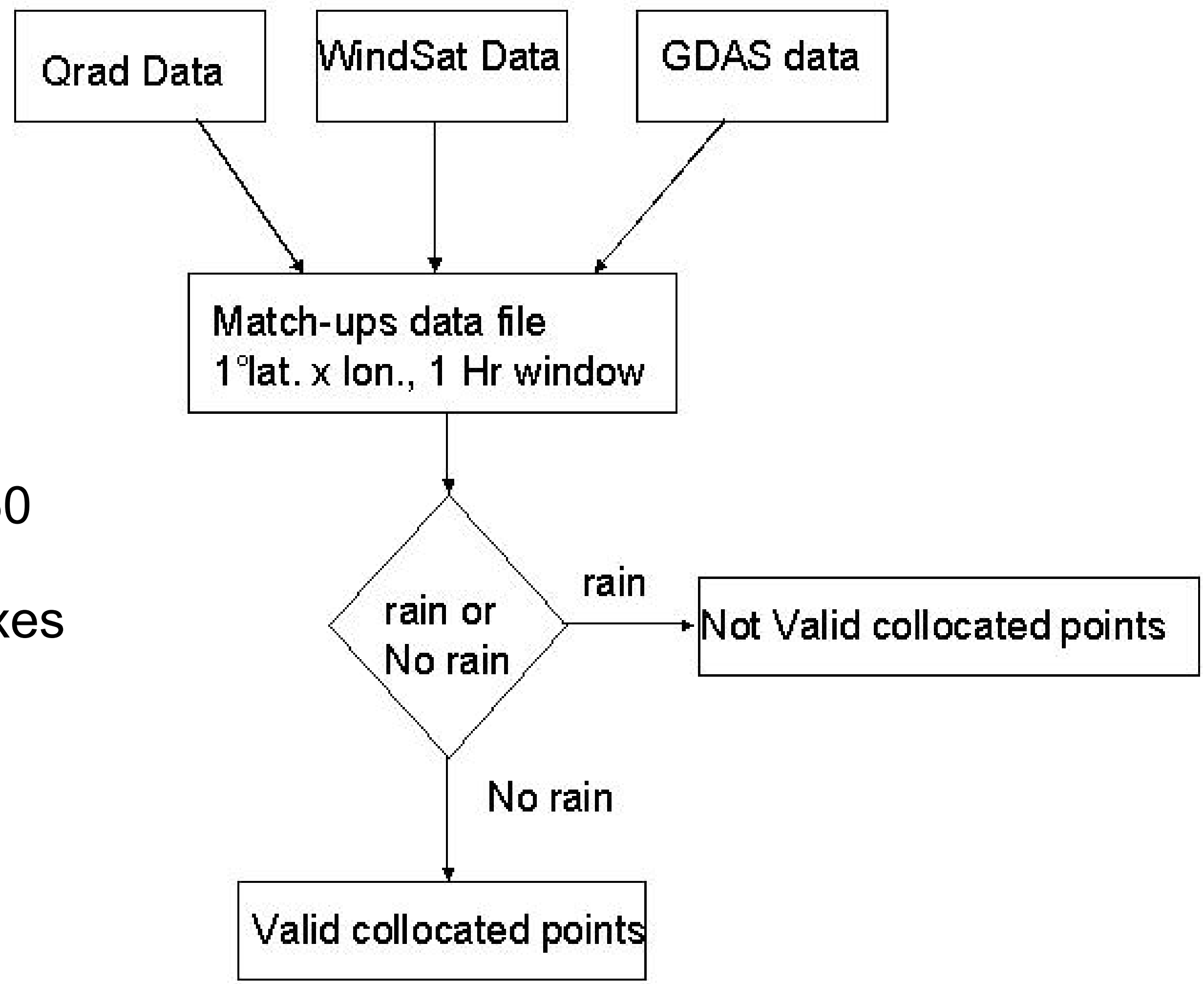
Match-up Data Sets



- Match-ups within ±60 minutes
- Spatial 1° lat & lng boxes
- ~ 200,000 # boxes/mo

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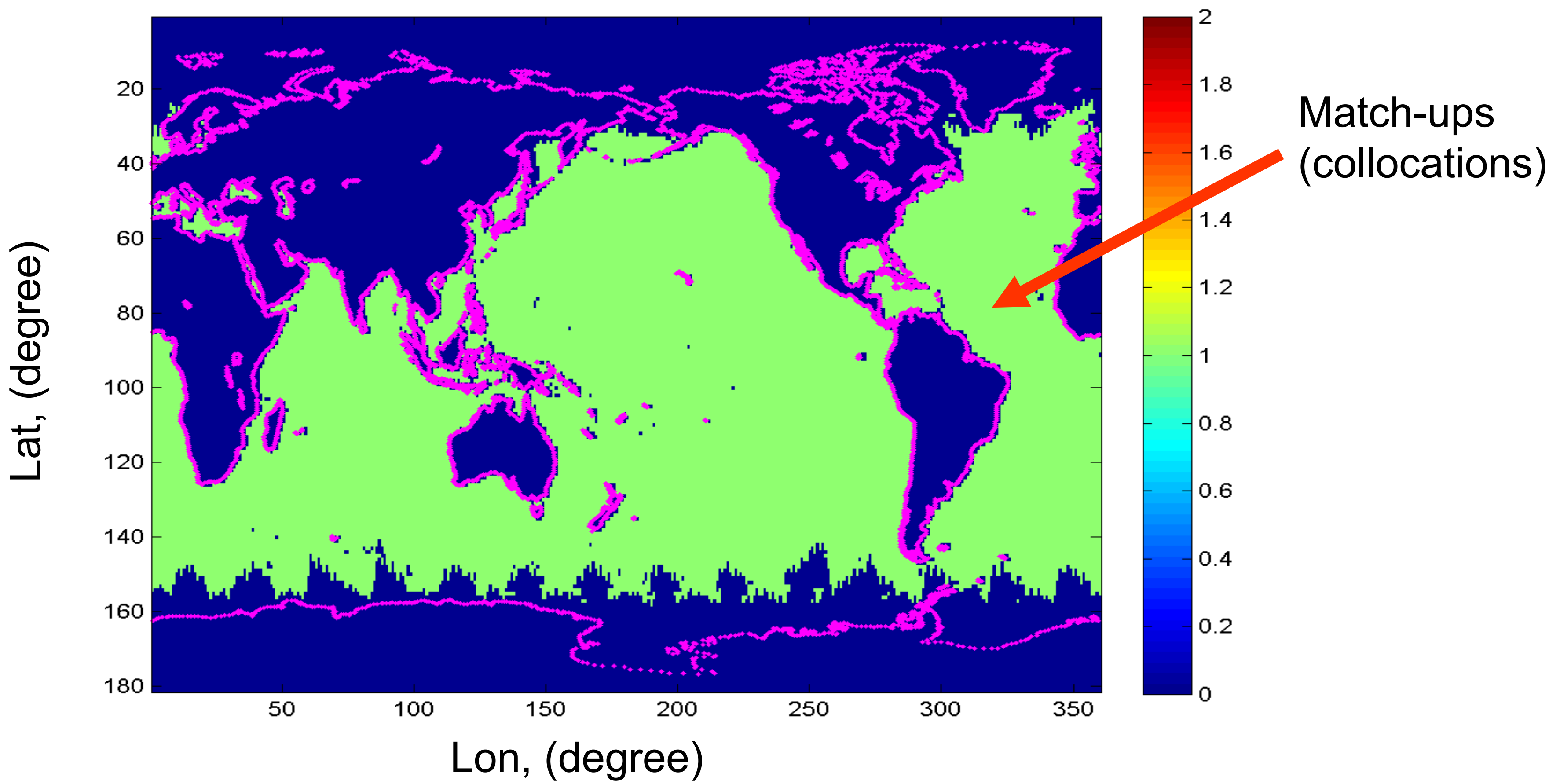
Typical Monthly QRad & WindSat Match-ups within ± 60 minutes



- ~200,000 match-ups per month

Tb Normalization

- WindSat *Tb* normalizations were required before QRad inter-comparisons were made
  - QRad operates at 13.4 GHz @ 46° & 54°
  - WindSat operates at 10.7 GHz @ 50.3°

- Radiative Transfer Model (RTM) was used to transform the WindSat 10.7 GHz measurements to the QRad equivalent frequency and the incidence angles

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WindSat Normalization cont.

- Run RTM
  - Calculate theoretical QRad T_b for environmental parameters (1°box)
    - $T_{b(QS\text{-}perdicted)}(f_{QS}, \Theta_{QS}, WS, SST, WV, CLW\ \ )$
      - Frequency = 13.4 GHz
      - Incidence angle = 54˚ (V-pol) & 46˚ (H-pol)
  - Calculate theoretical WindSat T_b for environmental parameters (1°box)
    - $T_{b(WS\text{-}perdicted)}(f_{WS}, \Theta_{WS,} WS, SST, WV, CLW)$
      - Frequency = 10.7 GHz & Incidence angle = 50.3˚
      - Incidence angle = 50.3˚ (V & H-pol)

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Expected Delta T_b (QRad to WindSat)

– Calculate the predicted (theoretical) T_b difference between QRad & WindSat

  - delta = $QRad_{predicted} - WS_{predicted}$

$$T_{b\ (Windsat\_13.4Ghz)} = WindSat_{\ (measured)} + delta$$

QRad Radiometric Bias

- $QRad\_bias = QRad_{(measured)} - T_{b\ (Windsat\_13.4Ghz)}$
  - $T_{b\ (Windsat\_13.4Ghz)}$ is the equivalent QRad brightness temperature derived from Windsat
  - $QRad_{(measured)}$ is the measured QRad brightness temperature

QRad Calibration Challenge - Large NEDT

- QRad radiometric precision or **noise equivalent delta-T** (NEDT) is large
  - NEDT = 27 Kelvin for a single radar pulse
  - NEDT = 11 Kelvin for L2A Tb in 25 km wind vector cell
- QRad Tb bias (mean values) calculated in 1° boxes
  - To improve mean bias estimate, zonal averages are performed (over all longitudes and 5°latitude bins) to form a latitude series

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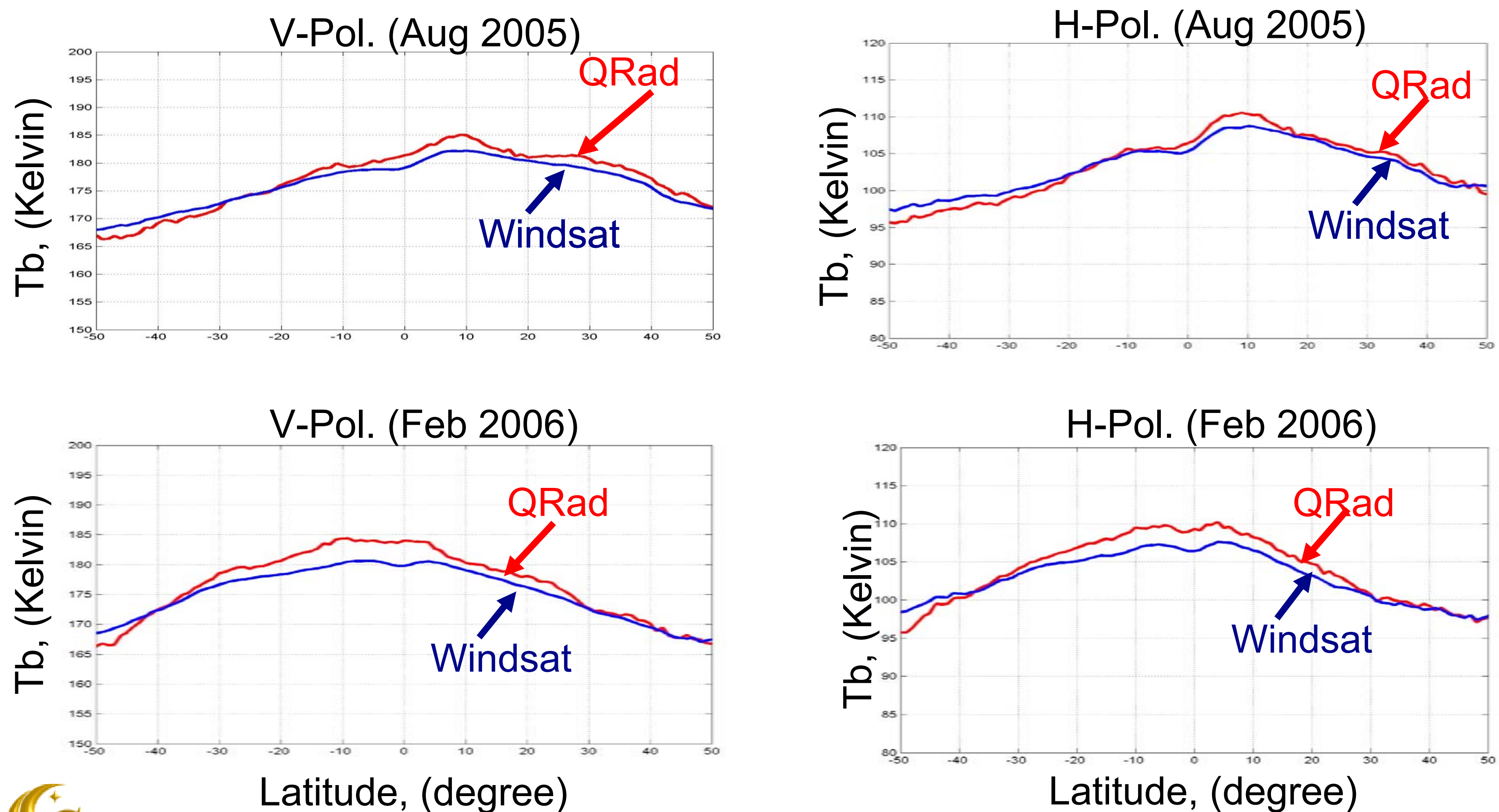
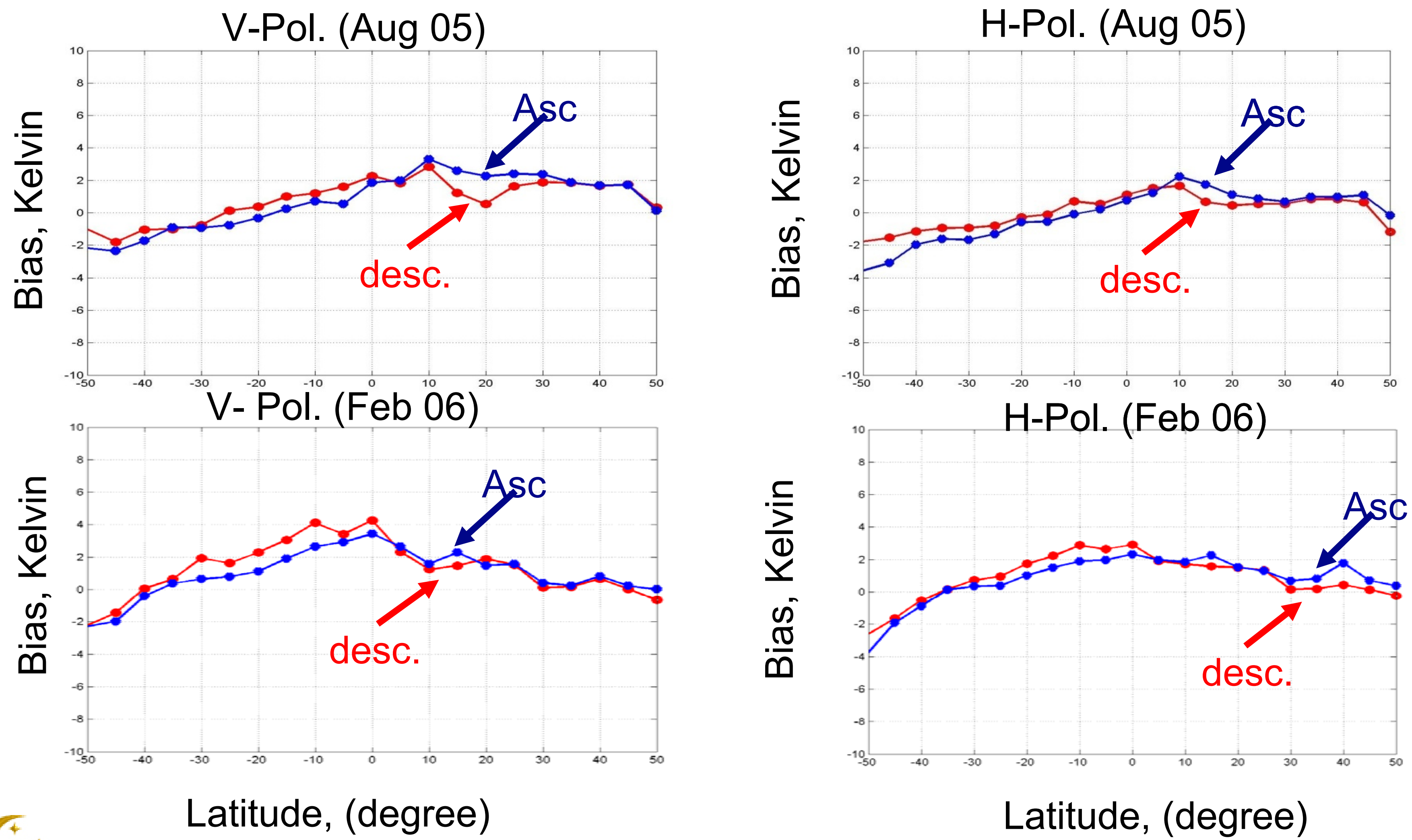
QRad Tb comparison with WindSat
Aug, 2005 & Feb, 2006



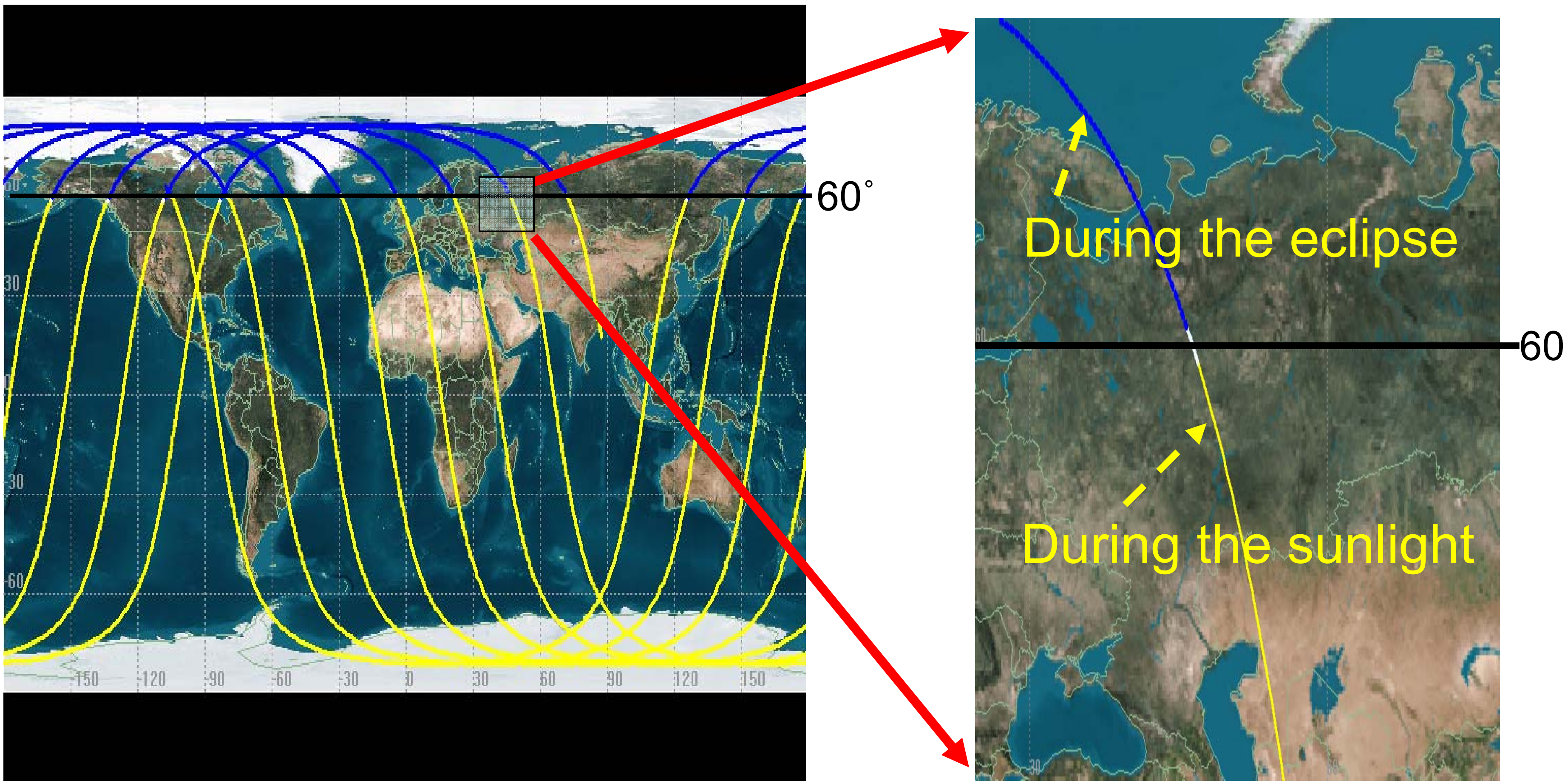
QRad Tb Bias Separated by Asc & Desc



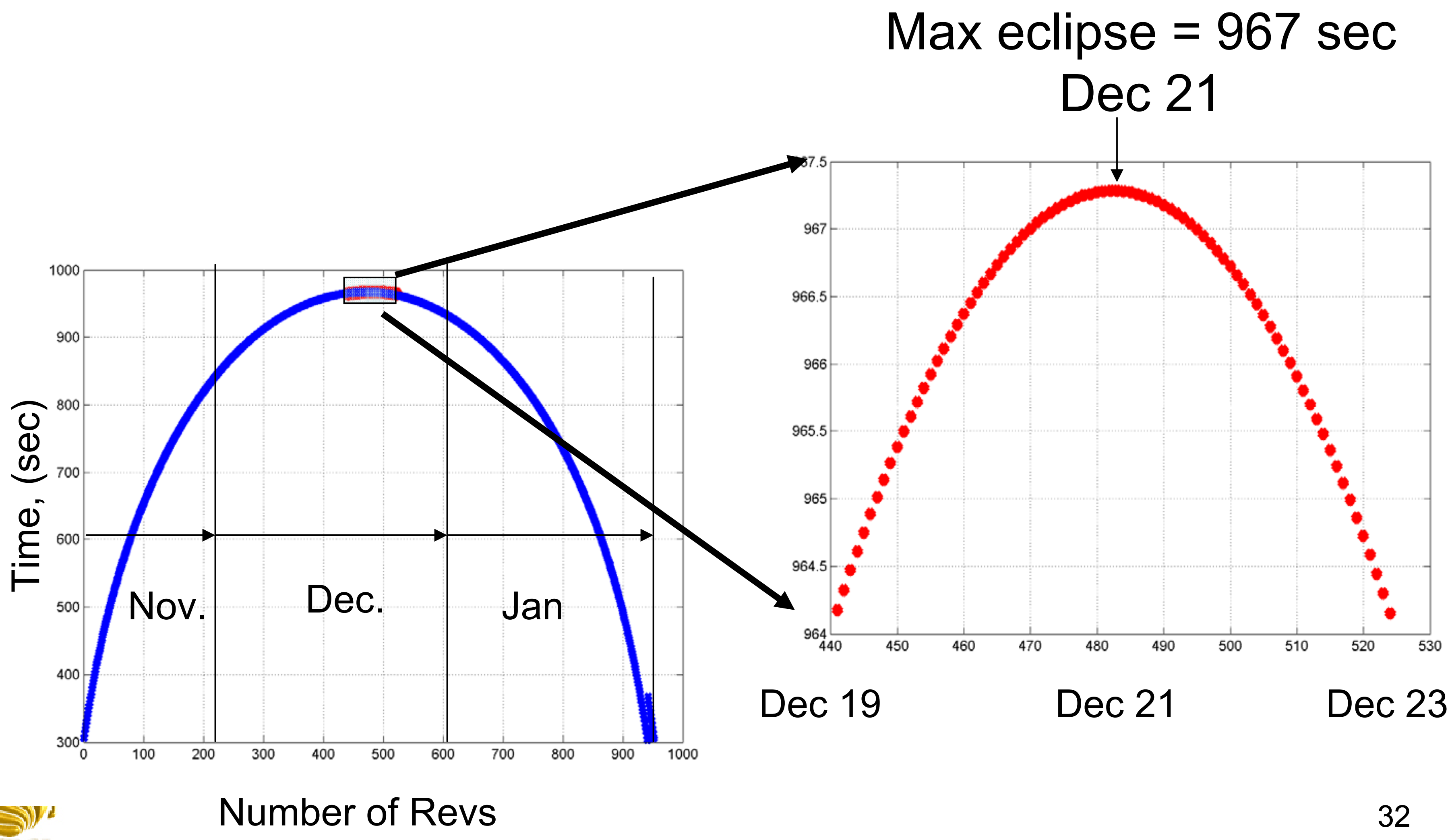
QRad Radiometric Biases During the Eclipse-Period Nov'05 - Jan'06

- During eclipse, the SeaWinds instrument undergoes a significant transient physical temperature cooling (from sunlight to night)
- Previous experience of SeaWinds on ADEOS-II demonstrated large Tb biases during dark side of the orbit

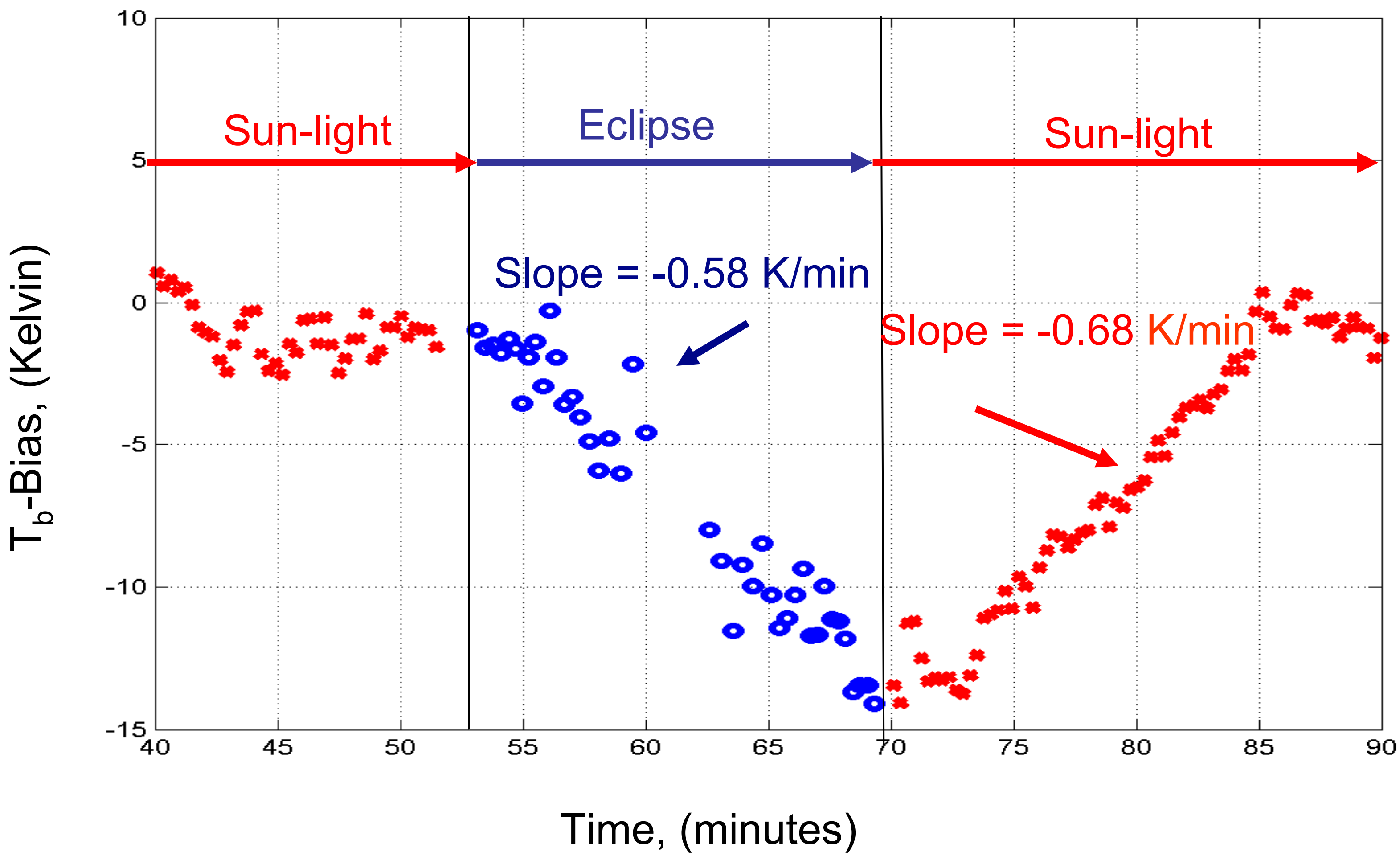
Typical QuikSCAT Ground Tracks
12 Hrs 12/21/05



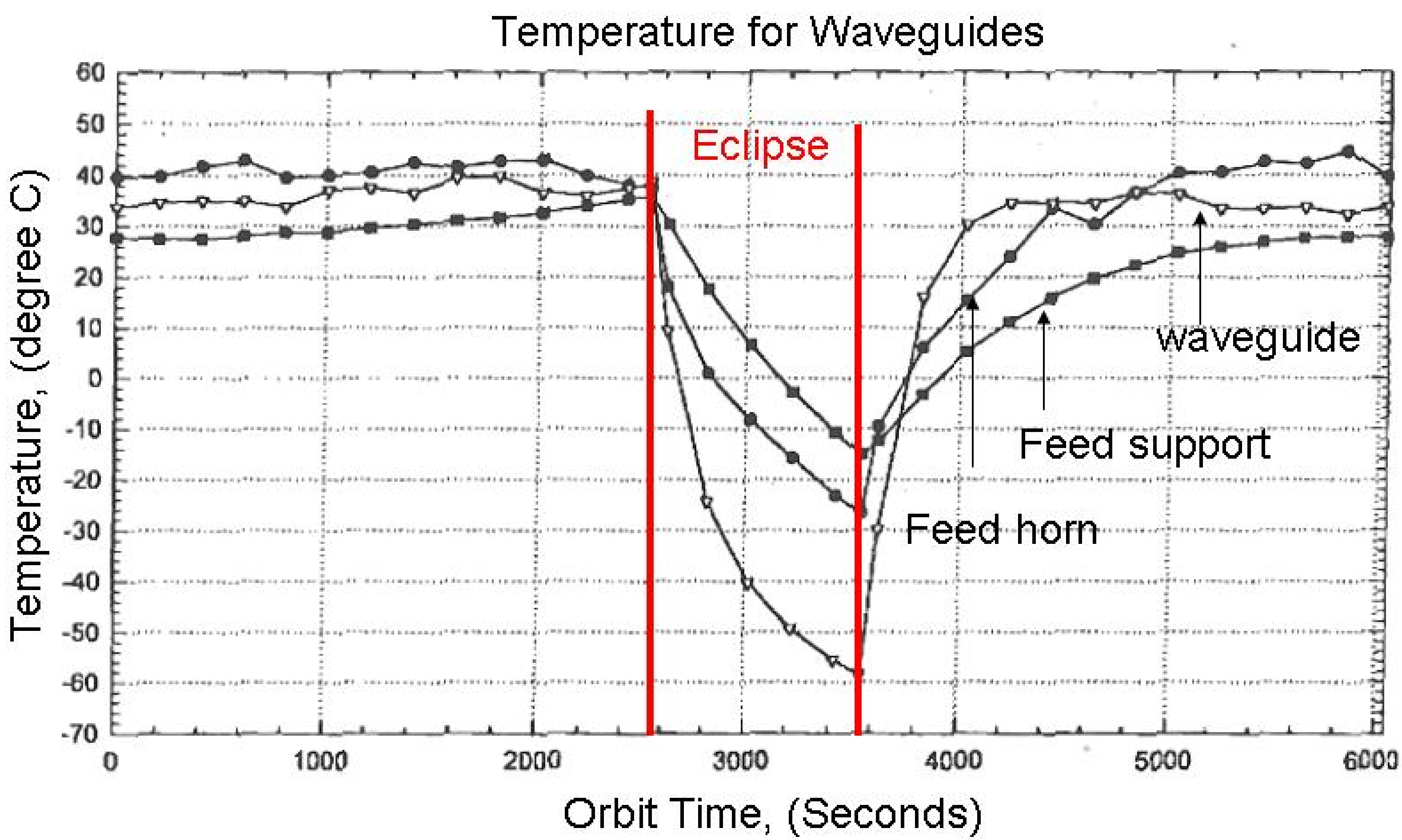
Eclipse period
11/14/05 through 1/30/2006



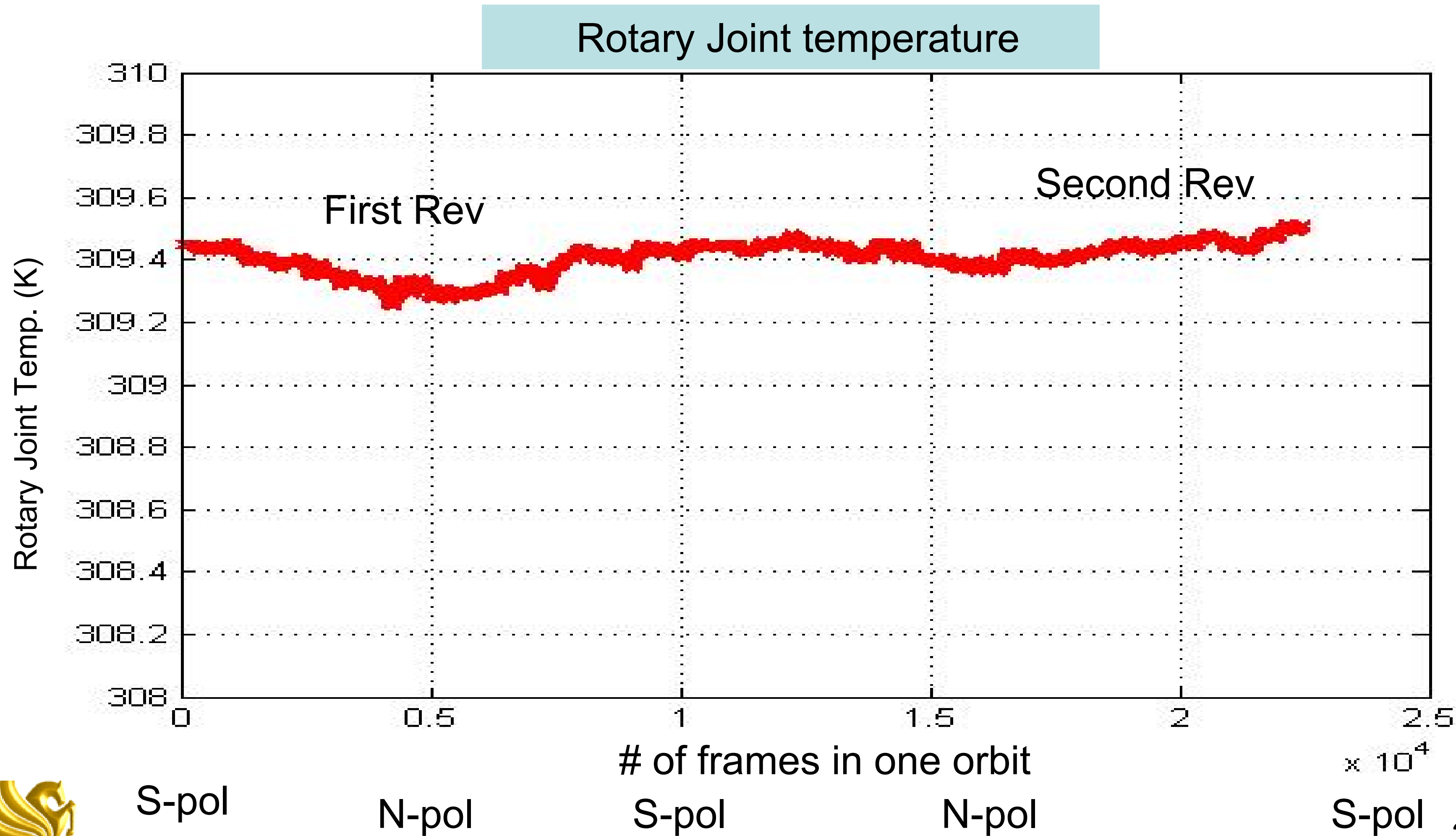
A Time-Varying Radiometric Bias During the eclipse and post-eclipse period (12/19/05-12/23/05)



JPL Thermal Model Results: SeaWinds Antenna Physical Temperatures During Eclipse



Assumed Front-end Loss Physical Temp During Eclipse



Characterize the radiometric bias for QRad during eclipse periods

- Front-end loses (L1B) = L1+L2+L3 = -1.06 dB,
  - wave guide loss L3 = -0.24 dB
  - Microwave rotary joint loss (L2) = -0.18 dB.
  - Feed assembly loss (L1) = - 0.64 dB
    - or a power ratio of 0.863
- The radiometric Tb bias introduced by this front-end loss during eclipse is:
  - (ΔTb_bias) = (ΔTphy) x (1- loss ratio)
    - (ΔTb_bias) = 95 x (1- 0.863) =~13 Kelvin

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QRad Tb Evaluation Over Land

QRad validation over land

- Differential energy calculation is more critical to radar echo cancellation over land
  - Provides a worst case scenario for evaluation of QRad transfer function
- Evaluate the effects of radar echo subtraction on QRad's T_b
  - Excess Noise (N_x) = $E_n - \beta * E_e$

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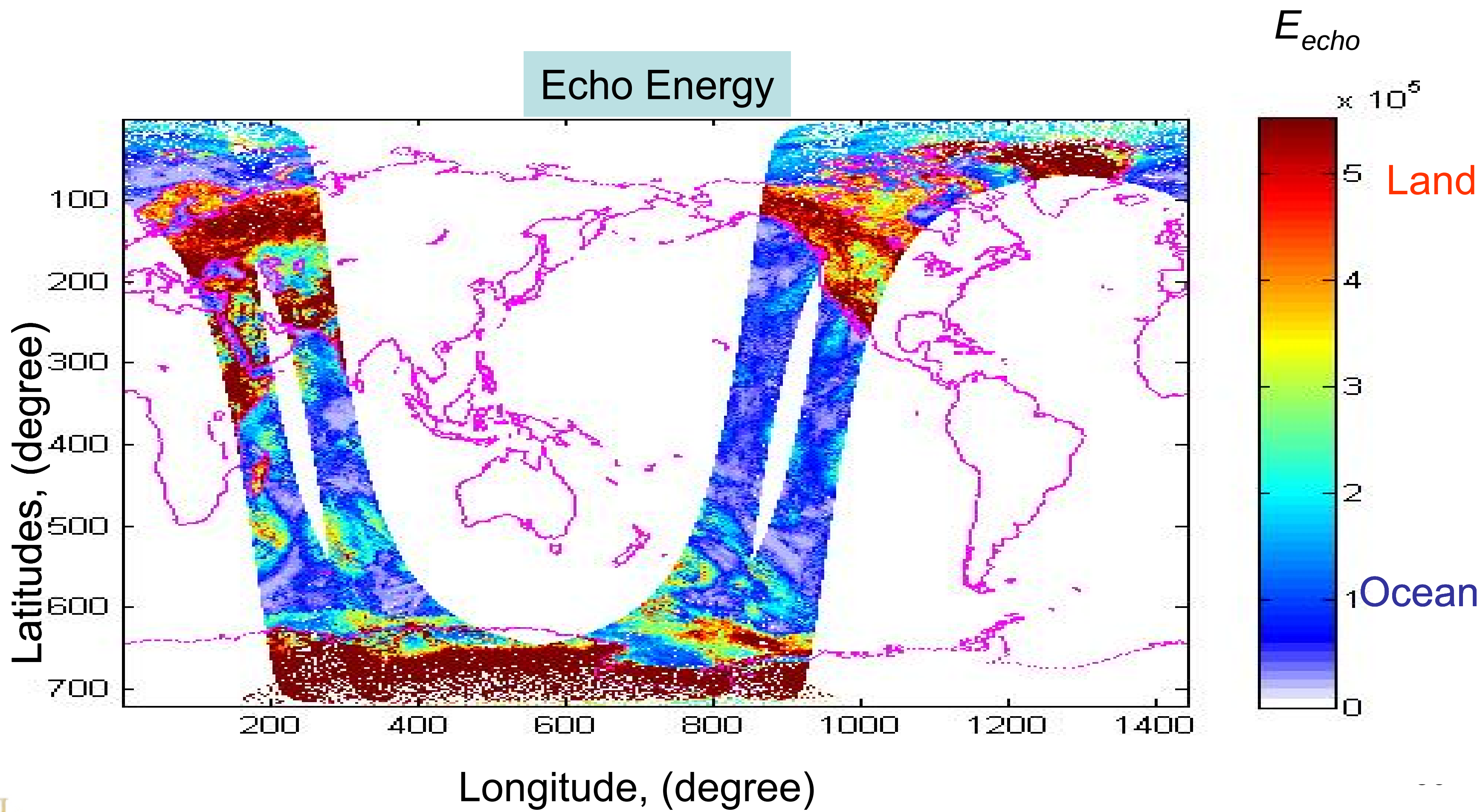
Echo Energy

- Average echo energy is five times larger over land than over ocean



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QRad Tb comparison with WindSat

- QRad's Tb's were compared to unadjusted Tb's from WindSat (@10.7GHz)
- Land surfaces are electromagnetically rough and emissivities are usually high (> 80%)
  - Change in Tb with incidence angle and frequency over 10 – 15 GHz range are usually small except for a small dc Tb offset
- Comparison was performed for five day average (Aug 1 through Aug 5)

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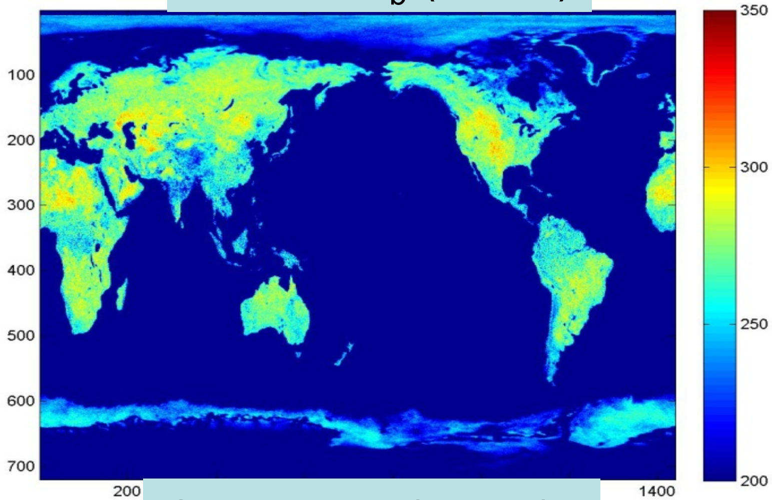
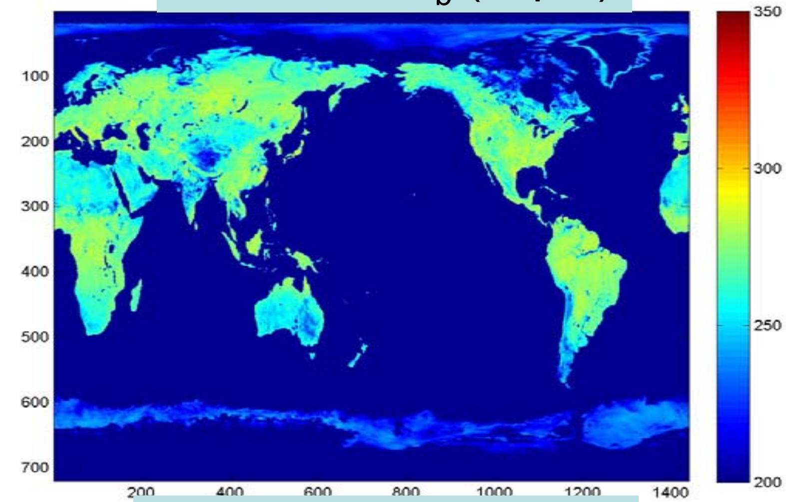
Average Tb over land (H&V-pol) (Aug 1-5)

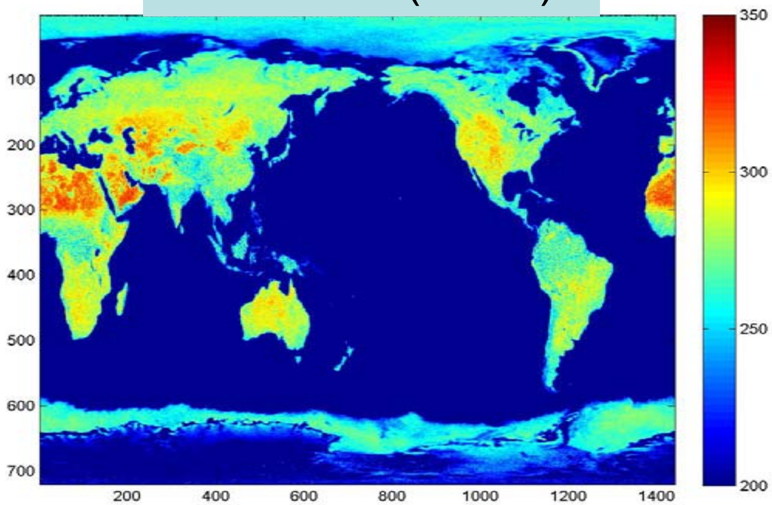
QRad's T_b (H-Pol)



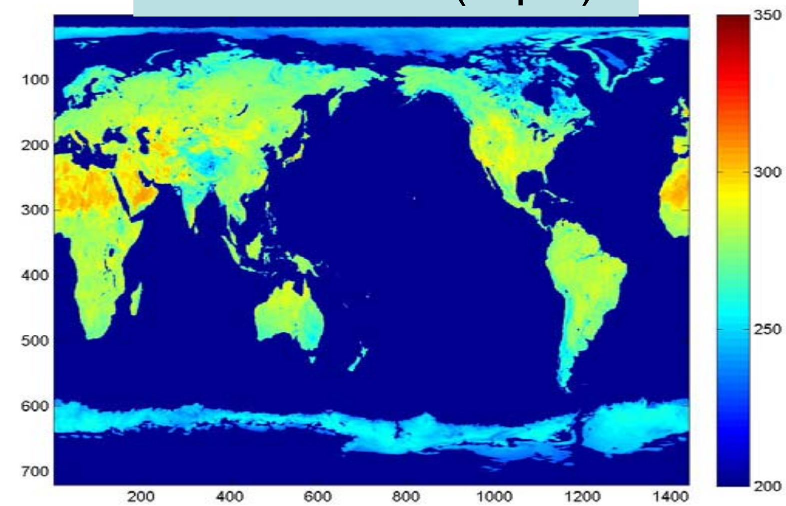
WindSat's T_b (H-pol)



QRad's Tb (V-Pol)



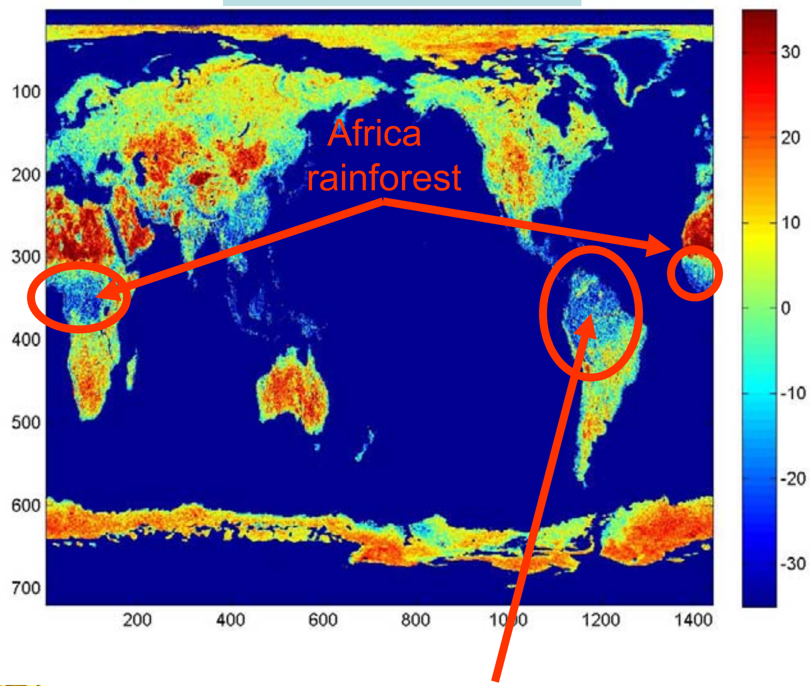
WindSat's Tb (V-pol)



T_b Bias Over Land (Aug 1-5)

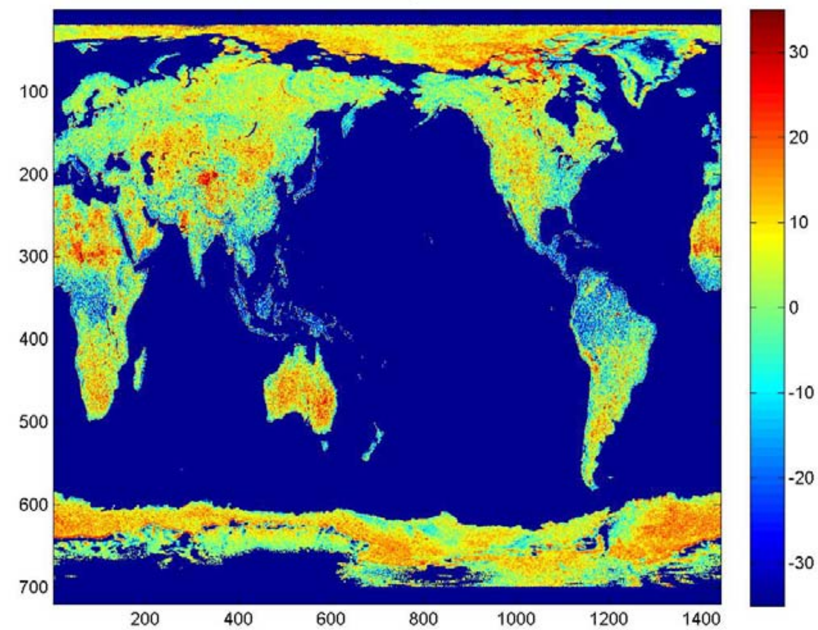
ΔTb = QRad - WindSat = Tb bias (H & V-pol)

Delta T_b H-Pol



Amazon rainforest

Delta T_b V-pol



Comparison Observations

- Systematic differences over large regions of desert, vegetated land, and sea ice
  - ΔT_b ~ -10 K (colder) over rainforest
  - ΔT_b ~ +15 K (warmer) Over deserts
- Tb differences are may be caused by
  - Geophysical (dielectric) property differences
  - Instrumental effects

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Instrumental Effect

- Instrumental effect can be easily examined by cross-correlating the echo channel energy (sigma-0) and QRad Tb bias ΔT_b
  - Effect of residual echo channel energy after subtraction on the ΔT_b
  - Echo channel energy is directly proportional to radar cross section(Sigma-0)

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Effects of radar echo subtraction (cont.)

- Tb transfer function was examined

$$Nx = E_n - \beta E_e = E_n - \beta P_r \tau - \beta k T_{sys} B$$

$$= E_n - \frac{\beta X \sigma \tau}{R^4} - \beta k T_{sys} B_e$$

  - QRad Tb is proportional to the excess noise (*Nx*)

- SeaWinds L2A data product was used to get 5 days averages of σ^o

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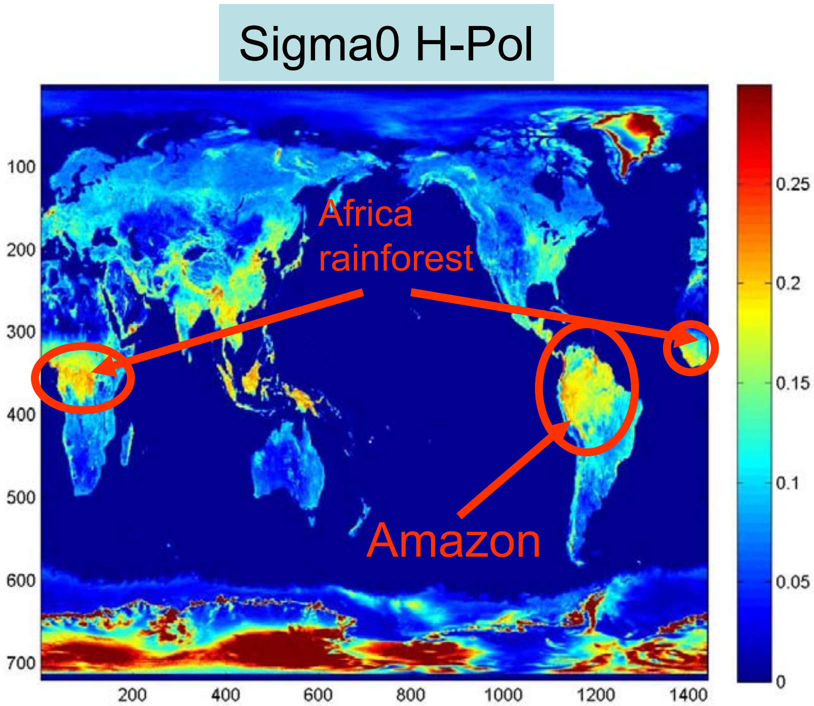
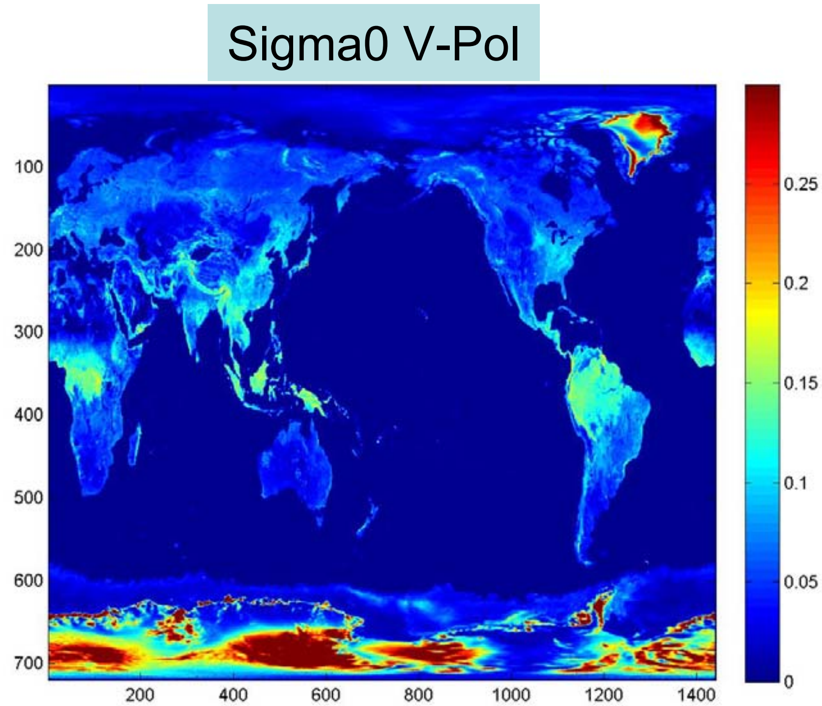
Surface Radar Cross Section (σ^o) (Aug 1-5)





- Sigma-0 is high over the tropical rainforest
- Sigma-0 is low over deserts

Surface Radar Cross Section Analysis

- Images of sigma-0 and ΔT_b are anti-correlated
  - high sigma-0 correlated with low ΔT_b bias and vice versa
  - Cross-correlation analyses were performed
    - ΔT_b versus sigma-0 for land
  - Data were averaged using 0.01 sigma-0 bins to establish the mean trend for both polarizations

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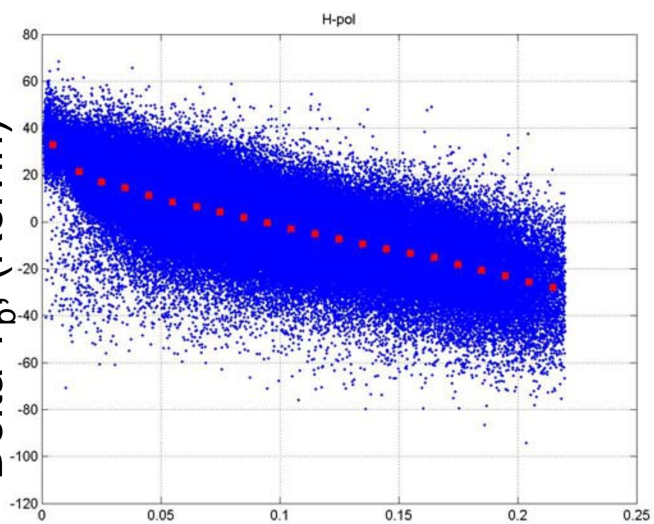
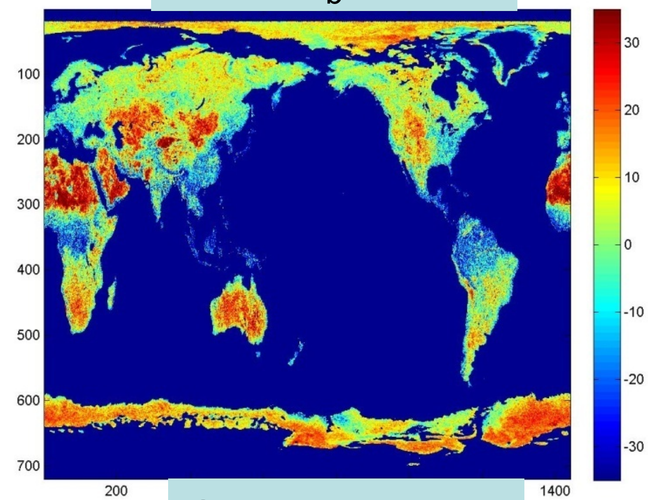
Comparison of delta Tb and sigma-0 Over Land (H-pol) (Aug 1-5)

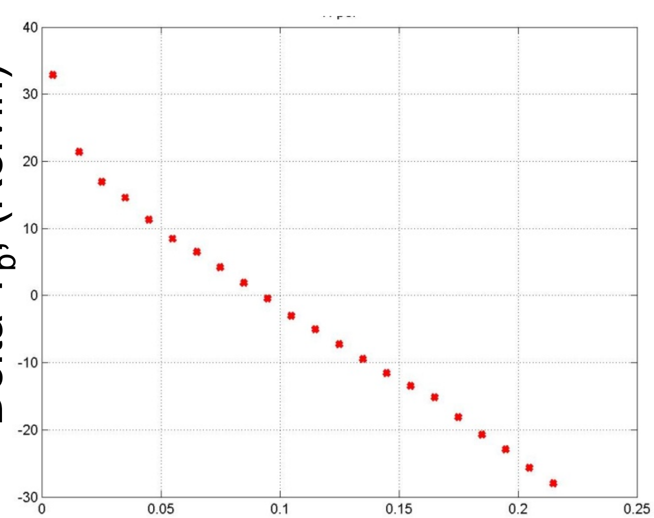
Delta T_b, (Kelvin)



Delta T_b H- pol.

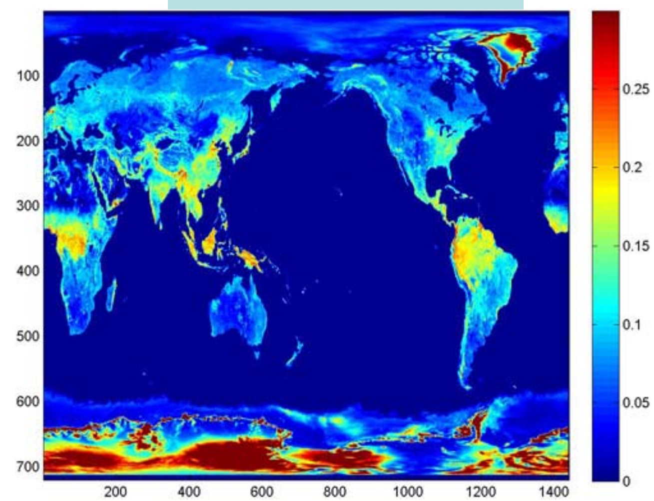


Delta T_b, (Kelvin)

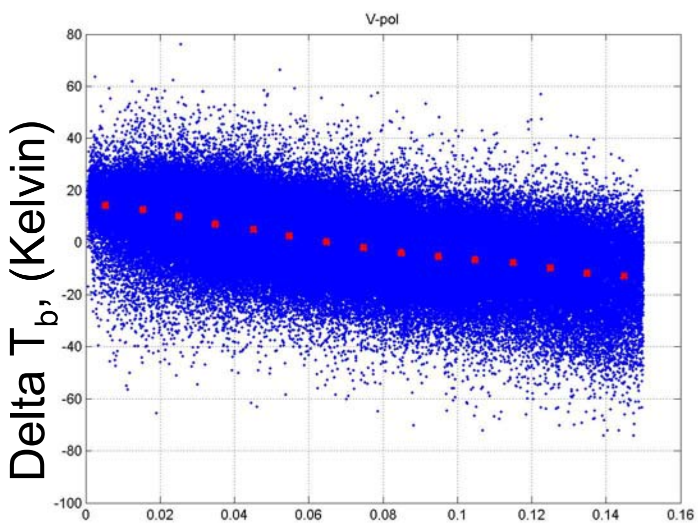


Sigma0 H-POL

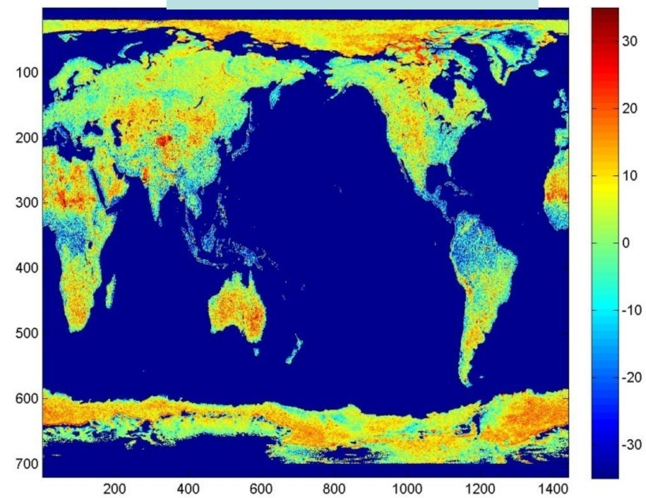
Sigma0 H- pol.

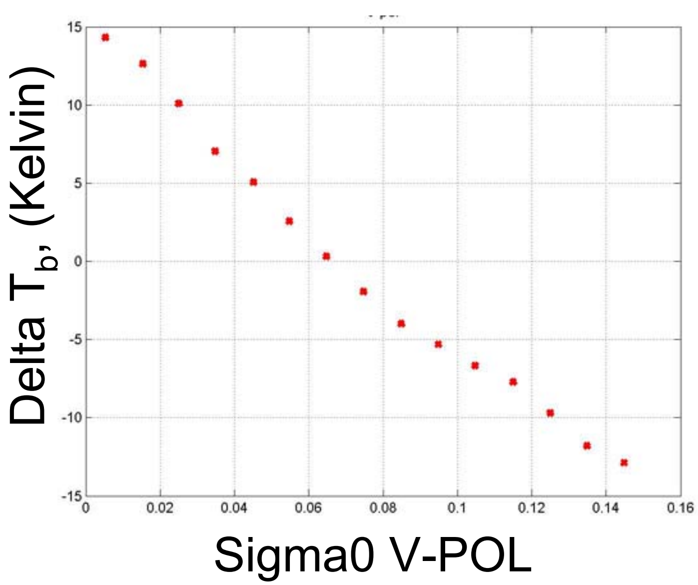


Scatter diagram for delta Tb and sigma0 (V-pol) (Aug 1-5)

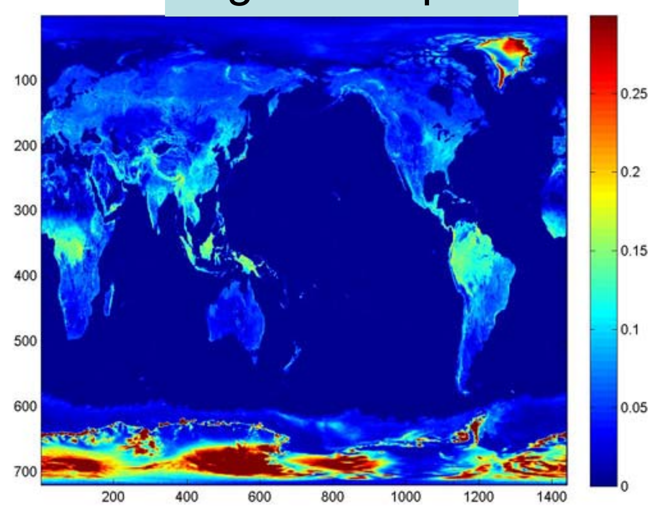


Delta Tb V- pol.





Sigma0 V- pol.



Tuning QRad Transfer Function Coefficient (β)

Tuning QRad Transfer Function

- QRad transfer function optimized to remove dependence of Tb on echo channel energy
- The optimum value for β makes the Tb bias over land independent of sigma-0
  - β parameter is the gain ratio = G_{noise}/G_{echo}

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CFRSL MatLab Code Development

- JPL's QRad Tb algorithm processing code was not available to tune the QRad transfer function parameters (β)
- A MatLab version of QRad T_b algorithm was developed
  - Algorithm input: JPL L1A and L1B data files
  - Algorithm output: equivalent L2A T_b's

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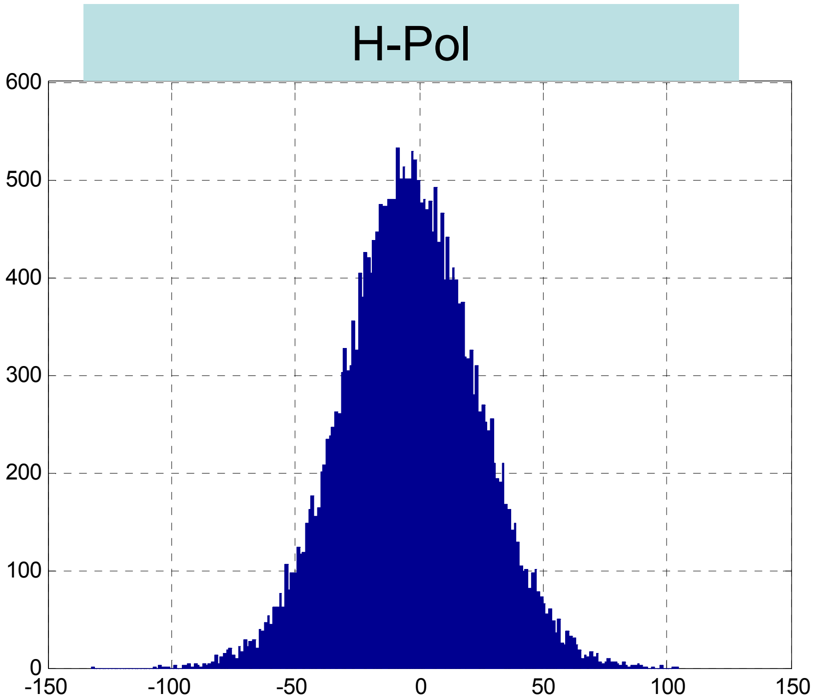
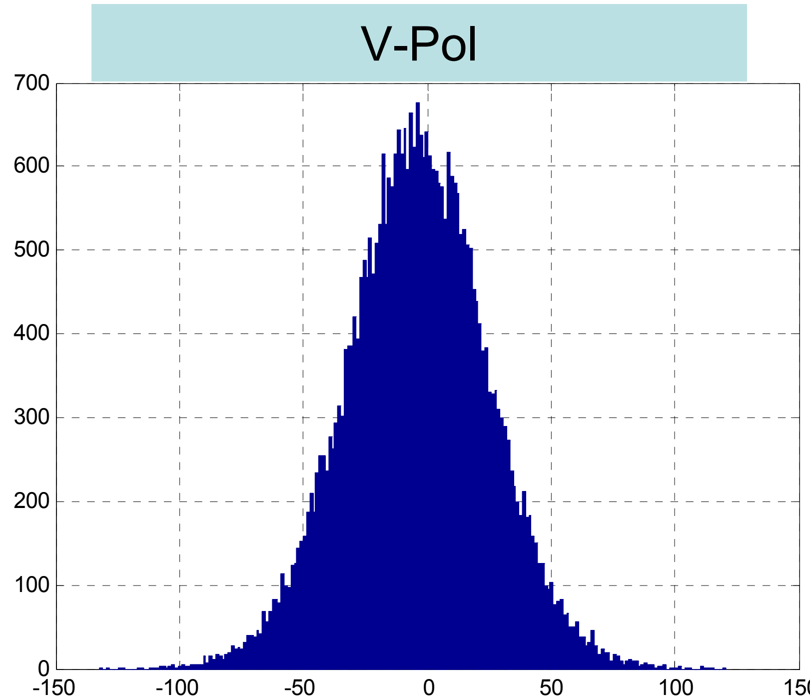
QRad T_b Differences over 25 km boxes: CFRSL - JPL





Mean value = -3.6113
STD = 26.7254

Mean value = -3.8301
STD = 28.5683

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Tuning Beta

- Five days (~75 revs) L2A Tb's processed
- QRad transfer function was optimized by parametrically adjusting β value
  - Beta parameter varied from 2.900 to 2.920
  - Delta Tb = QRad_modeled – WindSat
    - QRad_modeled is generated from L1A andL1B
- The optimum value was found to be 2.914 (instead of previously determined 2.917)

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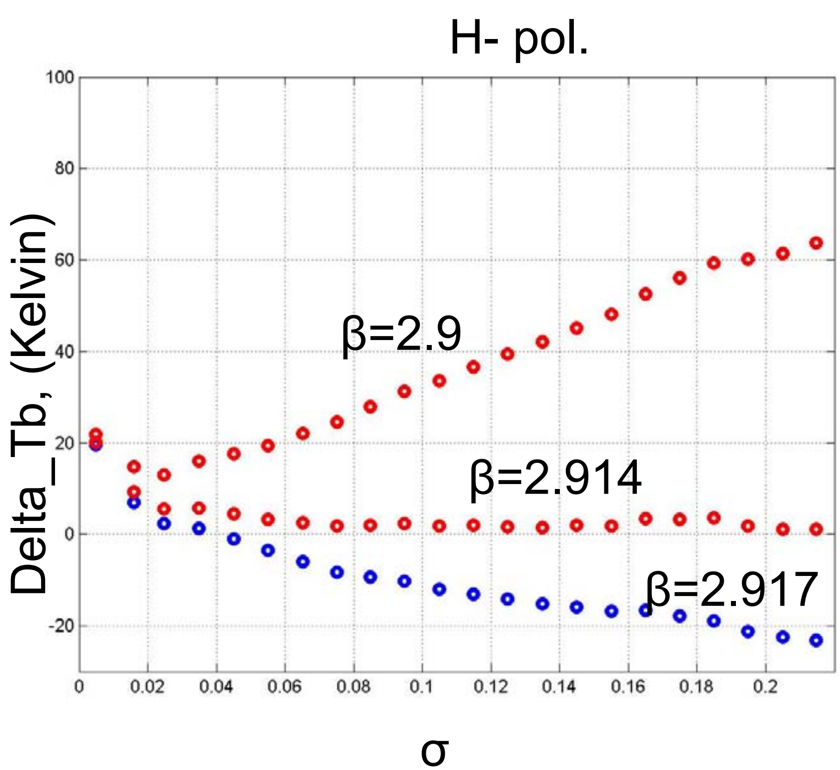
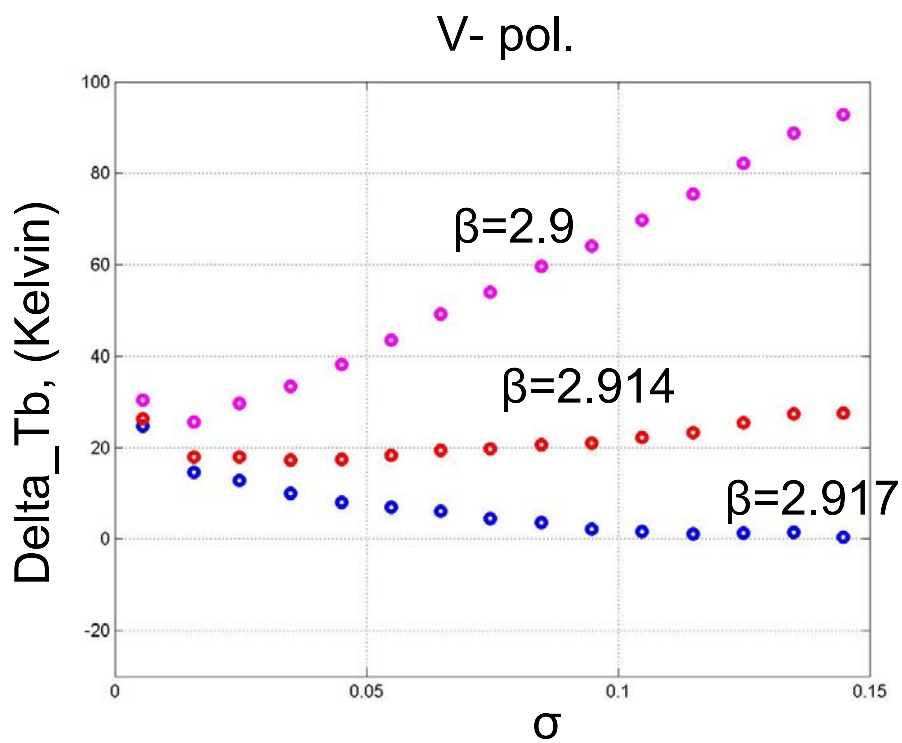
Beta Optimization Results





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Summary and Conclusion

- The QRad microwave brightness temperature algorithm (JPL L2A product) has been validated
- Inter-satellite radiometric calibration with WindSat was performed
  - QRad Tb calibration over oceans during continuous sun-lighted orbits
    - Absolute measurement accuracy
      - ± 2 K Mean Tb biases relative to WindSat (standard)
    - The radiometric precision (NEDT)
      - 15 K (V-pol) & ~12 Kelvin (H-pol)
    - Evaluate calibration stability
      - Small seasonal changes in QRad Tb biases (< 2 - 4 K)
      - Major changes during eclipse periods

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Summary and Conclusion

- Changes during eclipse periods (thermal transient case)
  - Biases are variable during eclipse orbits
    - Max QRad bias ~ - 13 K (too low) coming-out of eclipse
    - Cause is error in assumed antenna front-end loss physical temperature
    - Bias transient starts at eclipse and ends ~ orbit/4 post-eclipse
- Ocean T_b near land was evaluated
  - Must use conservative mask of ~ 400 km from land
- T_b over land was evaluated
  - Discovered systematic T_b calibration biases
  - Biases correlated withland sigma-0
- QRad T_b algorithm future improvements
  - Beta parameter set to 2.914 for the next version of the QRad Tb algorithm

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Conference Publications

- **Rafik Hanna**, Linwood Jones," Evaluation of QuikSCAT Radiometer Ocean Brightness Temperatures" USNC/URSI National Radio Science Meeting, June 2009
- Linwood Jones, **Rafik Hanna,** "Validation of QuikSCAT Radiometer Brightness Temperatures " SeaWinds OVW Science Team Meeting, Sept. 2008
- **Rafik Hanna**, Linwood Jones," Brightness Temperature Validation for SeaWinds Radiometer using Advanced Microwave Scanning Radiometer on ADEOS-II" IGARSS'07, July 2007
- Guillermo Gonzalez, **Rafik Hanna**, Liang Hong, and W. Linwood Jones, "HF Communications Analysis for Varying Solar and Seasonal Conditions" SoutheastCon '07, June 2007

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Journal Publications

- **Rafik Hanna**, Linwood Jones," Evaluation of QuikSCAT Radiometer Ocean Brightness Temperatures", to be submitted to IEEE TGARS, Summer 2009

Backup Charts

QRad/WindSat Ocean Radiometric Calib:

- Sun-lighted Orbits
- Eclipse

Characterize the radiometric bias for QRad during sun-lighted orbits

- To investigate the cause for this systematic Tb difference between QRad and Windsat, the radiometric bias was examined separately for ascending (asc) and descending (dec) portions of the orbit.
- zonal averages were performed, using 5° latitude bins (to compensate for the reduced number of samples) to form a latitude series, which preserved the once per orbit pattern of radiometric biases.

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Cause of radiometric bias: Examine QRad transfer function

- QRad's T_b were colder than the WindSat's T_b in the southern hemisphere by ~2K and warmer in the northern hemisphere by ~2-3 K for both H- and V-pol
- Ascending and descending portions track each other with latitude, and the difference is generally within ± 1 K.
- This is a very favorable result in that the biases are nearly identical with relative orbit time (latitude) and stable during the continuous sun-lighted orbits for both winter and summer
- This supports the notion that the bias is a common-mode effect within the QRad Tb algorithm and eliminates the possibility that the cause is related to ascending and descending effects, which are manifested in a local time of day phenomenon for the ocean Tb's.

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Possible Causes for Systematic Tb Biases versus Lat

Hypothesis:

- The orbital variation in receiver (noise) temperature (Tr) could cause the observed Tb bias pattern

$$T_{ant} = T_{sys} - T_r$$

$$T_r = f(T_o)$$

Where

T_o is the receiver physical temp

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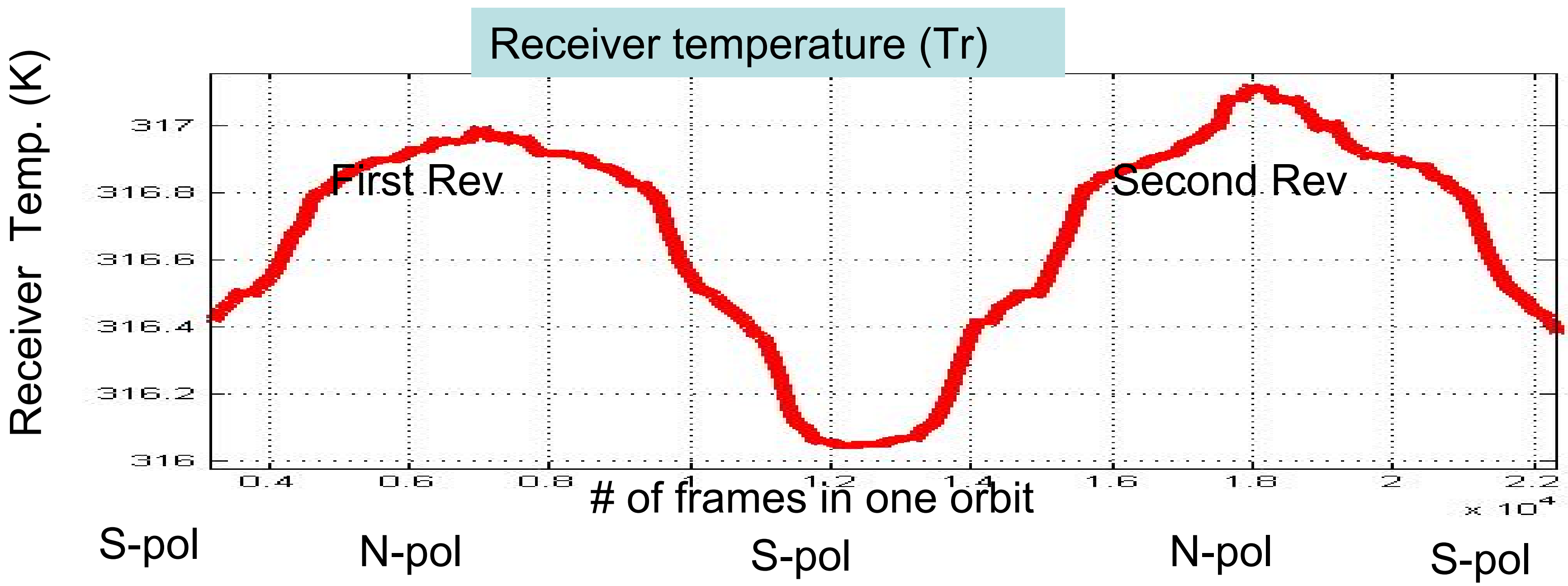
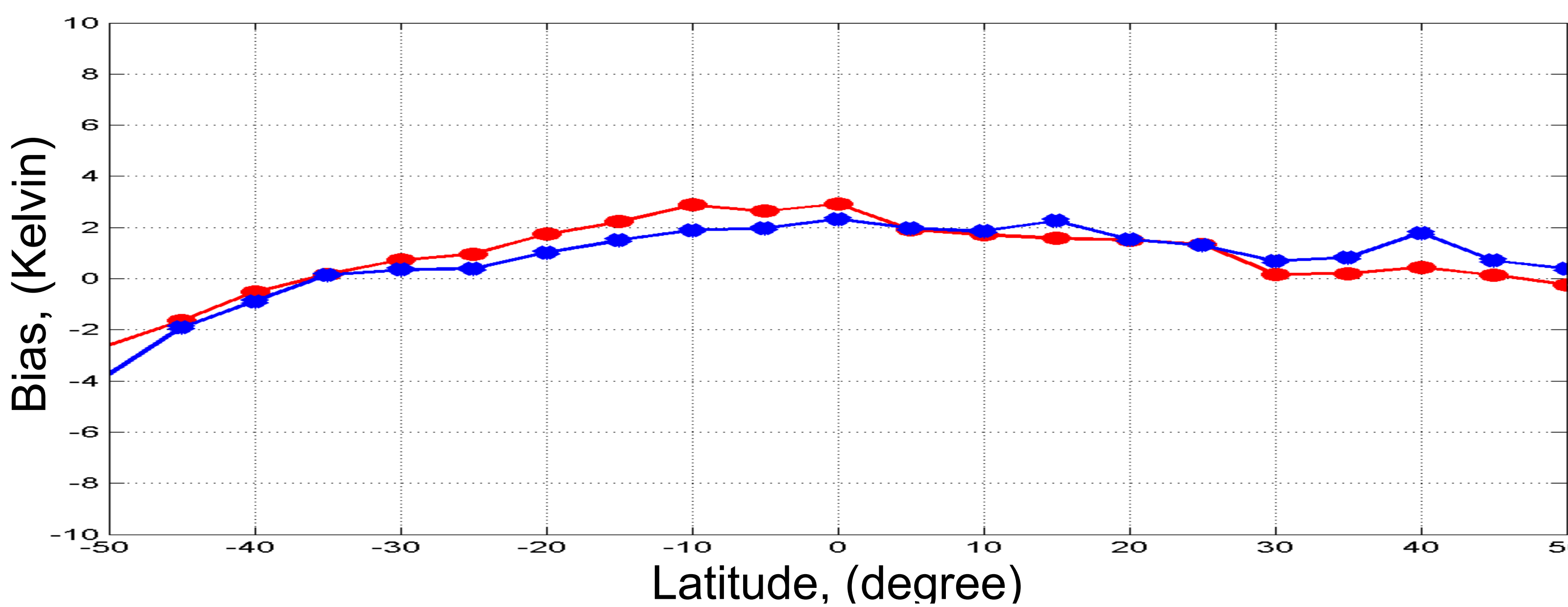

Receiver temperature (Tr)
Receiver Temp. (K)
317
316.8
316.6
316.4
316.2
316
First Rev
Second Rev
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
x 10^4
# of frames in one orbit
S-pol
N-pol
S-pol
N-pol
S-pol


Bias, (Kelvin)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-50
-40
-30
-20
-10
0
10
20
30
40
50
Latitude, (degree)

QRad Radiometric Calibration During the Eclipse-Period

- During these periods, the SeaWinds instrument undergoes a significant physical temperature cooling transient (from sunlight to night)

- To assess the quality of the QRad during the eclipse period, zonal averages were performed over longitude using 5° latitude bins Latitude series were created, and monthly averages for month (January)

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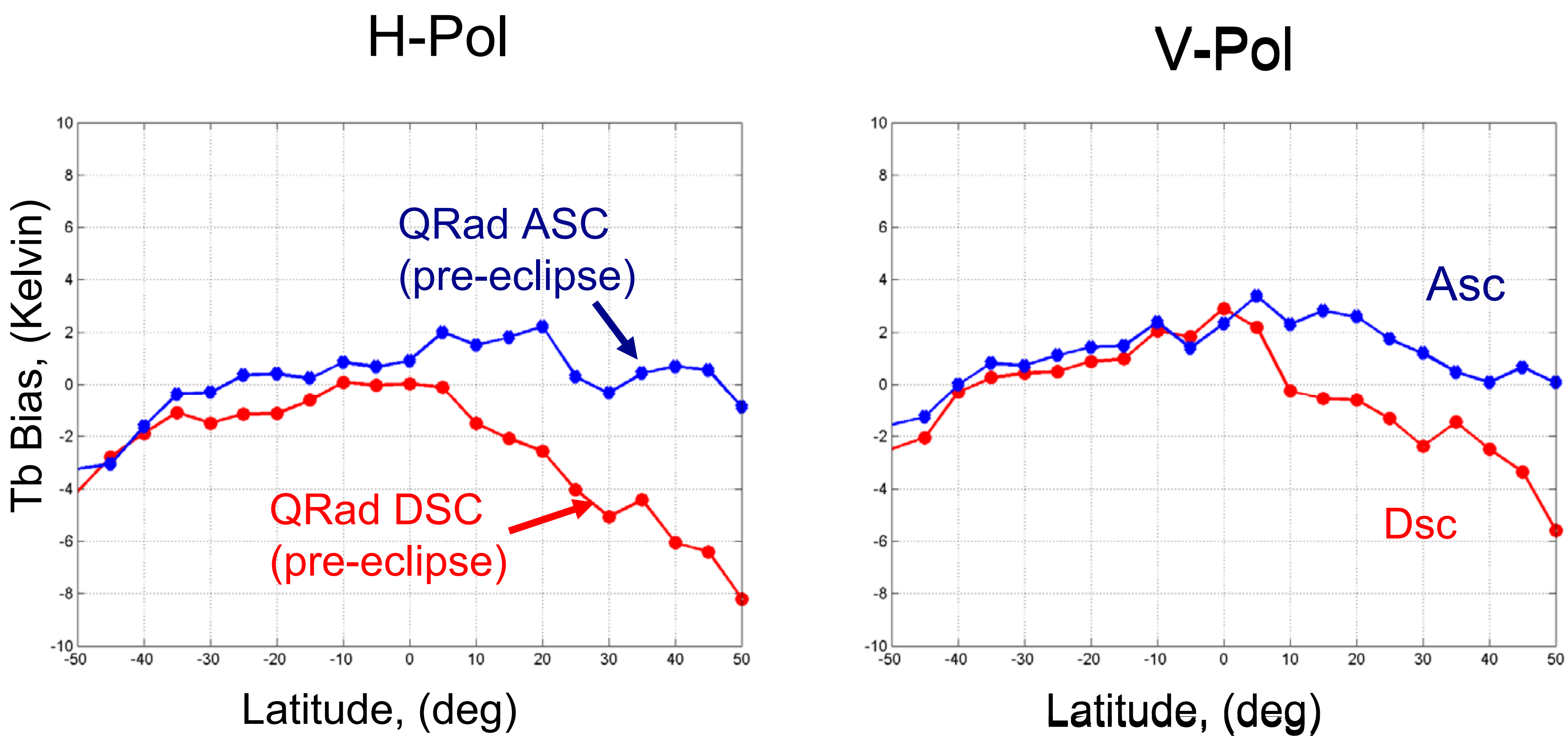
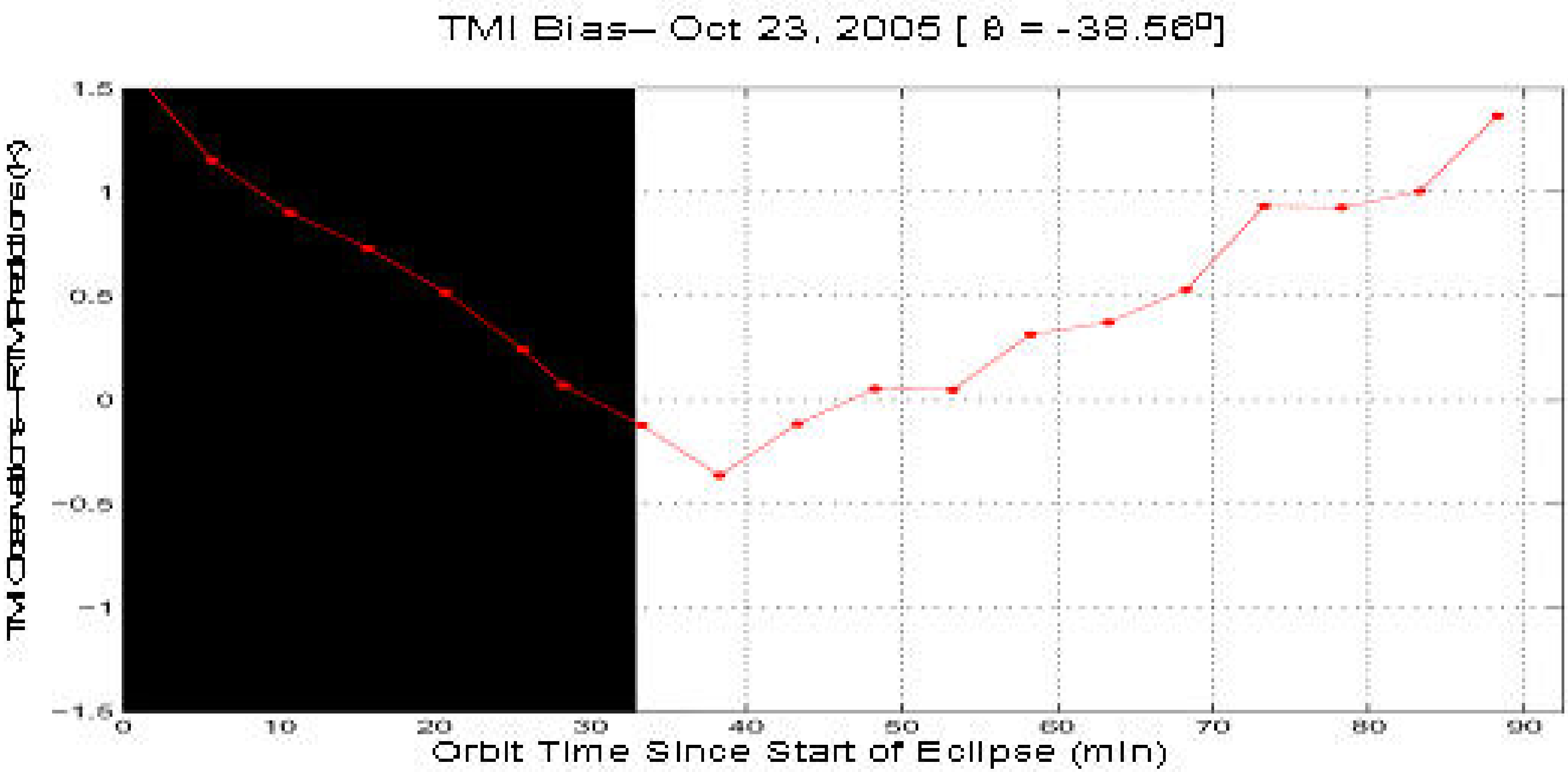
QRad Tb-Bias during the eclipse period (cont.)



QRad *Tb* bias (during eclipse period) for January 2006

TRMM Microwave Imager Tb Bias

- Similar Tb orbital bias pattern was observed during the TMI inter-satellite radiometric calibration as reported by Gopolan et al.



Antenna Pattern Sidelobe Spill-over Effects on Ocean Tb

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Antenna Pattern Effects on Ocean Brightness Temperatures

- Because SeaWinds is a radar, its antenna pattern was designed to provide spatial resolution and not the high beam efficiency usual for radiometer antennas
    - significant "Tb contamination" for pixels near land
- QRad radiometric biases (Qrad - Windsat at 13.4GHz) in 0.25° pixels for a ten-day period in (August 2005) along the west coast of North America

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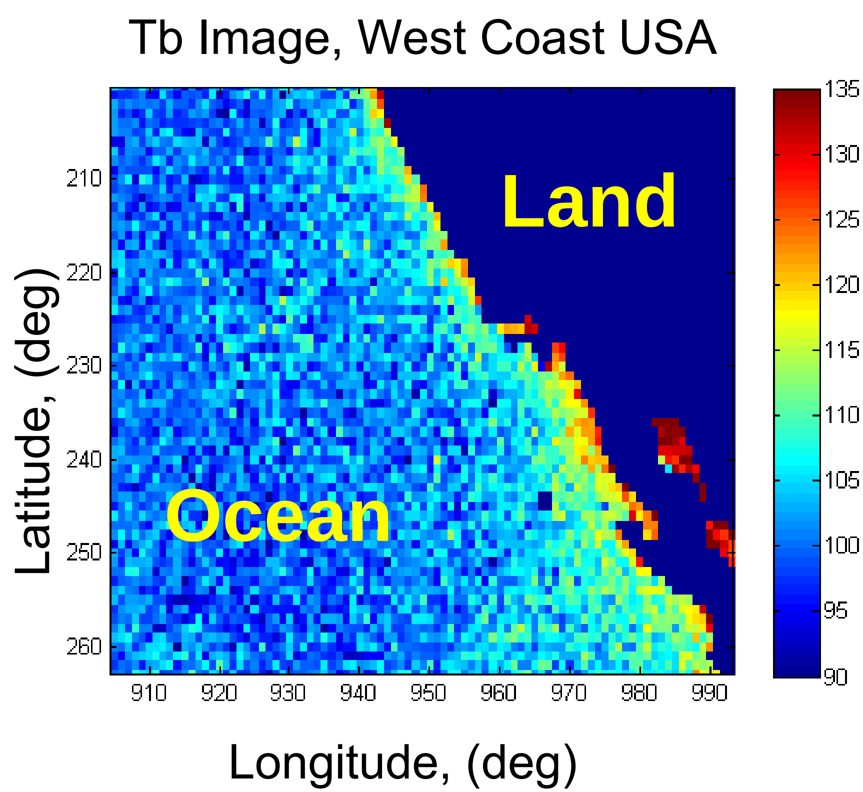
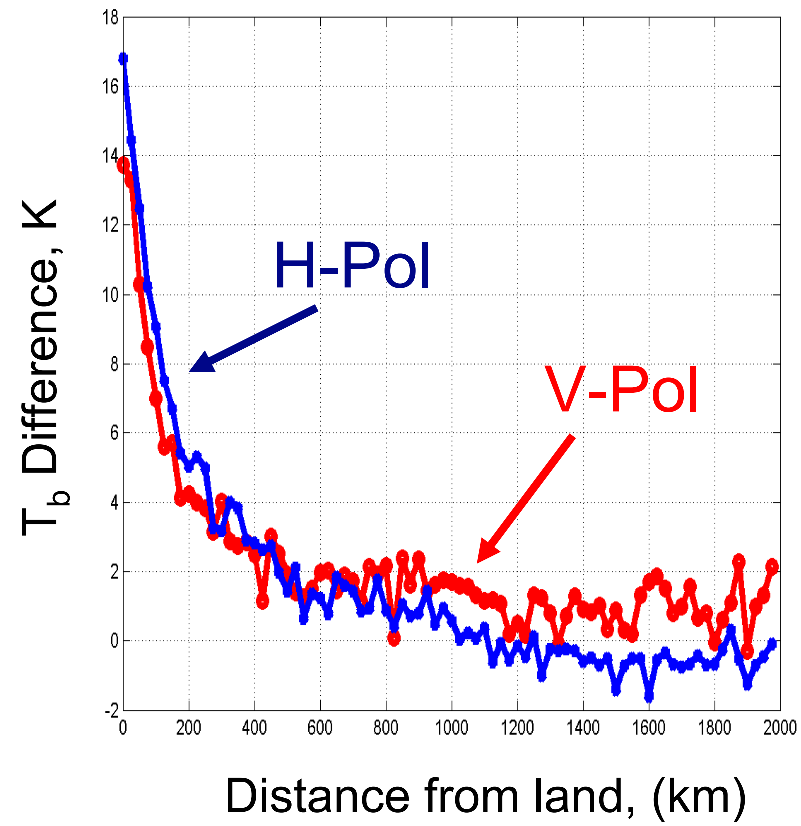
Antenna Pattern Effects on Ocean Brightness Temperature (cont.)





Noise Equivalent Differential Temperature (NEDT)

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- The noise equivalent differential temperature (NEDT) is a measure of the sensitivity of the measured Tb to changes in the scene brightness, NEDT was estimated by:

$$NEDT = T_{SYS}\left(\sqrt{\frac{1}{B\tau n}} + \left(\frac{\Delta G}{G}\right)^2\right) \qquad G = \frac{En\_cal}{K\,\tau B_n T_{cal}}$$

$$\frac{\Delta G}{G} = \frac{std(G)}{<G>} - mean(T_{cal}) * \left(\sqrt{\frac{1}{B_n * \tau * n}}\right)^2 = 0.021$$

NEDT for V-pol = 15.09 Kelvin

NEDT for H-pol = 14.08 Kelvin

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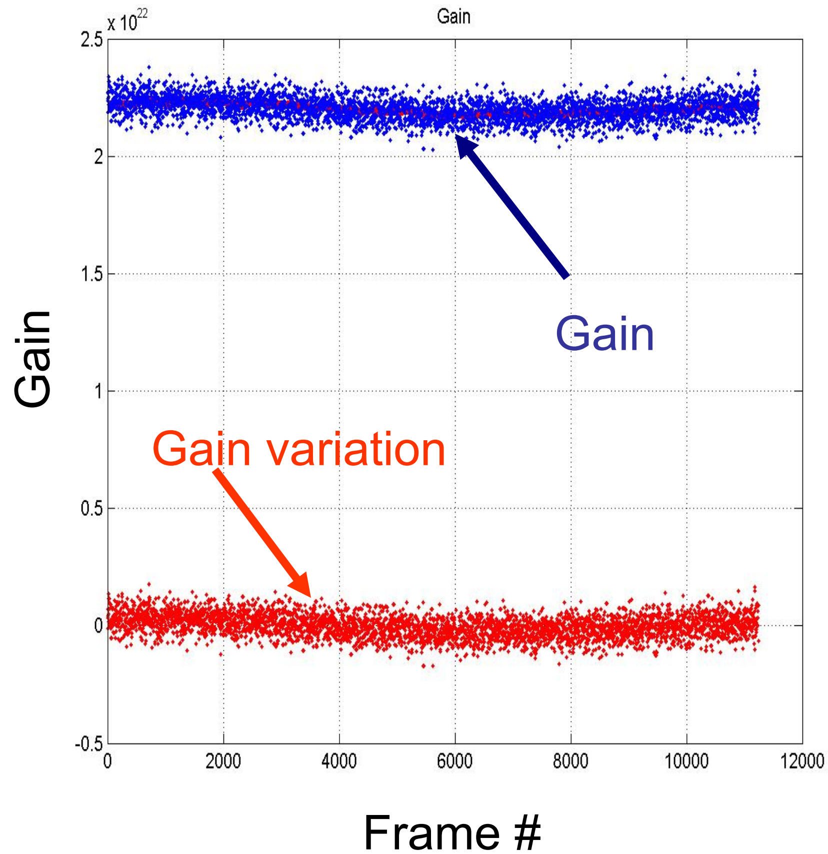
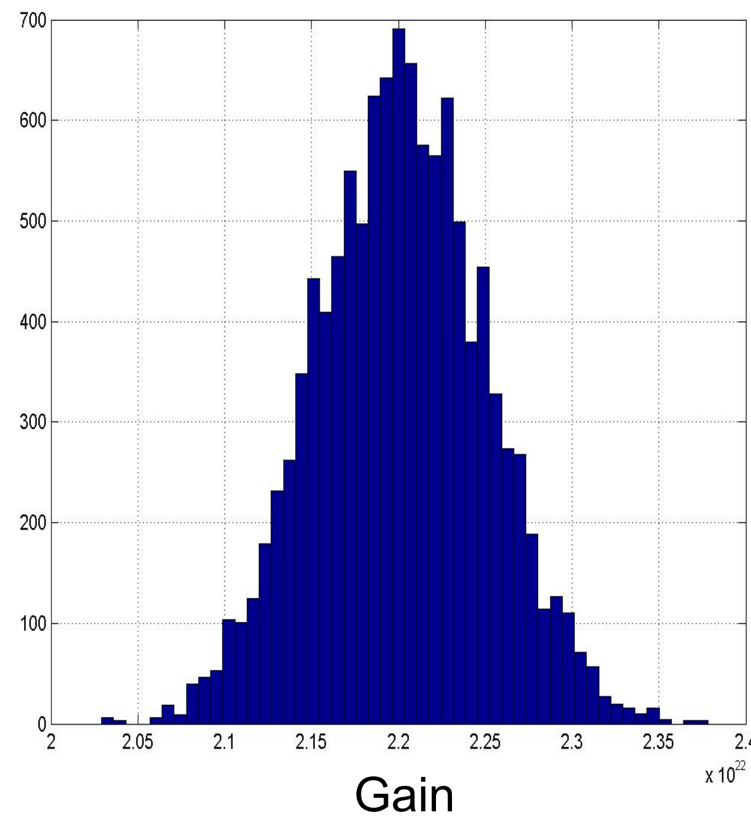
Gain Variation in one orbit





Gain variation= Gain- mean (Gain)

Mean= ~2.2*10^{22} & STD= 4.86*10^{20}

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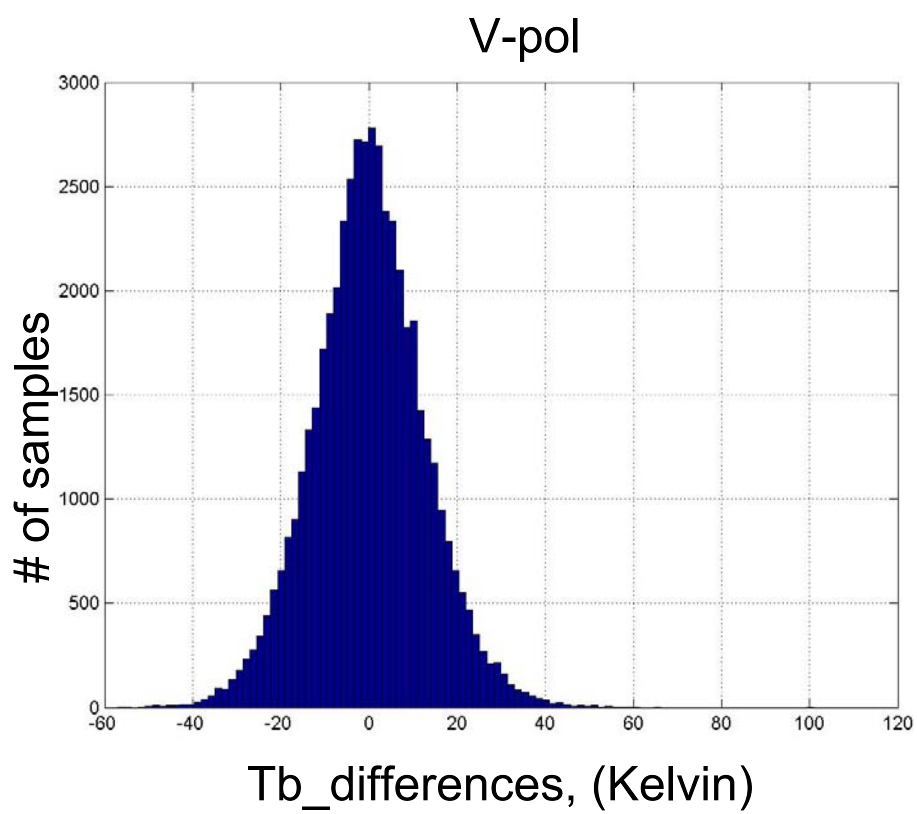
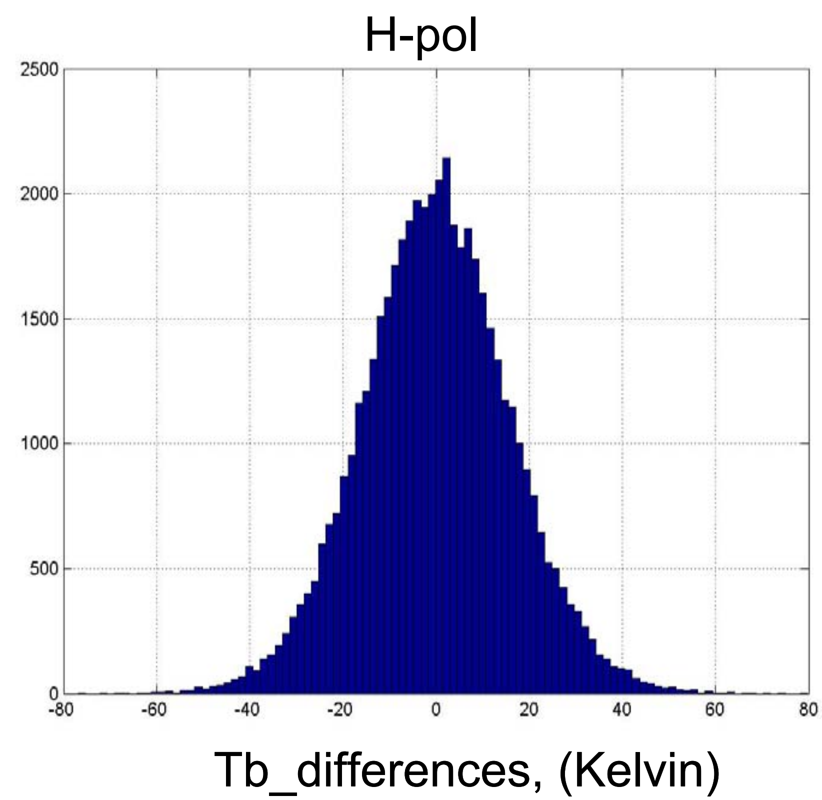
QRad STD for August
STD_V=15.59 & STD_H=12.52





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Standard Deviation Stability

Month	V-pol	H-pol
January	15.99	12.72
August	15.59	12.52
November	16.15	12.98

QRad Tb Evaluation over Land

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QRad Tb over Land: Effects of radar echo subtraction

- Before subtraction, the echo channel gain must first be normalized to the noise channel gain, then the signal power may be exactly cancelled in the noise channel by subtraction
- If the gain normalization factor (β) is in error
  - there will be a residual signal left (too much or too little)
  - Further, this residual will be proportional to the signal power
- Over ocean, the radar echo channel energy is small compared to the system noise power
  - Tb bias is also small.
- Over land, the radar echo energy is much larger and the residual signal after subtraction is likewise larger than the ocean case; so the Tb bias will depend upon the beta and the radar echo energy

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Tb Comparison over Land