Hurricane Wind Speed and Rain Rate Measurements Using the Airborne Hurricane Imaging Radiometer (HIRAD)

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Ph.D. Final Defense

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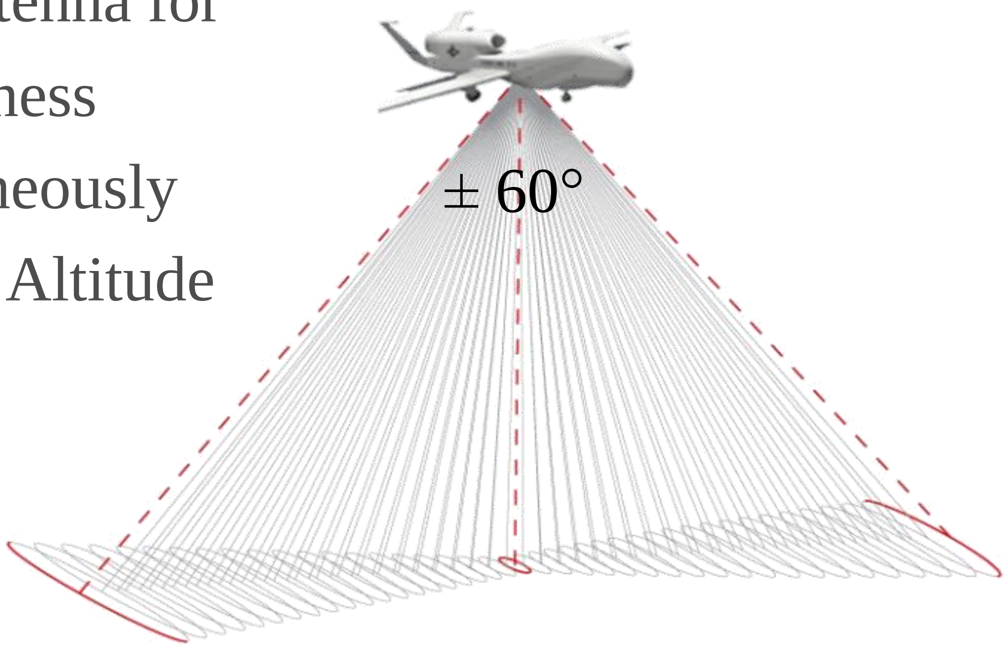
Dissertation Objective

- To develop an end-to-end computer simulation of HIRAD brightness temperature measurements in hurricanes
  - Uses numerical hurricane models to provide realistic 3D environmental "nature runs"
  - Forward microwave radiative transfer model
- To develop a HIRAD inversion algorithm to estimate the ocean surface wind speed and rain rate in hurricanes
  - Uses Monte Carlo simulation to characterize retrieval errors as a *f(WS, RR & EIA)*

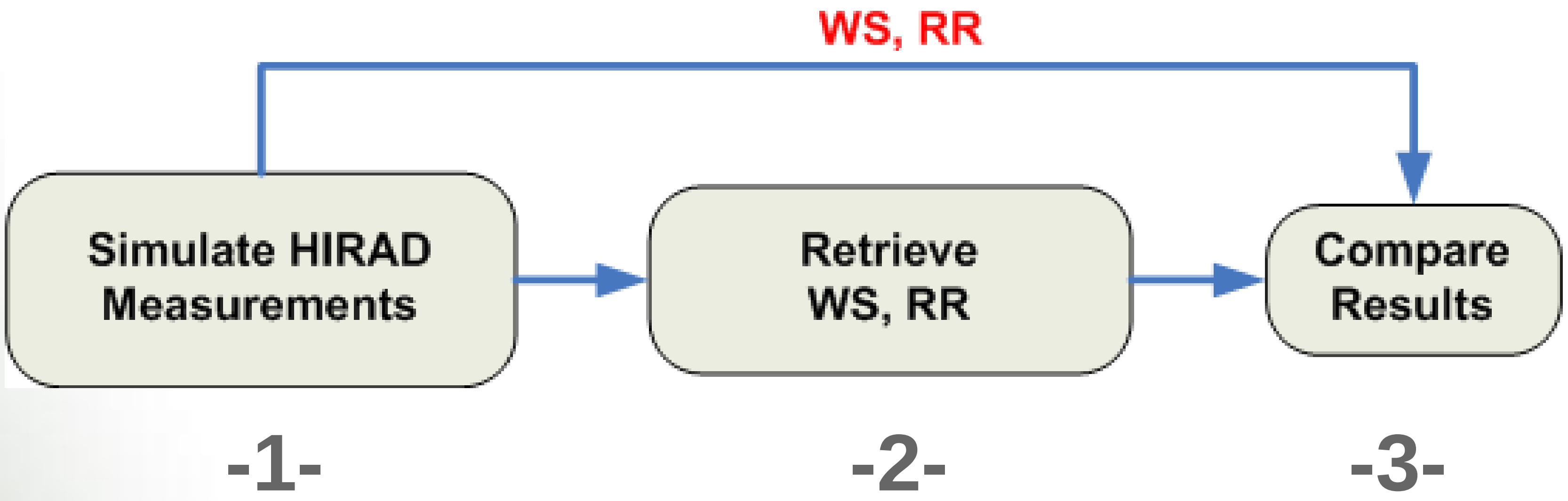
HIRAD Instrument Configuration

- 4-Freq C-band Radiometer (4 - 6.6 GHz)
- Synthetic Thinned Array Radiometer
  - Equivalent pushbroom antenna for cross-track imaging brightness temperature scene simultaneously
  - Measurement swath ~ 3 × Altitude

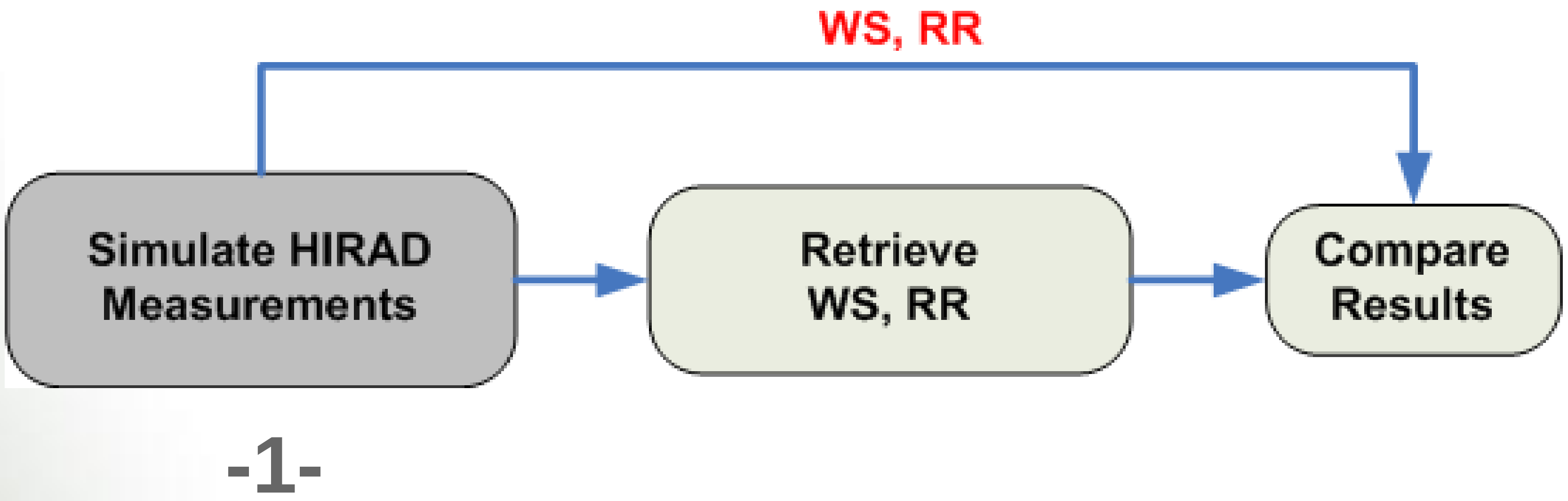


41 Pushbroom Antenna Beams

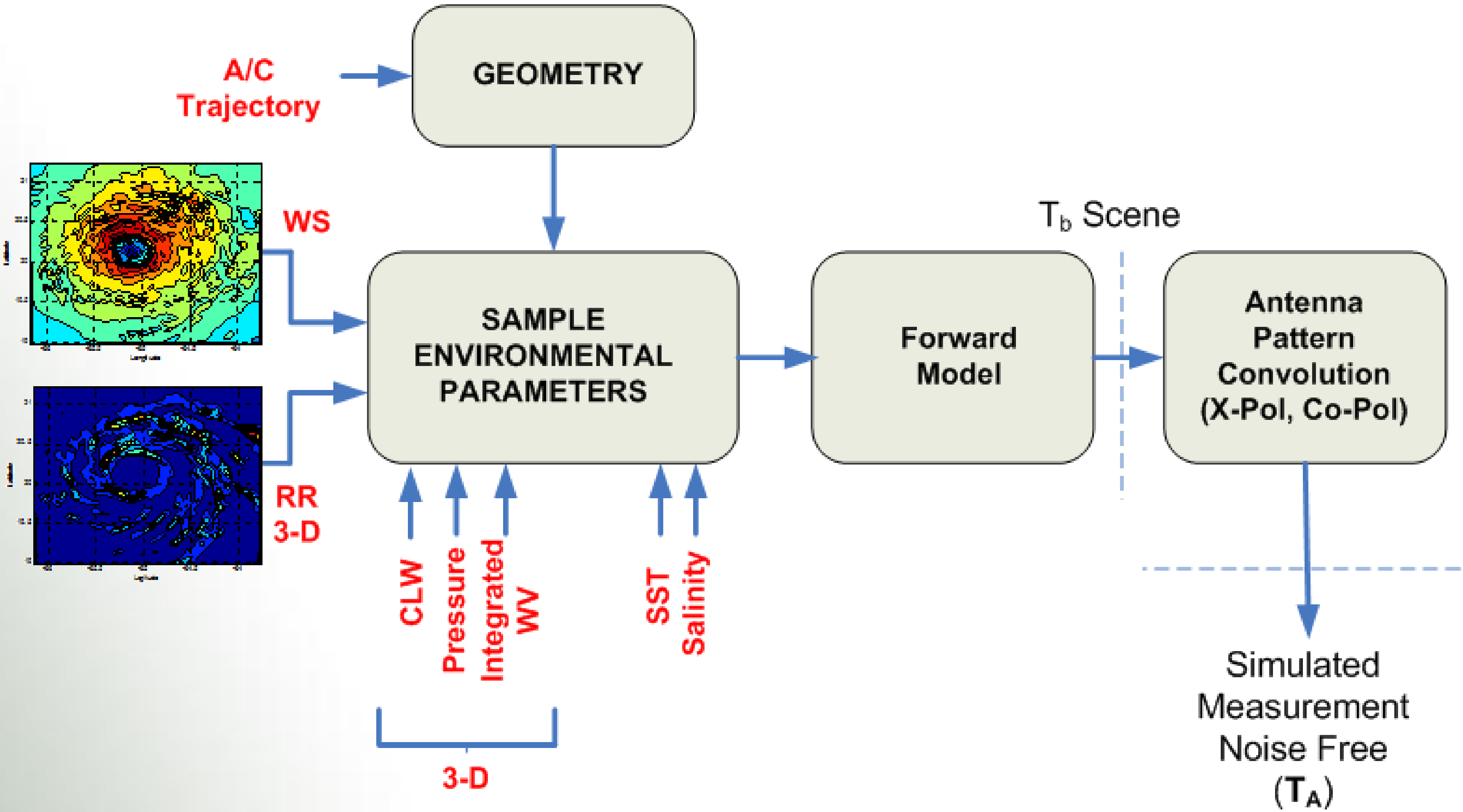
Simulation Top Level Diagram



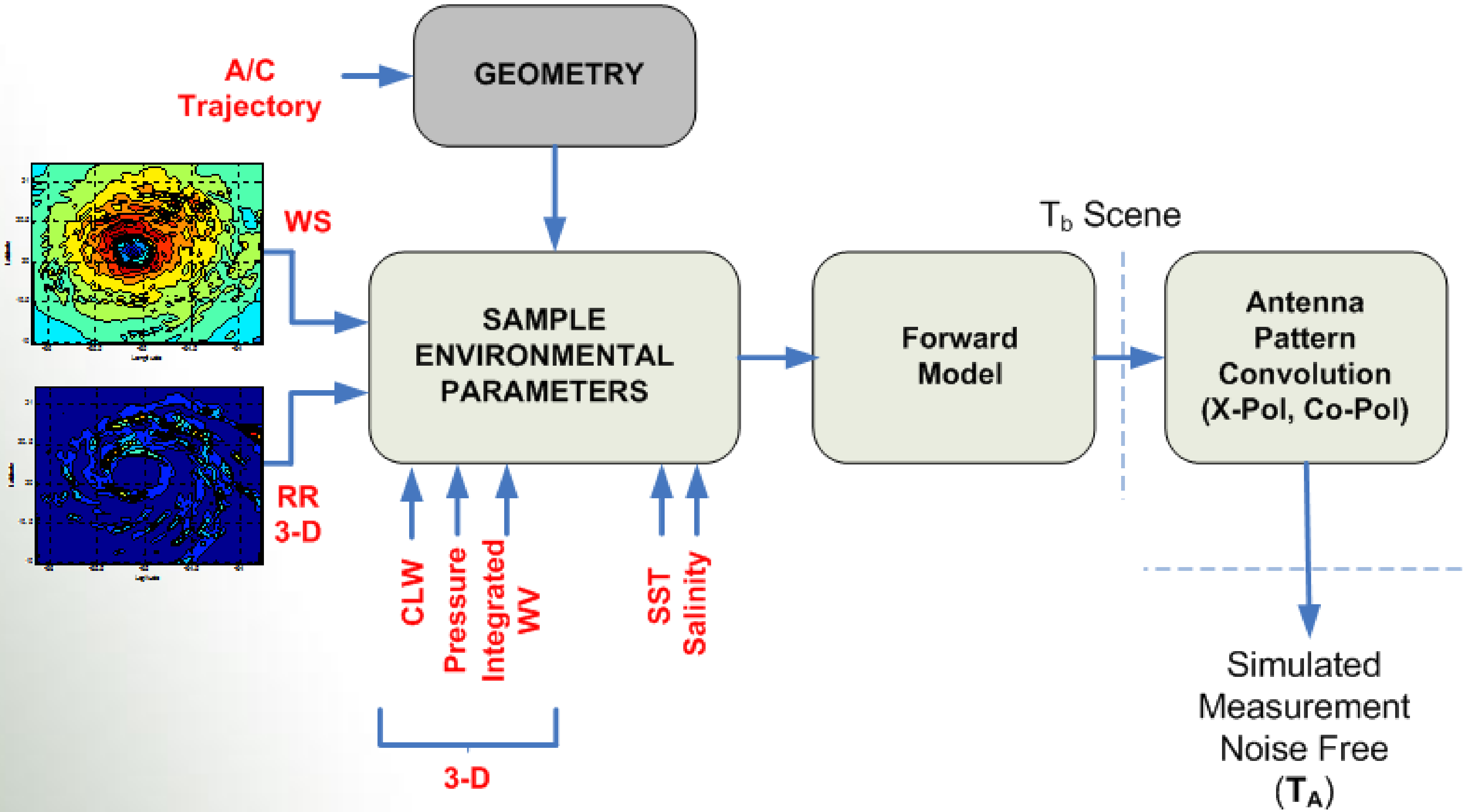
Simulated HIRAD Measurements



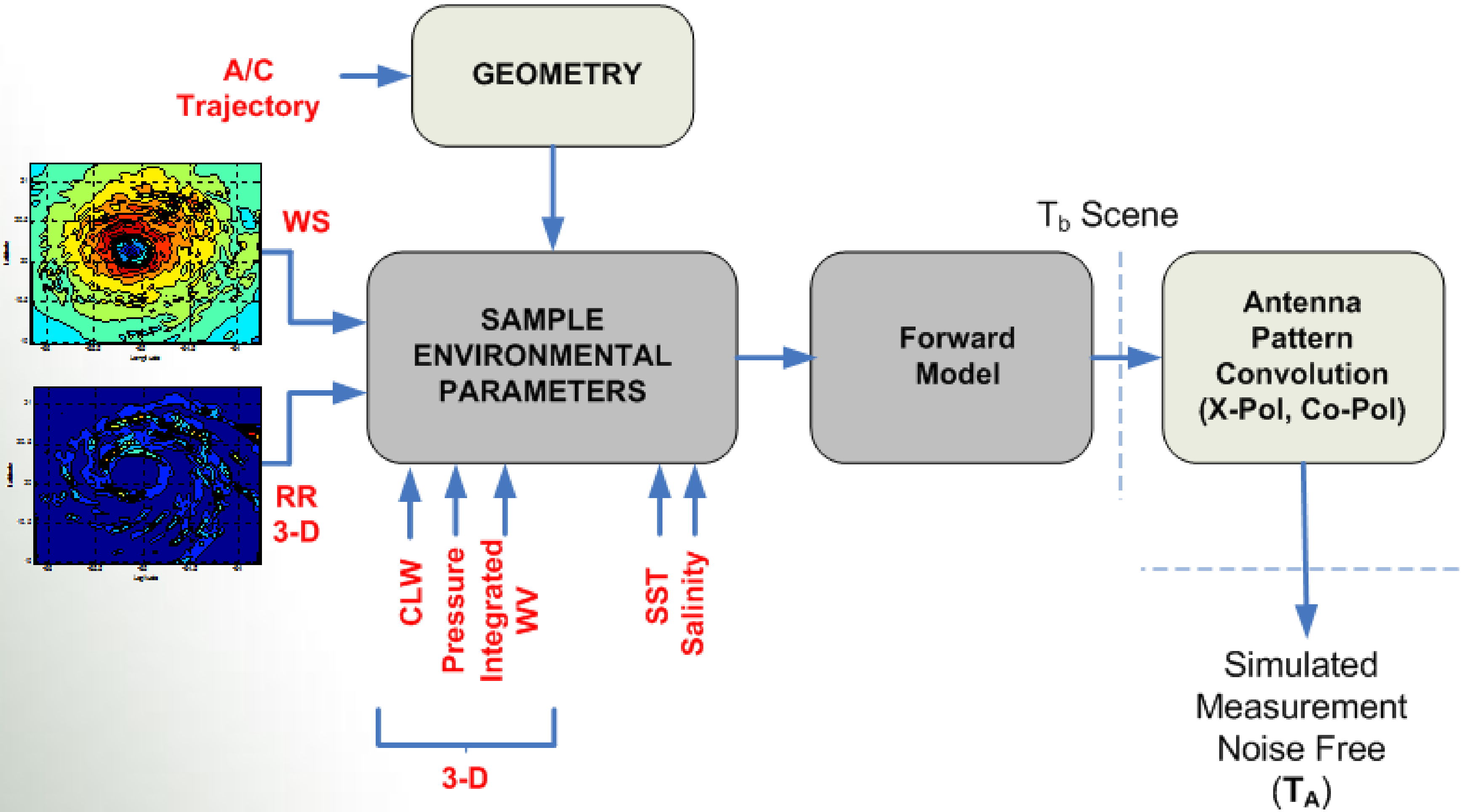
Simulation of HIRAD Measurements



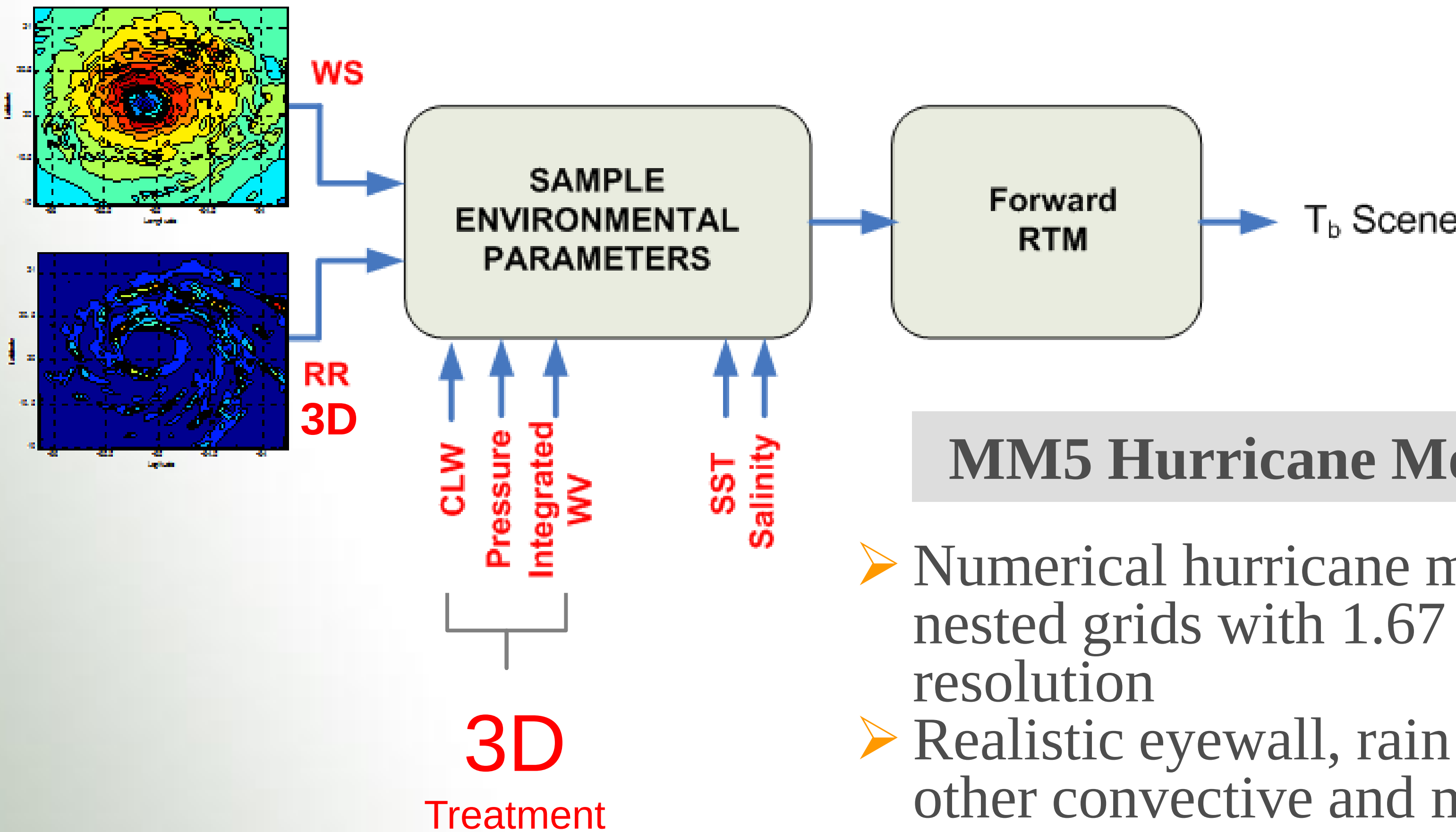
Simulation of HIRAD Measurements



Sample Environmental Parameters



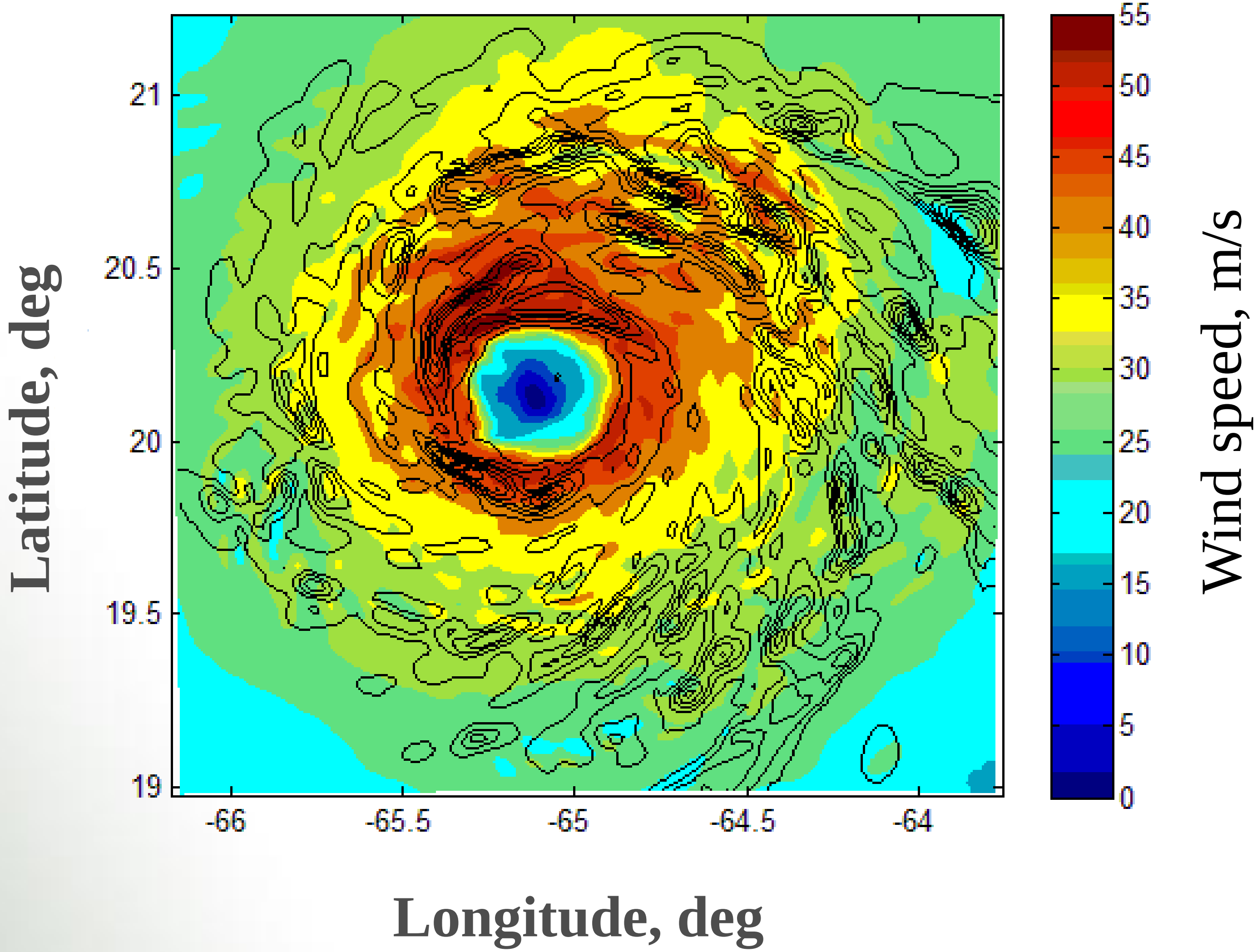
Simulation of HIRAD Measurements: Forward Model



MM5 Hurricane Model

- Numerical hurricane model with nested grids with 1.67 km resolution
- Realistic eyewall, rain bands and other convective and mesoscale structure

Hurricane Wind & Rain Fields

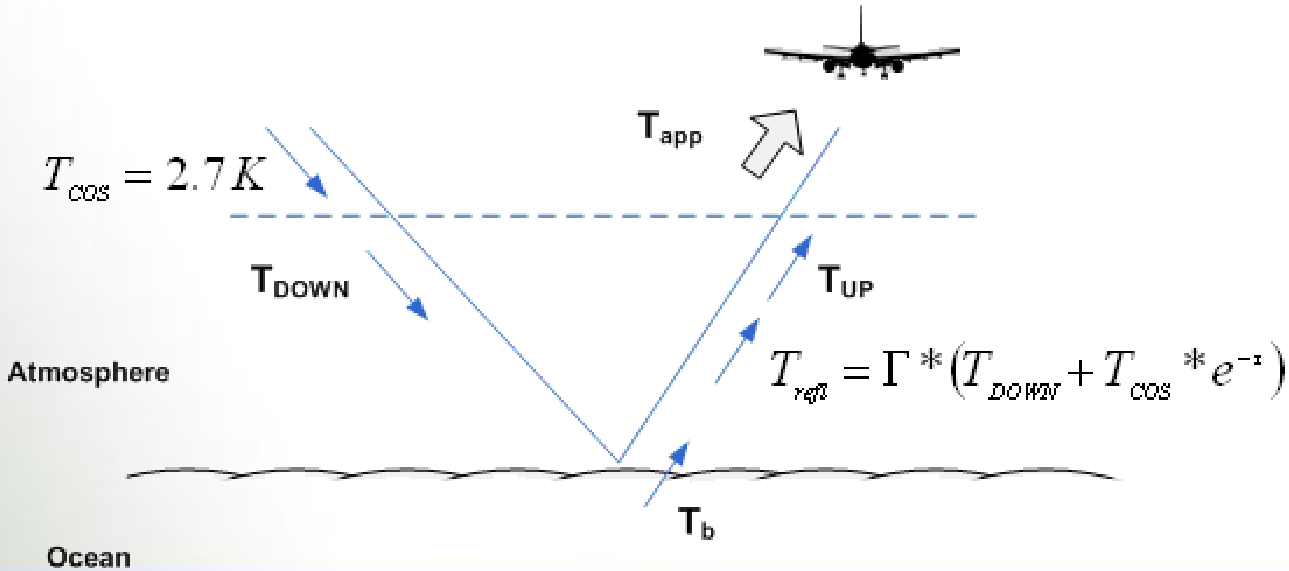


HIRAD T_b Forward Model

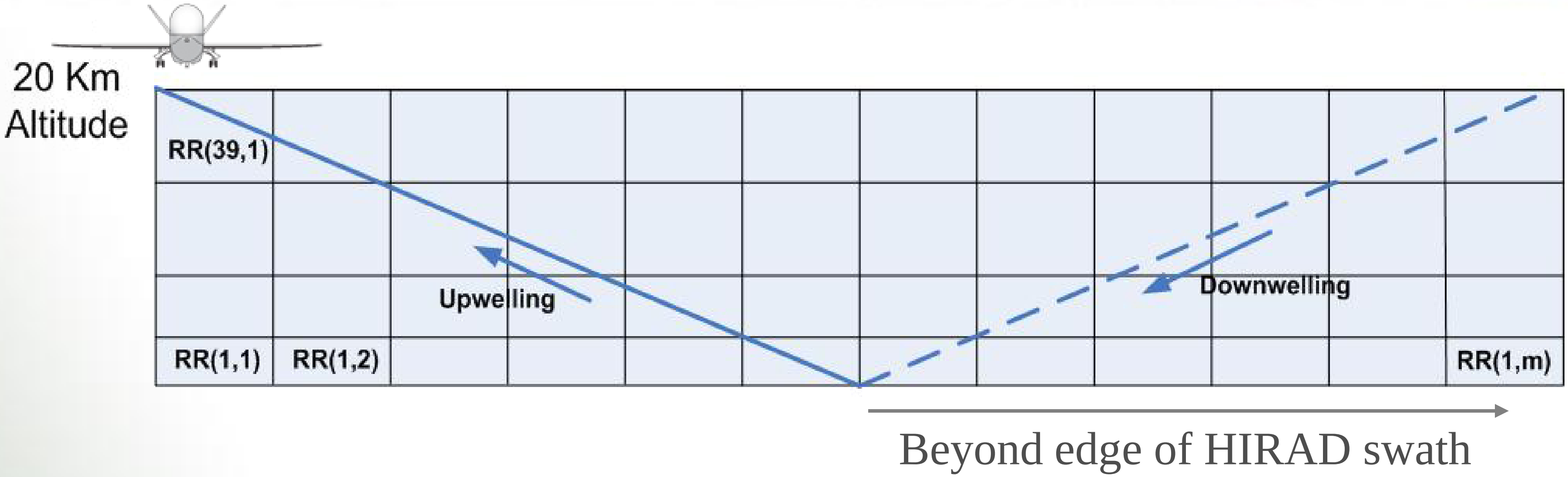
Forward Model - RTM

- Atmospheric T_{ap} has three components: upwelling radiance (T_{UP}), reflected down-welling radiance (T_{refl}) & surface emission (T_b)

$$T_{ap} = T_{UP} + e^{-\tau}\left(T_b + T_{refl}\right)$$



Rain Simulation in Forward RTM

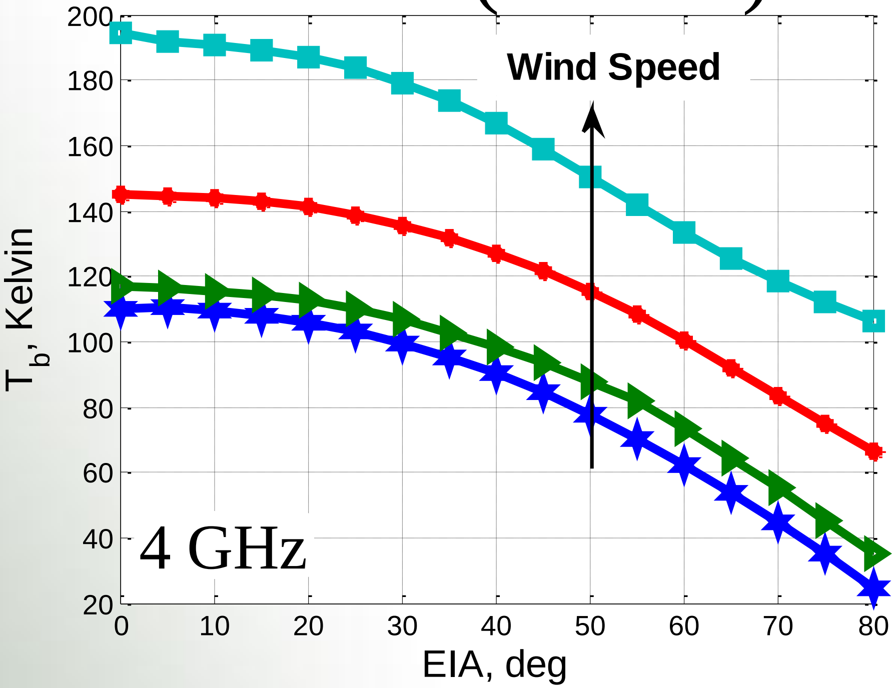


- Simulation uses:
  - Forward model
    - 3-D Varying rain rate
    - Covers both upwelling & downwelling slant path
      - Maximum width = 41 cells,
  - Retrievals
    - RR assumed uniform along line-of-sight slant path

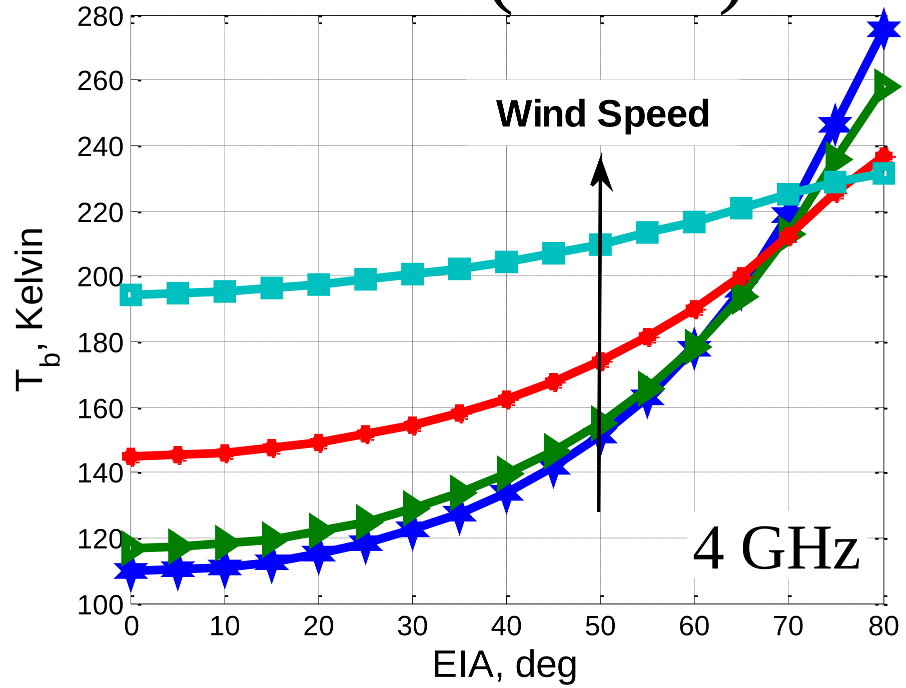
CFRSL - Ocean Emissivity Model

scaled for SST = 300 K

H-Pol (Co-Pol)



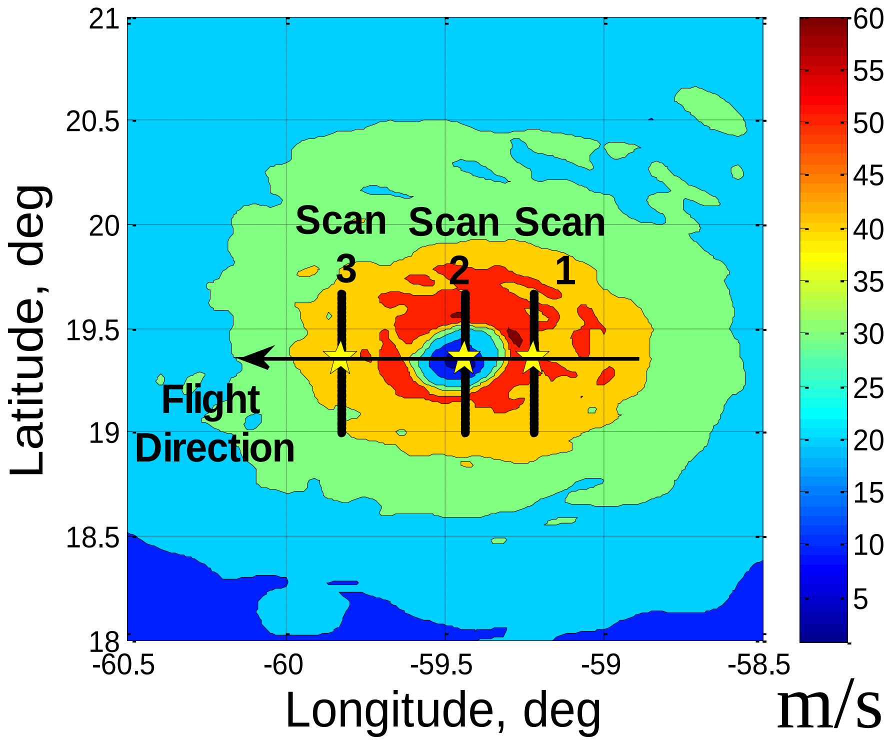
V-Pol (X-Pol)



- Ocean surface emissivity model developed for HIRAD studies
- Based upon SFMR & WindSat hurricane observations

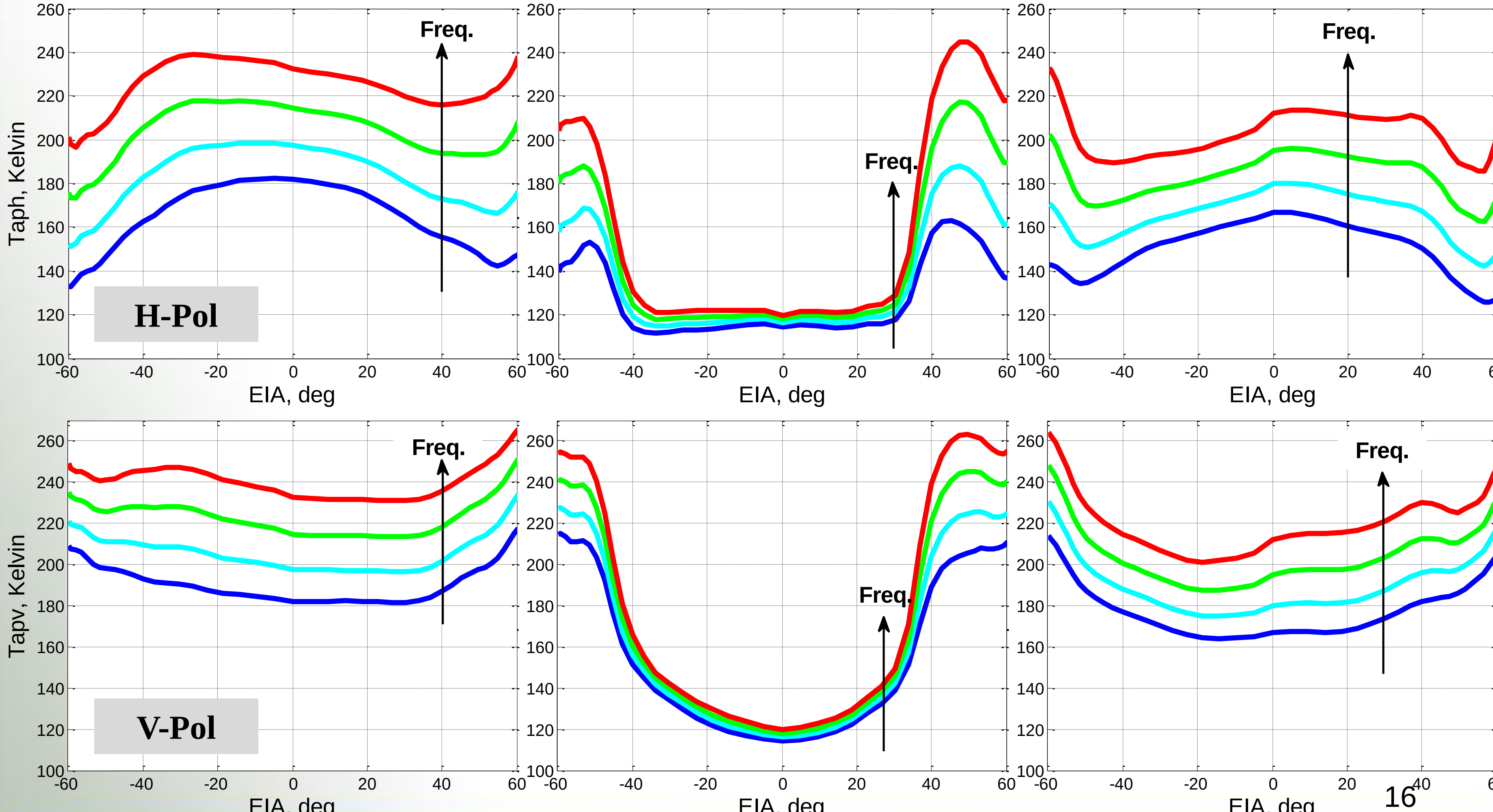
Sample Cross-track Scans Hurricane Frances

- HIRAD simulation cross-track scans (3 locations)
- Aircraft 20 km altitude
  - **Scan 1→**
    - eyewall region with highest winds (right)
  - **Scan 2→**
    - through the center of the eye (middle)
  - **Scan 3→**
    - Outer edge of eyewall region (left)

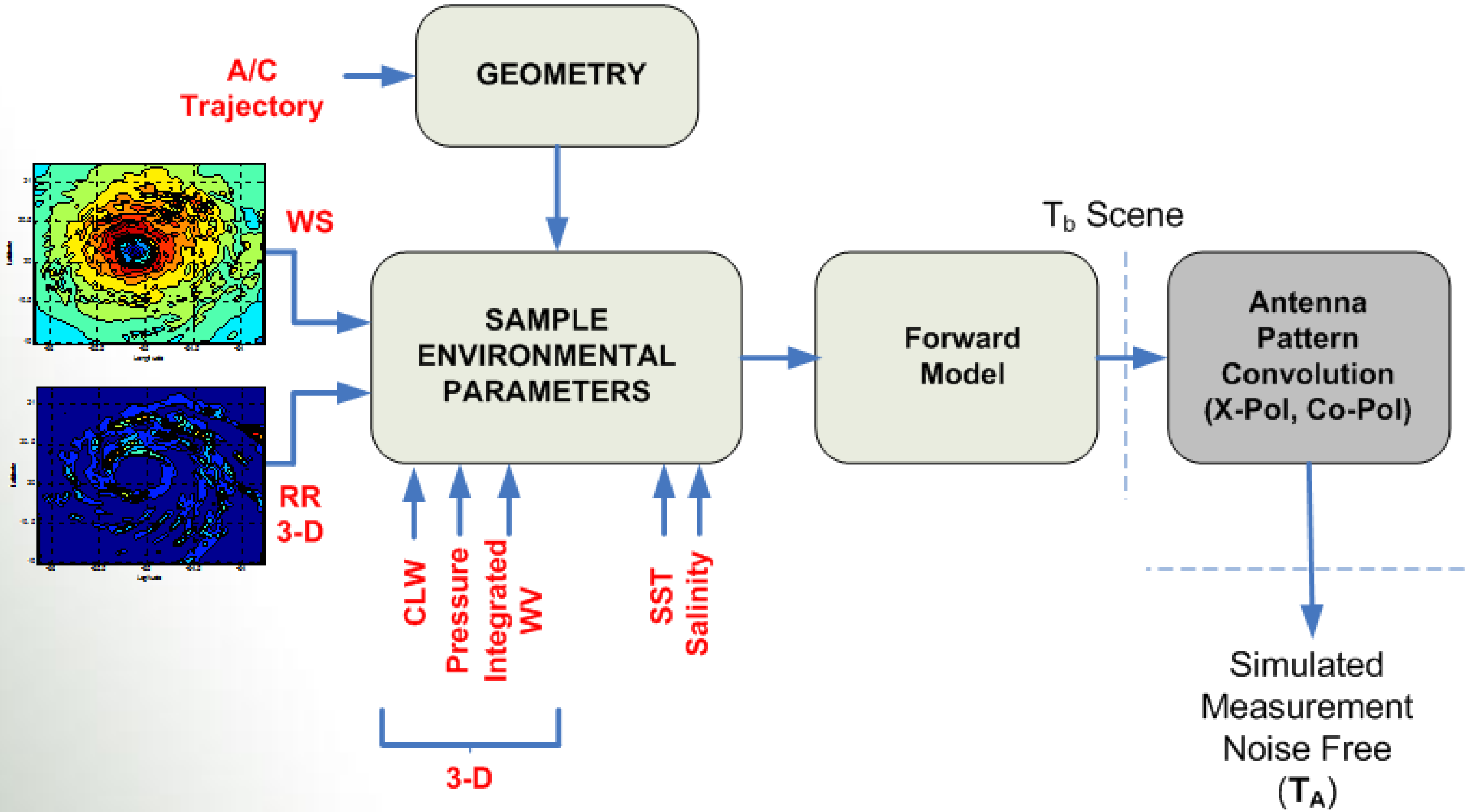


True Brightness Temperature Scene

Scan 1 | Scan 2 | Scan 3



Antenna Pattern Convolution

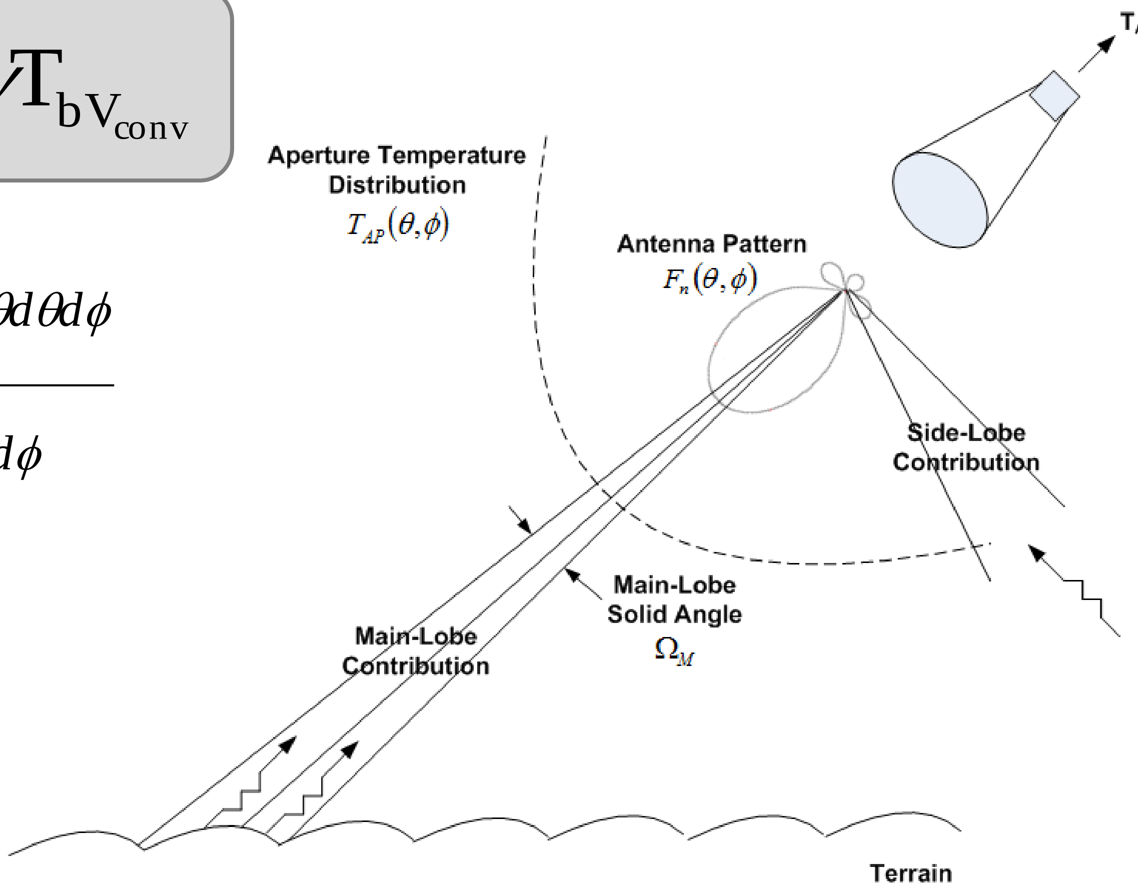


Antenna Temp (T_A) Simulation

$$T_A = (1-\gamma)\, T_{bH_{conv}} + \gamma T_{bV_{conv}}$$

$$T_{B_{conv}} = \frac{\int_0^{2\pi}\int_{-\theta}^{\theta} T_b(\theta,\phi) F(\theta,\phi) \times \sin\theta\, d\theta\, d\phi}{\int_0^{2\pi}\int_{-\theta}^{\theta} F(\theta,\phi) \times \sin\theta\, d\theta\, d\phi}$$

$$\gamma = \frac{\int_{FirstNulls} XPol}{\int_{FirstNulls} XPol + \int_{FirstNulls} CoPol}$$

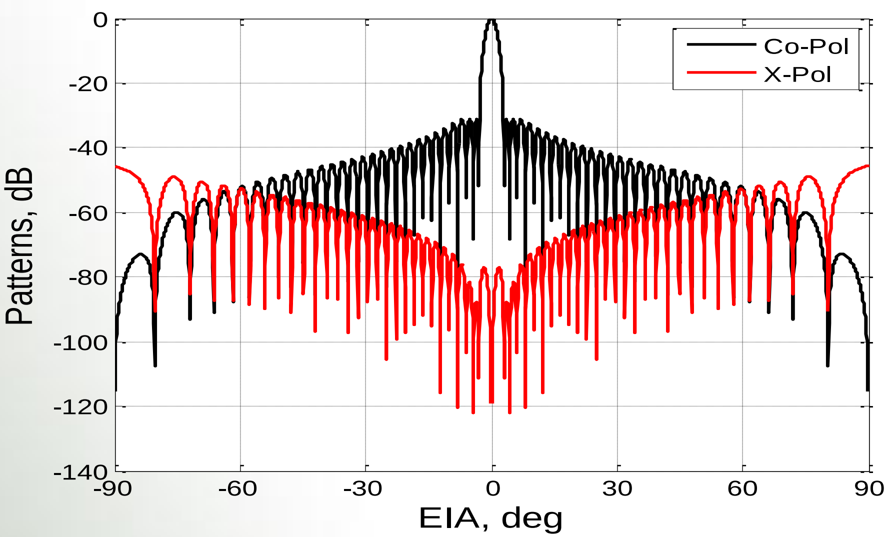


Pushbroom Antenna Simulation

- Real aperture pushbroom radiometer equivalent of HIRAD synthesized beams
  - Matches HIRAD cross-track resolution (41 pushbroom beams)
- Real aperture phased array antennas
  - Each frequency has an independent antenna design
  - Good beam efficiency (lower 90%'s)
  - Patterns approximately match HIRAD synthesized beamwidths and X-Pol coupling

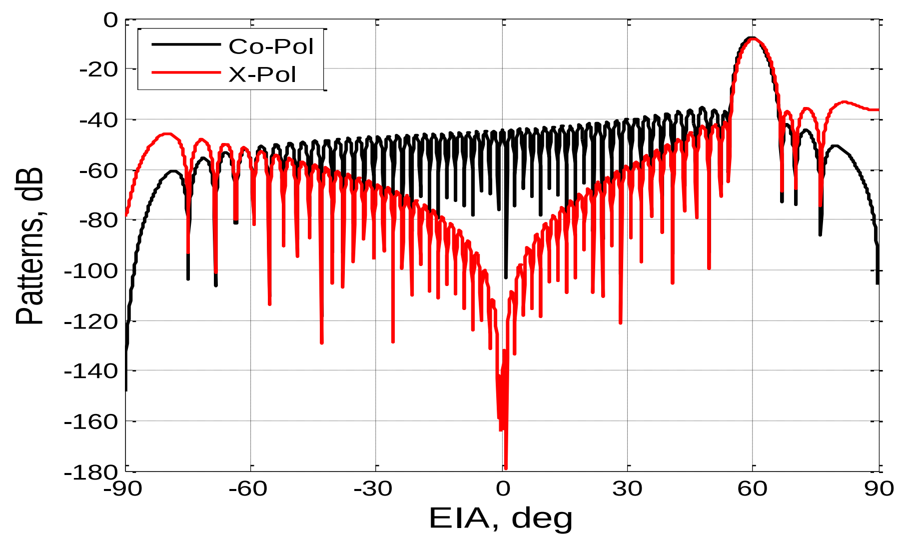
Co-Pol & X-Pol Patterns at 6.6 GHz

0 deg Scan Beam



Freq	3dB BW (deg)			γ	η
	Filled	**Ratio**	**HIRAD**		
4	2.6	1.24	2.1	0	93.1
5	2.2	1.29	1.7	0	93.5
6	2.2	1.47	1.5	0	93.8
6.6	2.3	1.64	1.4	0	93.7

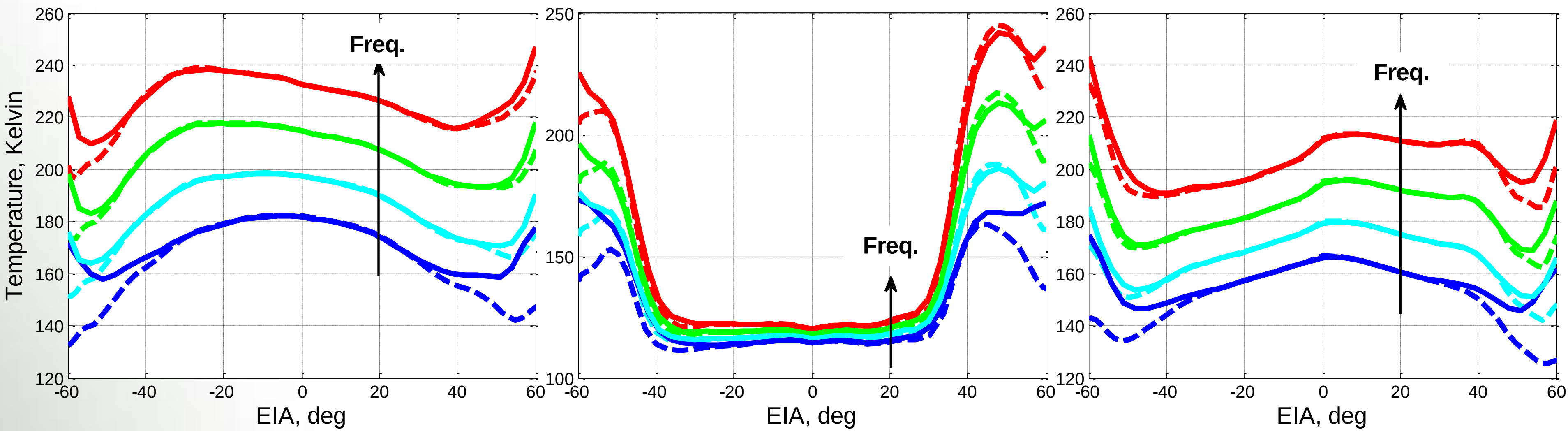
60 deg Scan Beam



Freq	3dB BW (deg)			γ	η
	Filled	**Ratio**	**HIRAD**		
4	5.2	1.58	3.3	0.47	95.2
5	4.5	1.61	2.8	0.29	92.37
6	4.4	1.69	2.6	0.29	90.57
6.6	4.5	1.61	2.8	0.49	91.7

T_A Scene

Scan 1 **Scan 2** **Scan 3**



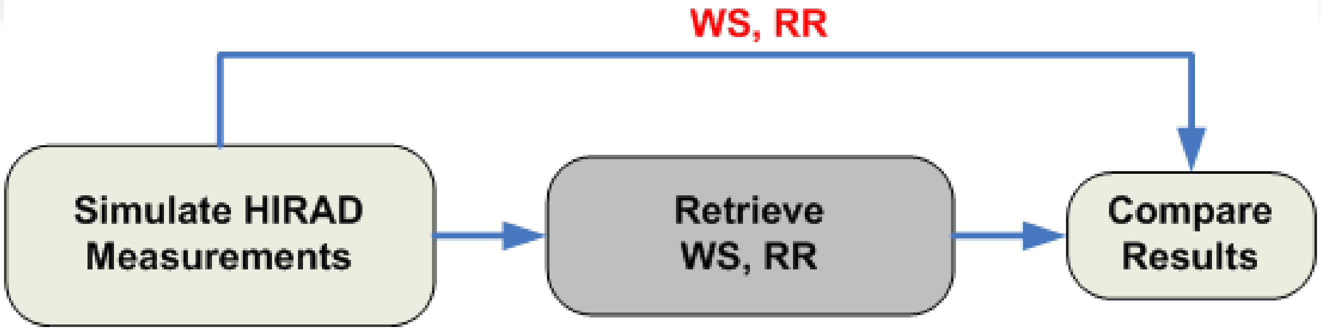
Antenna T_A Scene ———

True T_b Scene - - - -

Note:

Effect of polarization mixing with the X-Pol

Retrieve Geophys Pars: WS & RR



-2-

- Develop an inversion model for inferring wind speed (WS) & rain rate (RR)
  - *Error:* Retrievals - nature run
  - Characterized as a *f*(WS, RR & EIA)
- Perform Monte Carlo simulations
  - Different hurricanes & flight tracks

A’ Priori Retrieval Information

Parameter	Included
Water Vapor	Hurricane climatology
SST	Constant = 28 deg Celsius
Cloud Liquid Water	Hurricane climatology
Oxygen	Hurricane climatology

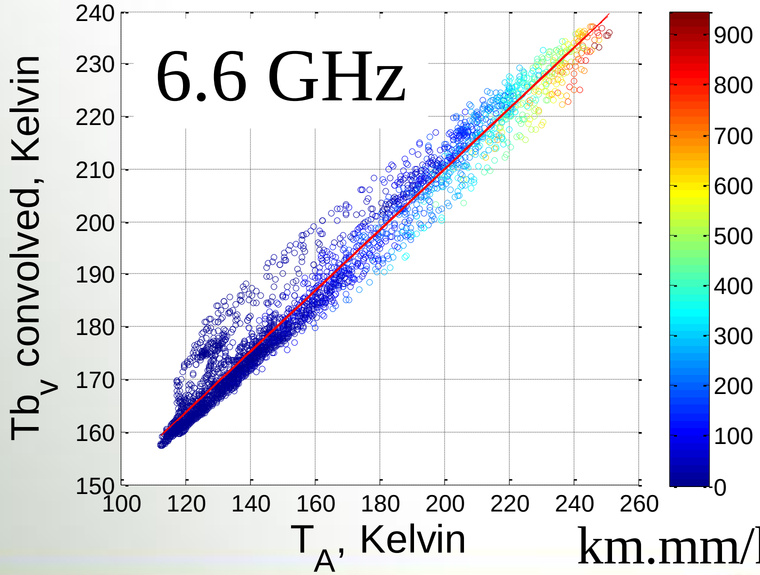
Antenna Pattern Correction - 1

- Remove X-Pol (V-Pol) effect from the total T_A

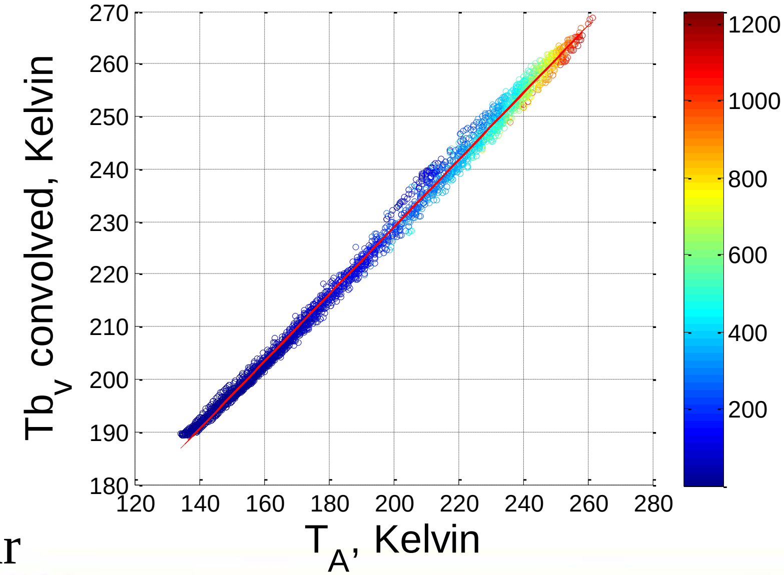
$$T_{bH_{conv}} = \frac{T_A - \gamma T_{bV_{conv}}}{1 - \gamma}$$

T_{bVconv} estimated based on best linear fit relationships with T_A

30 deg **60 deg**



km.mm/hr

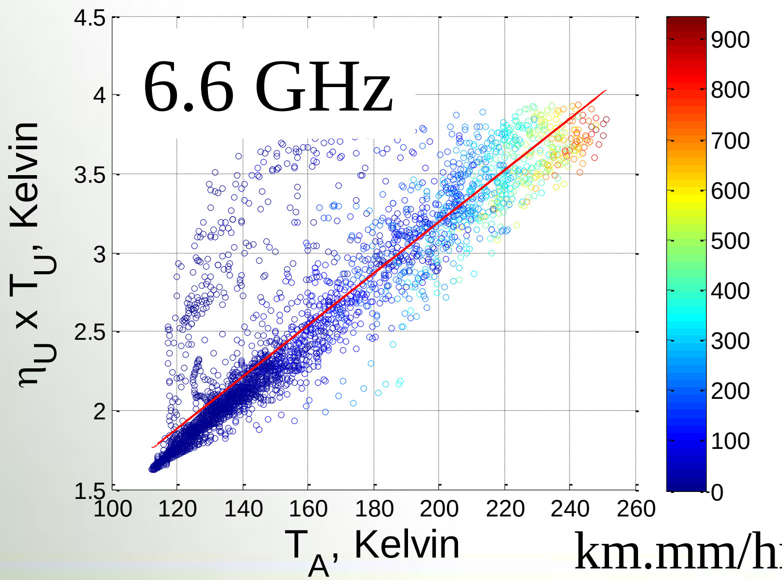


Antenna Pattern Correction - 2

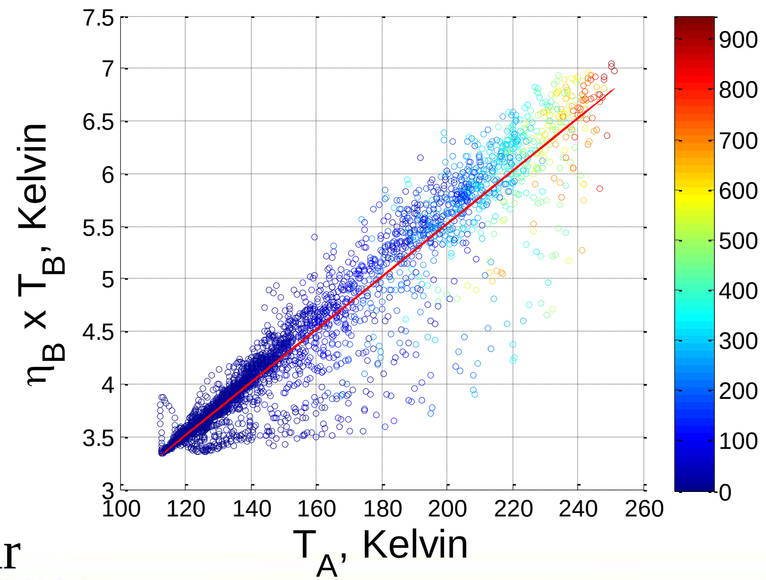
- Correct for antenna pattern

$$T_{corr} = \frac{1}{\eta_{MB}}\left[T_{bH_{conv}} - \eta_U \times T_U - \eta_B \times T_B\right]$$

  - T_U and T_B correspond to sidelobe contributions “above” and “below” the boresight”

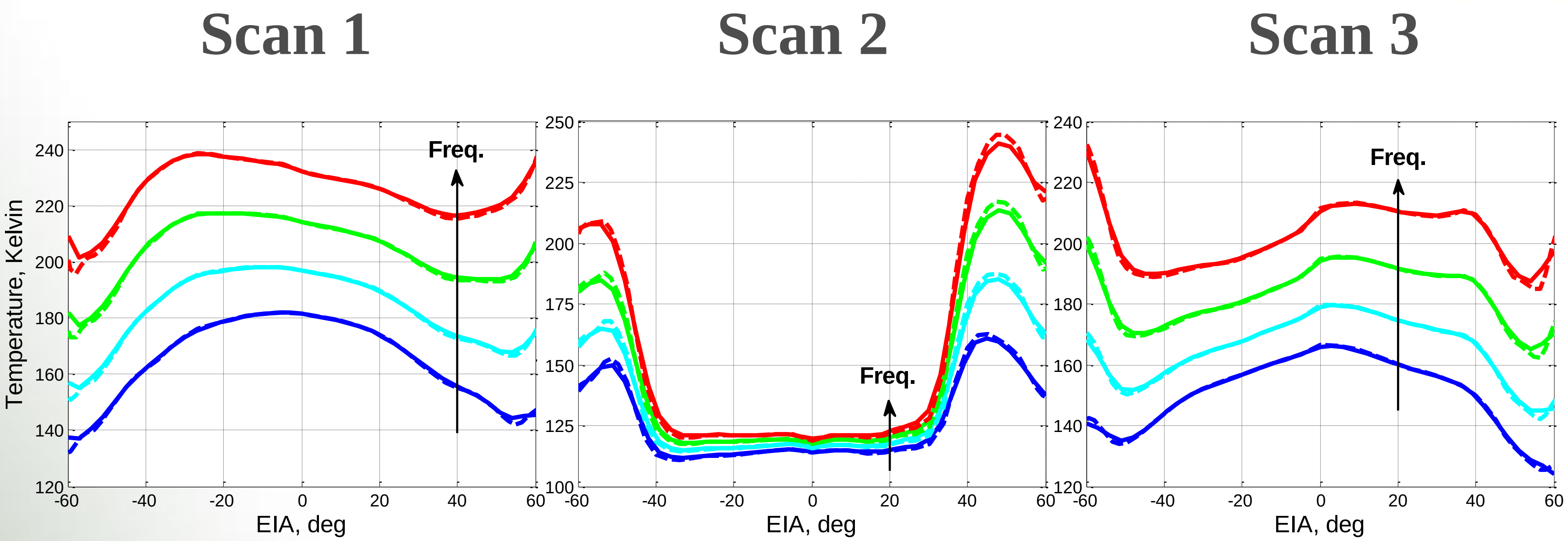


km.mm/hr



30 deg

Corrected Brightness (T_{corr}) Scene



Antenna T_{corr} Scene ——

True T_b Scene - - - -

Note:

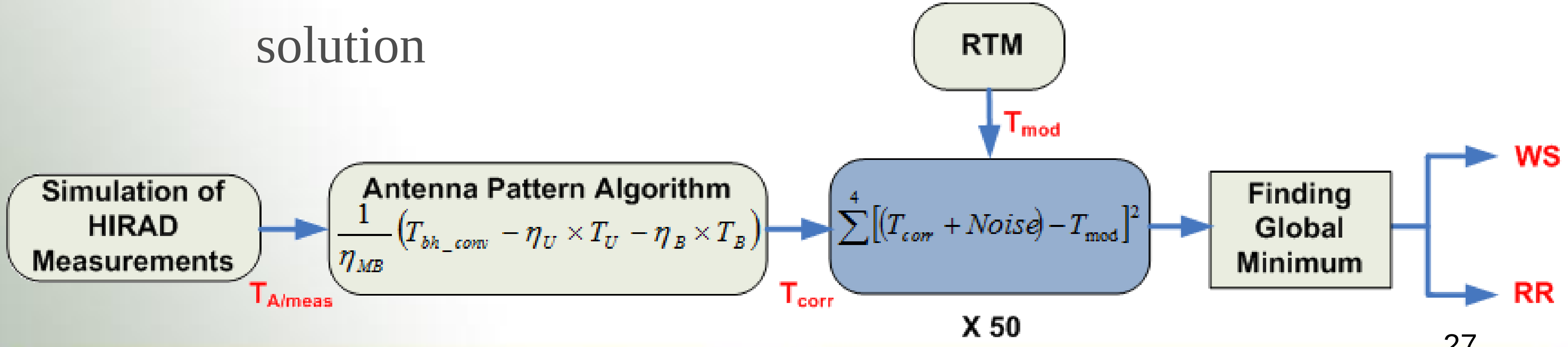
Antenna pattern effect is negligible after correction

Retrieval Algorithm

- Implemented in MATLAB
  - Evaluates least squares "Cost" function

$$\sum_{i=1}^{4}\left[\left(T_{\text{meas}}\right)_i - \left(\hat{T}_{\text{model}}\right)_i\right]^2$$

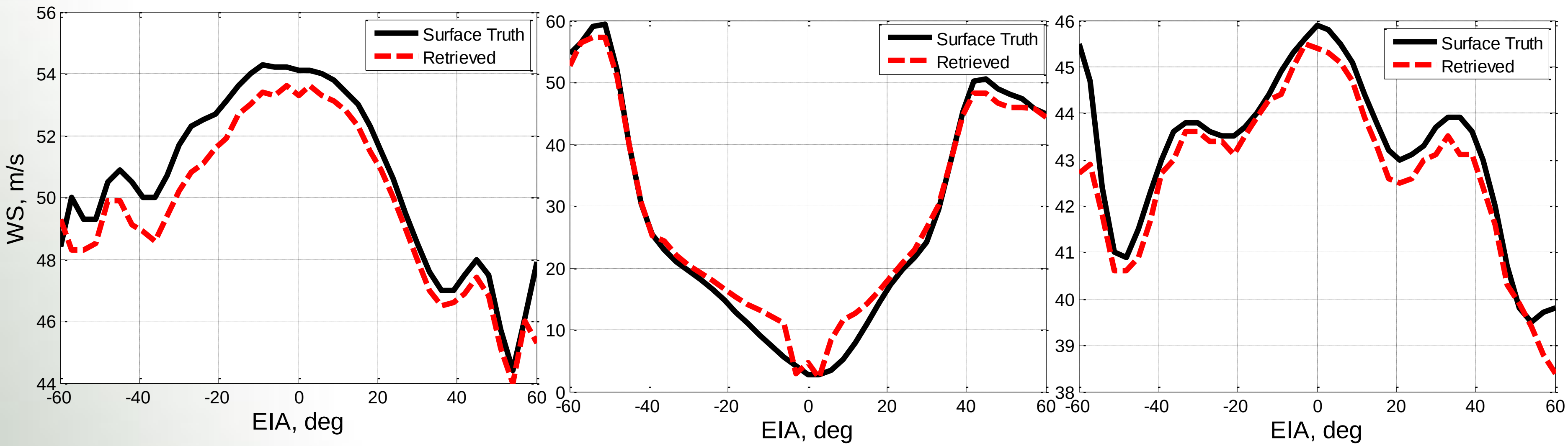
  - All possible combinations of
    - WS 0: 0.1 :70 m/s
    - RR 0: 0.8 :120 mm/hr
  - Single global minimum solution



Retrieved WS Scenes, m/s

0 Kelvin Random Errors

Scan 1 **Scan 2** **Scan 3**



Surface Truth WS ———

Retrieved WS - - - -

Retrieval Errors

- Three major sources of errors:
  1) Instrument T_b measurement random errors
     - Monte Carlo simulation run parametrically:
       - 1, 2, 4 & 8 K
     - HIRAD ~ 4K RSS random error
       - NEDT & ΔG/G (2K)
       - Geophyscial Model Function (surface emissivity) (3K)
       - A/C attitude (1K)
  2) Antenna pattern correction errors
  3) Retrieval RTM modeling error

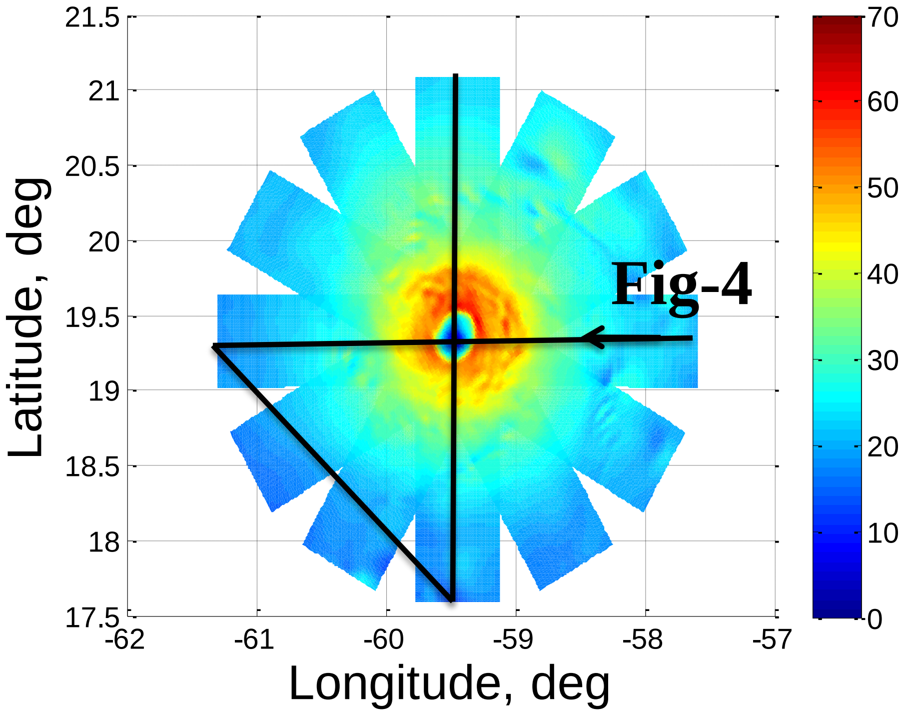
Model Validation

- To verify:
  - Algorithms are performing properly
  - Codes are written properly
    - Run cases where answers are known
- Model validation cases include:
  - Atmosphere
  - RR Treatment
  - SST
  - Antenna Pattern Correction
  - Quantization Errors

Simulation Statistics

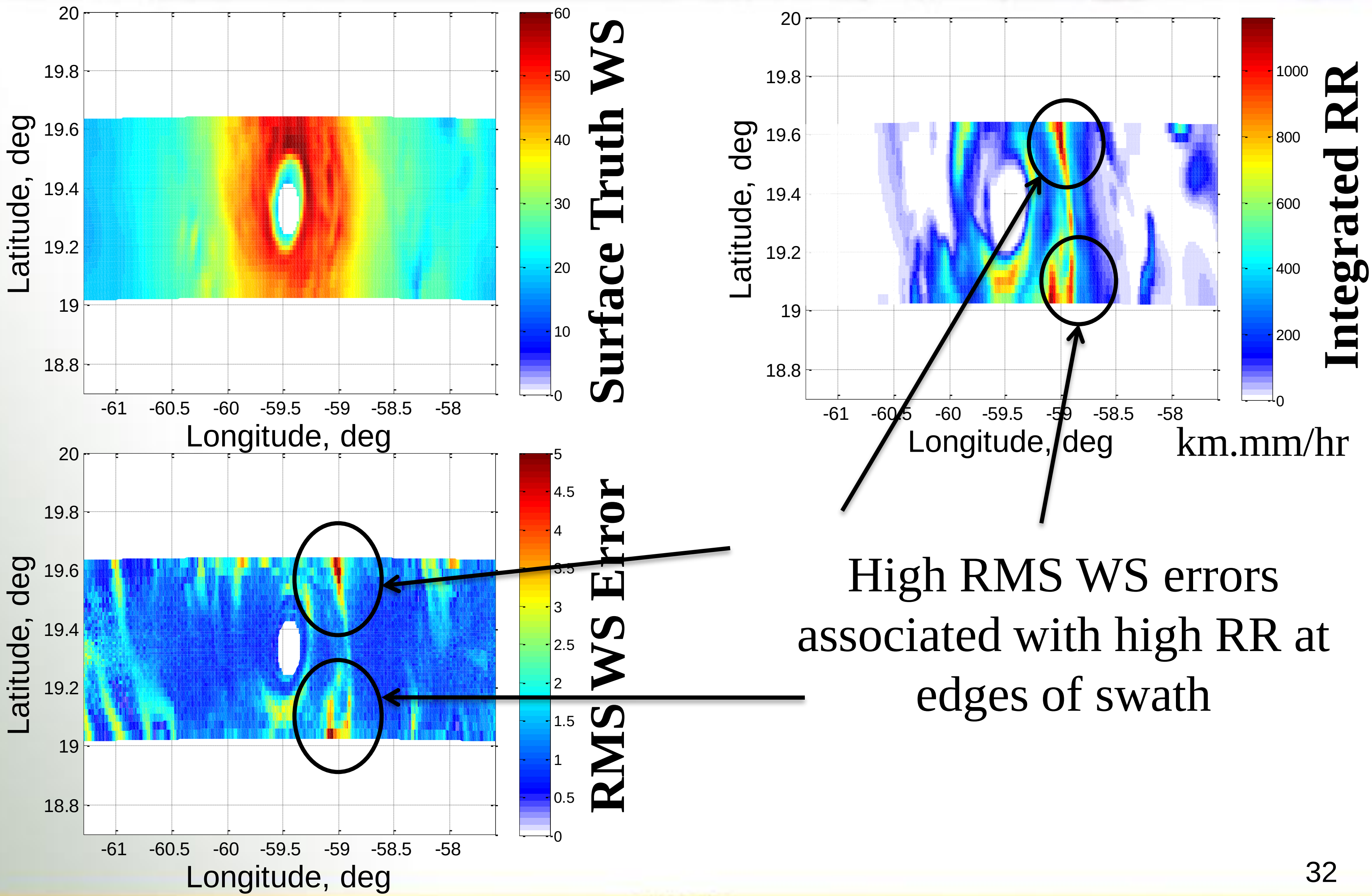
- Total number of cases
  - 3 Fig-4 flight patterns
  - 2 additional legs outside eye

  8 (legs) × 240 (scan/leg) = 1920 total scans
- Total 9 hours run time per leg
  - Includes 5 cases of different random errors



RMS Wind Speed Retrieved Errors

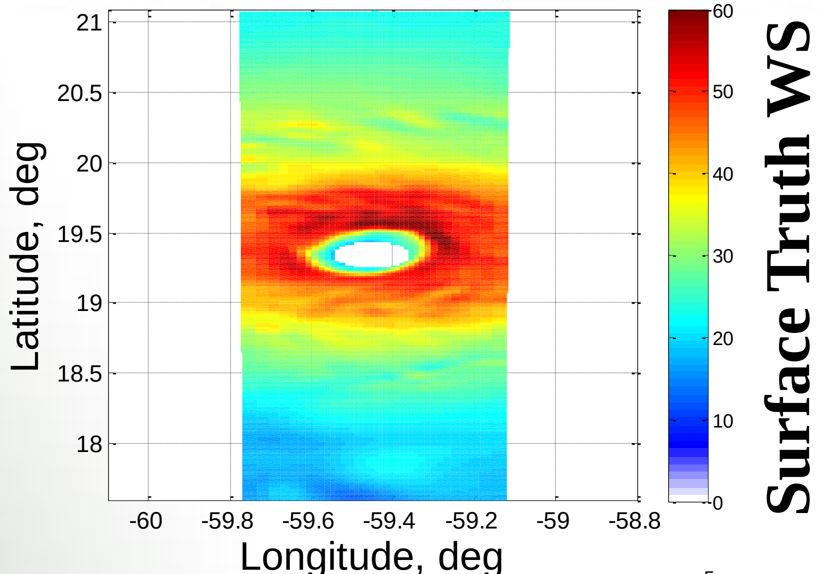
1 Kelvin Random Errors

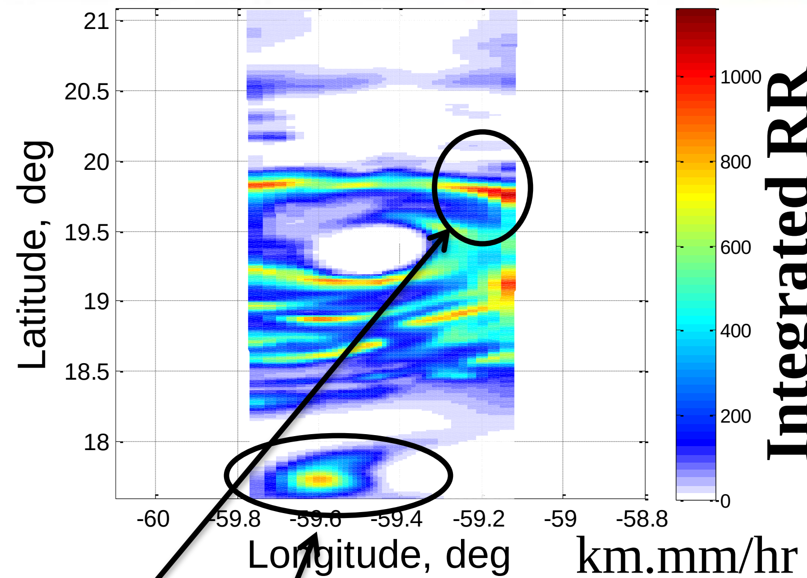


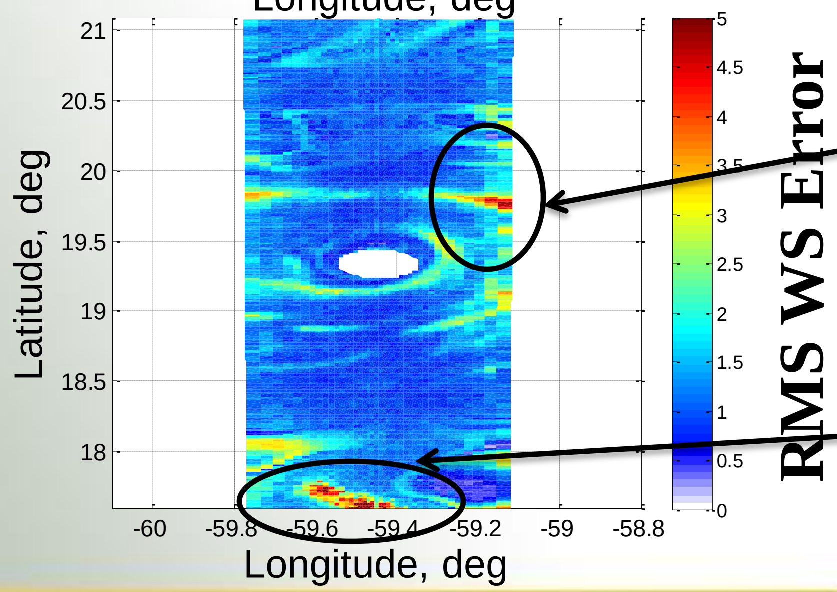
High RMS WS errors associated with high RR at edges of swath

RMS Wind Speed Retrieved Errors

1 Kelvin Random Errors







High RMS WS errors associated with high RR at edges of swath

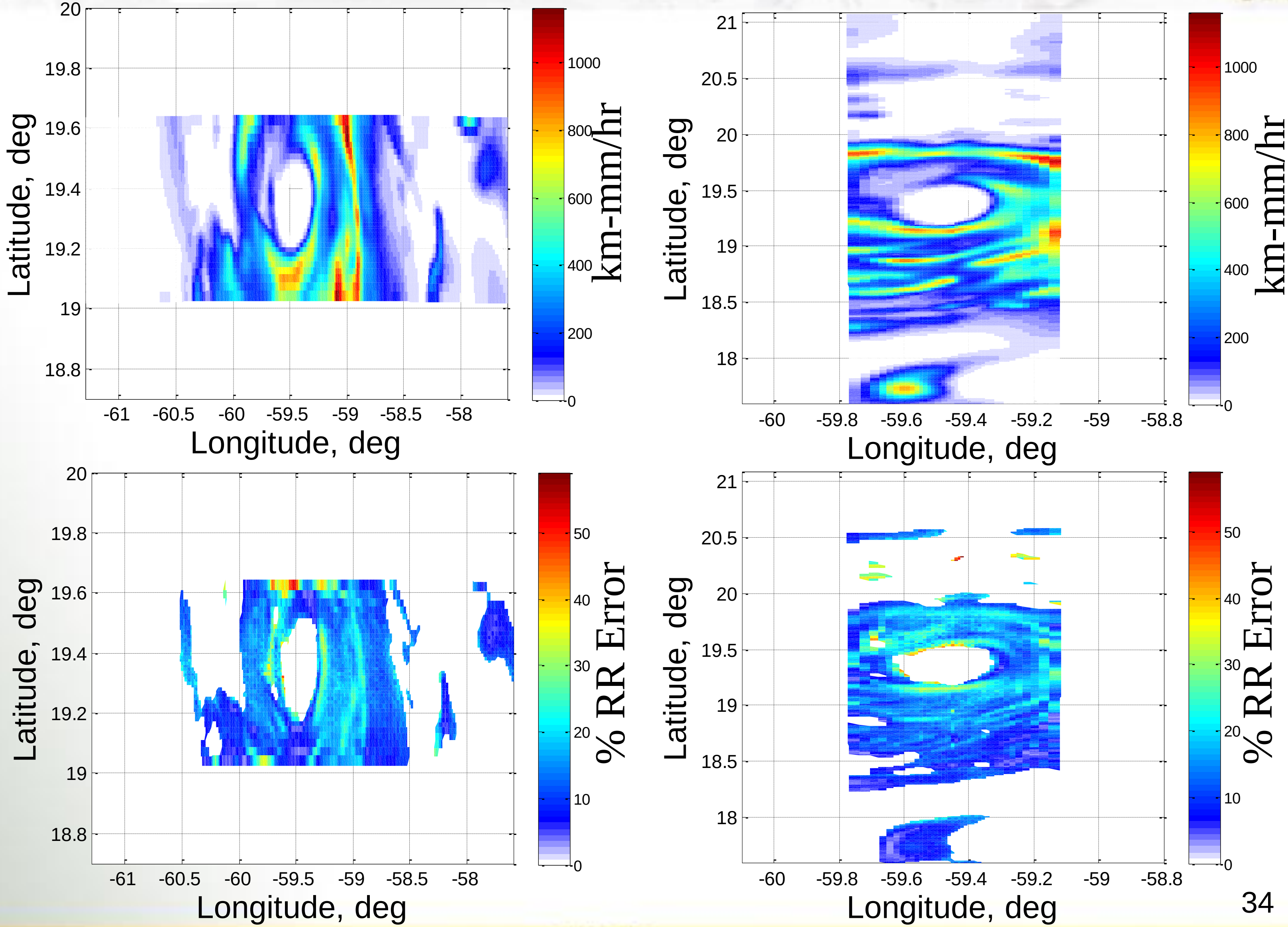
High RMS WS errors associated with RR and low WS

RMS Rain Rate Retrieved Errors

1 Kelvin Random Errors

Integrated RR

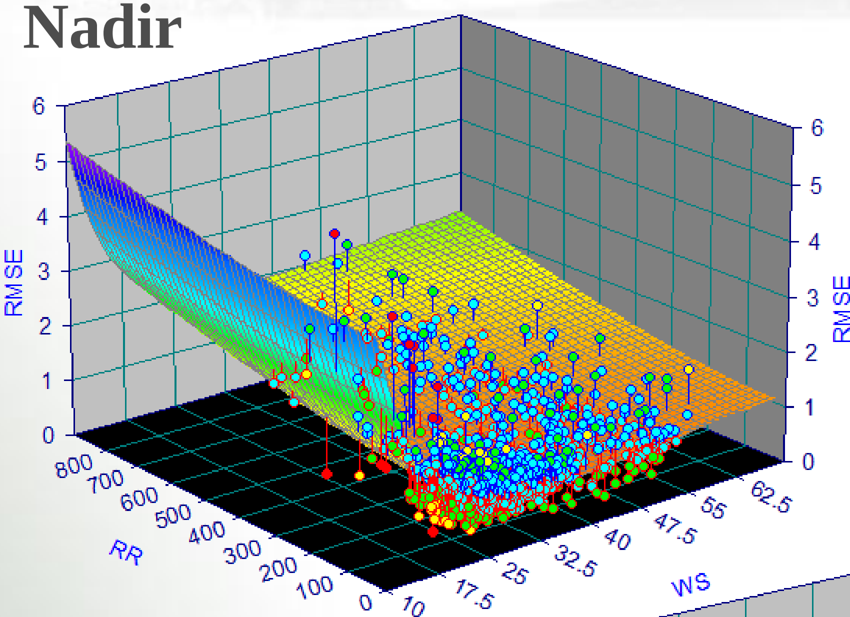
RR Error



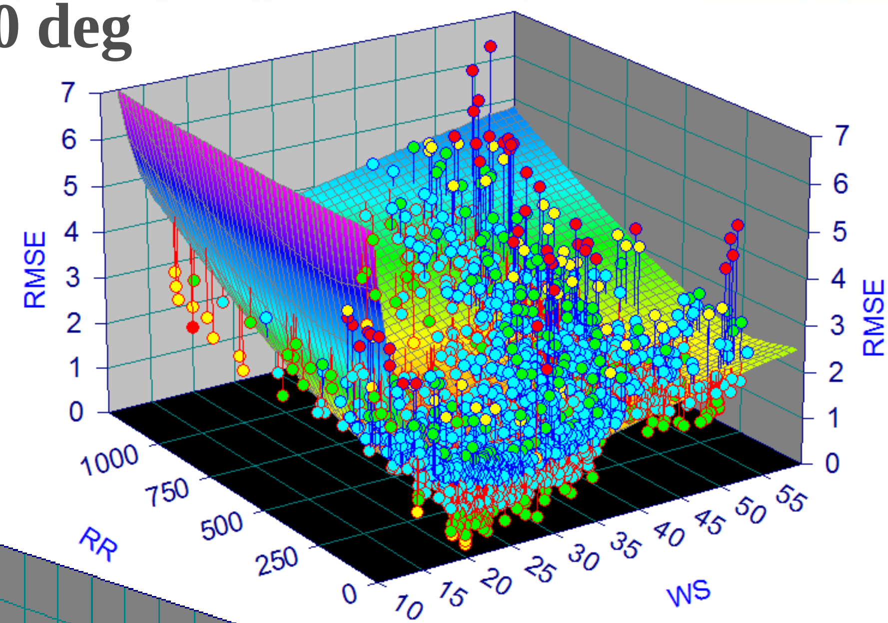
WS Error Surface

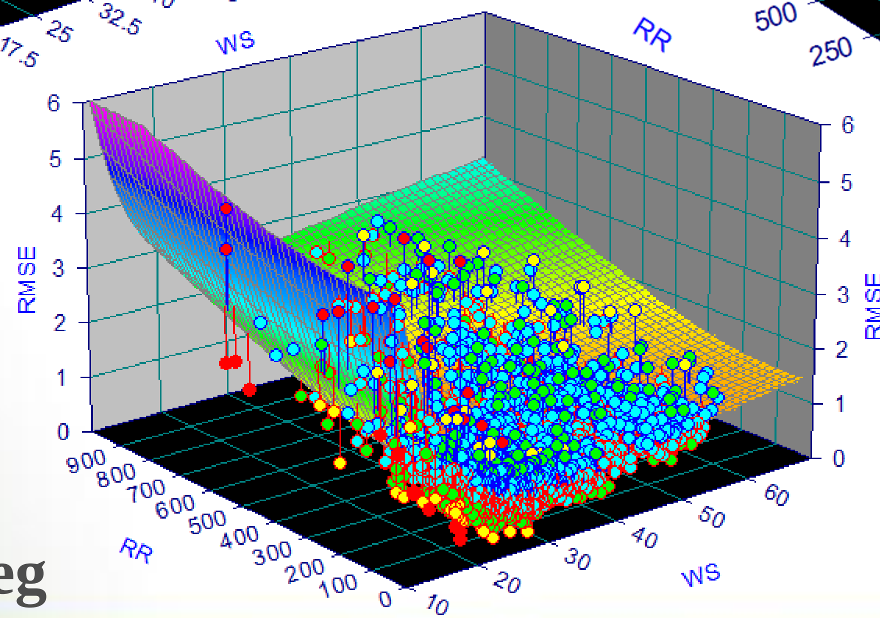
1 Kelvin Random Error - Total of 8 Legs

Nadir



60 deg

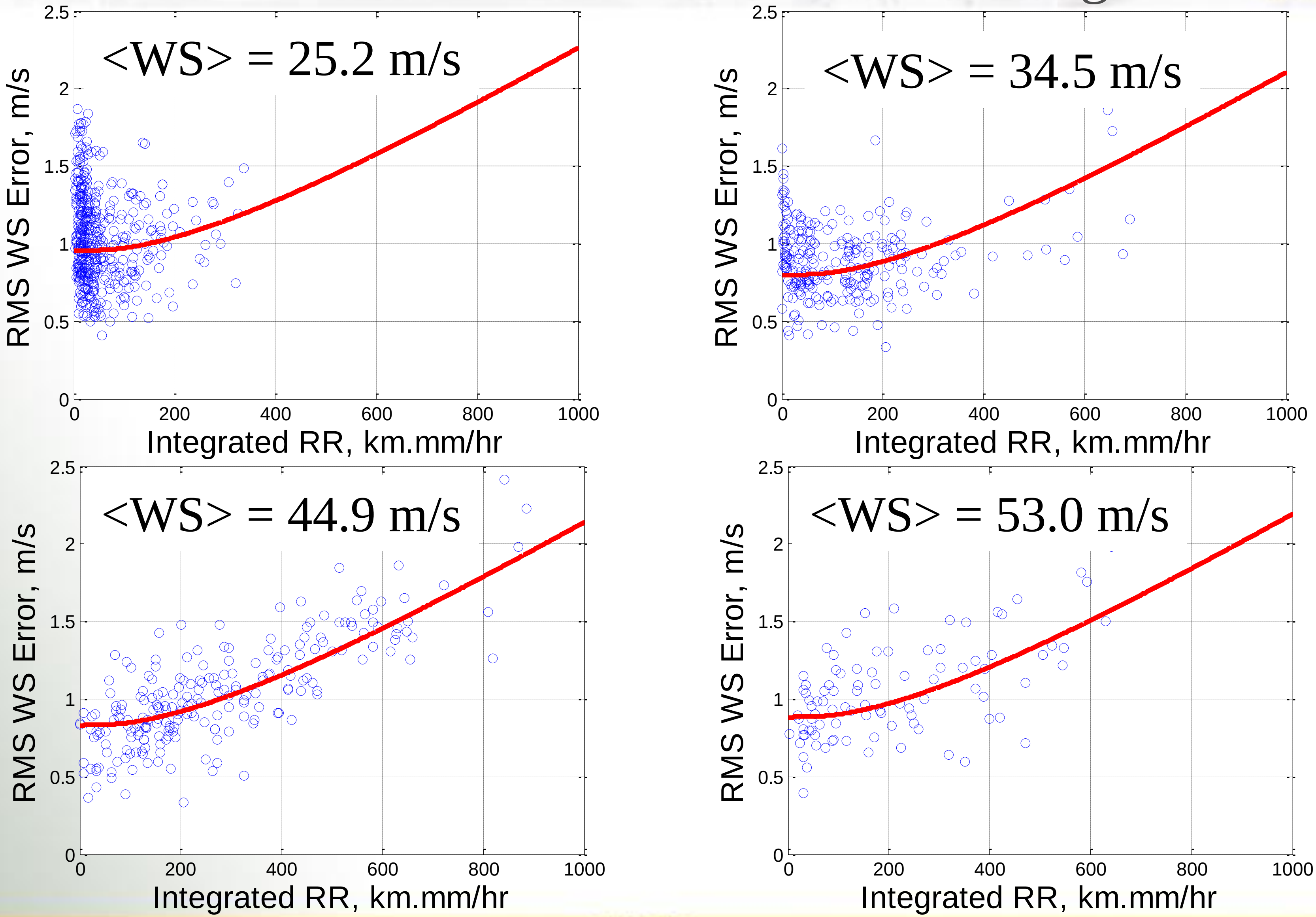




30 deg

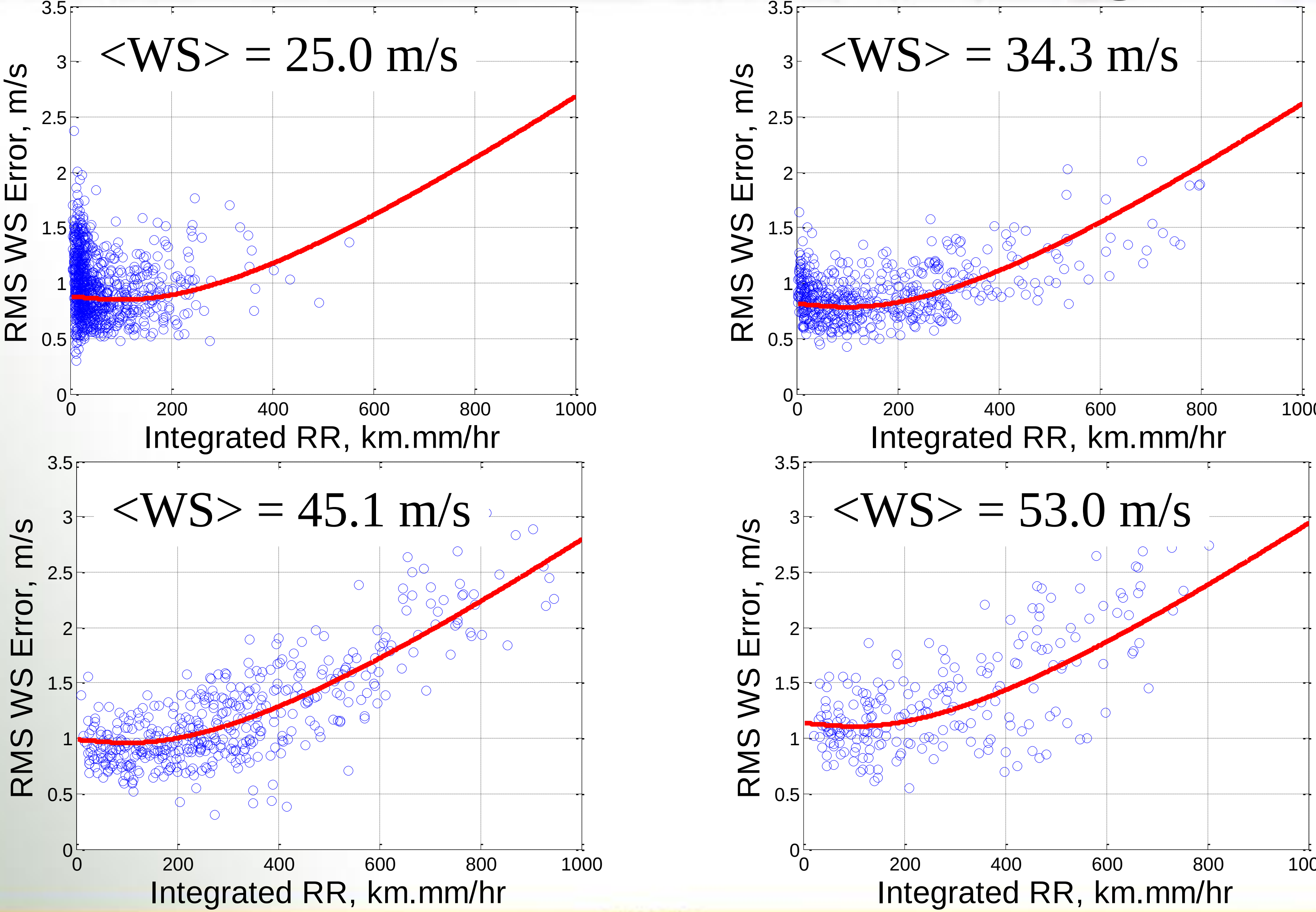
RMS WS Error @ Nadir

1 Kelvin Random Error - Total of 8 Legs



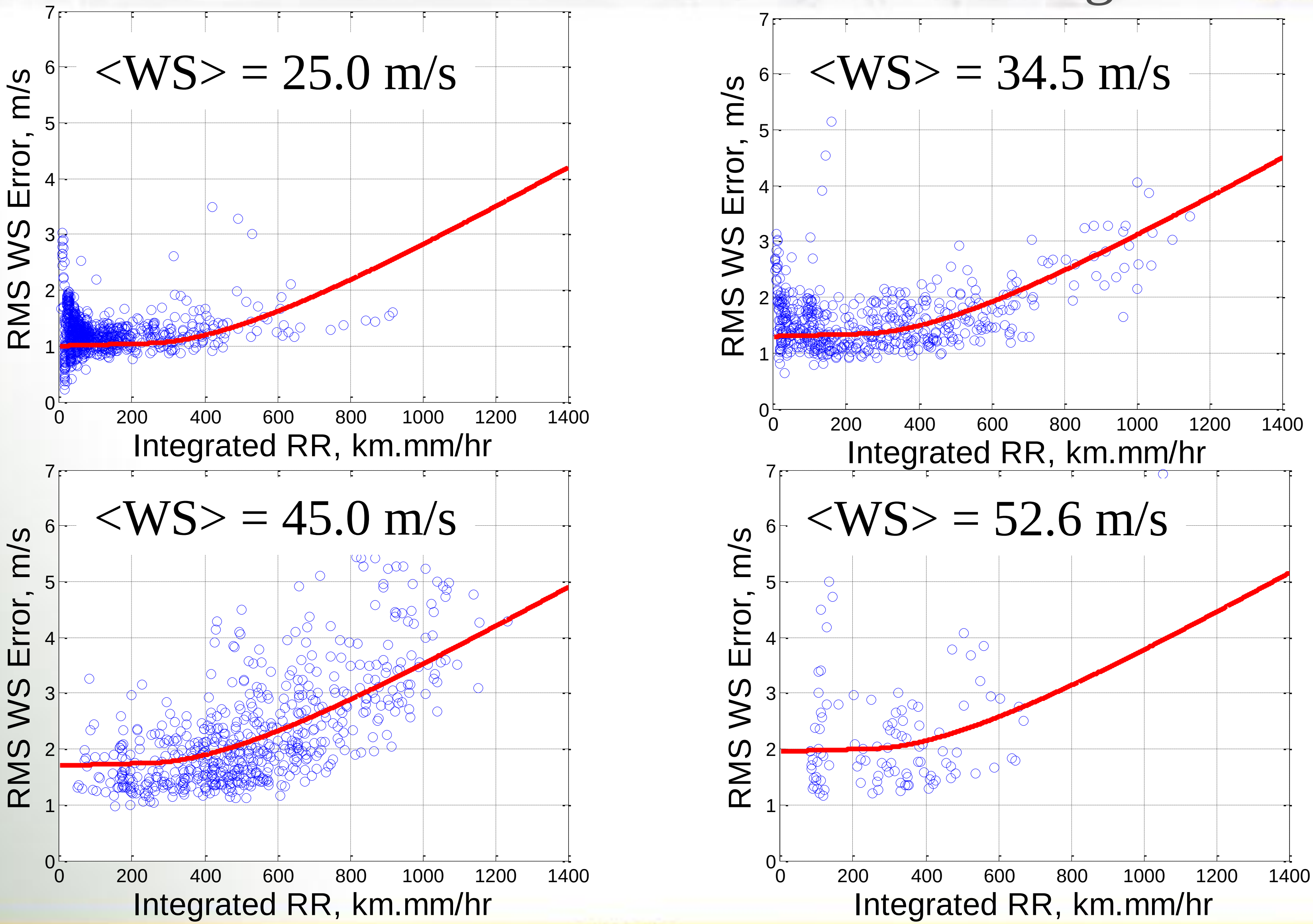
RMS WS Error @ ± 30°

1 Kelvin Random Error - Total of 8 Legs



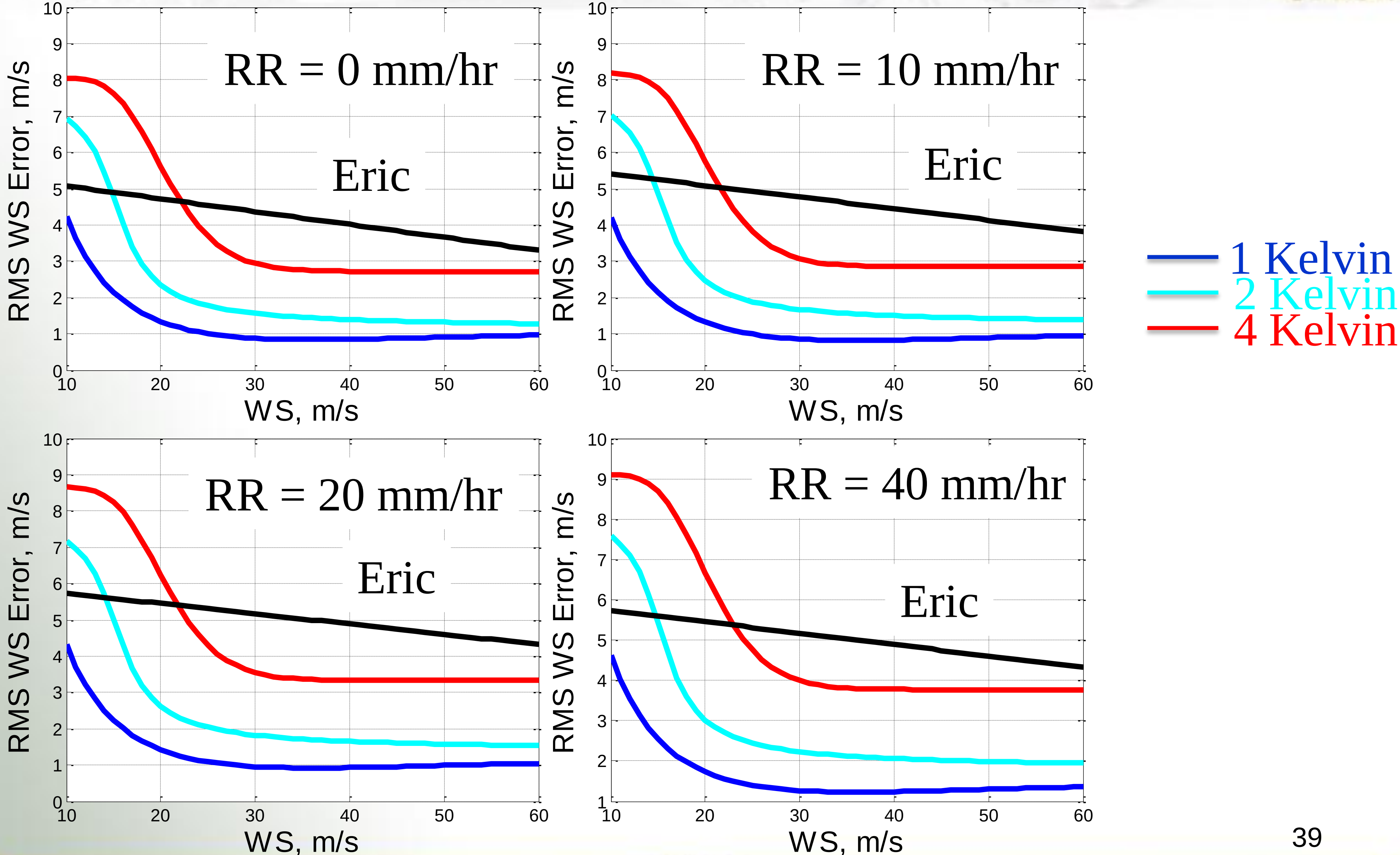
RMS WS Error @ ± 60°

1 Kelvin Random Error - Total of 8 Legs



RMS WS Error @ Nadir

Different Random Errors



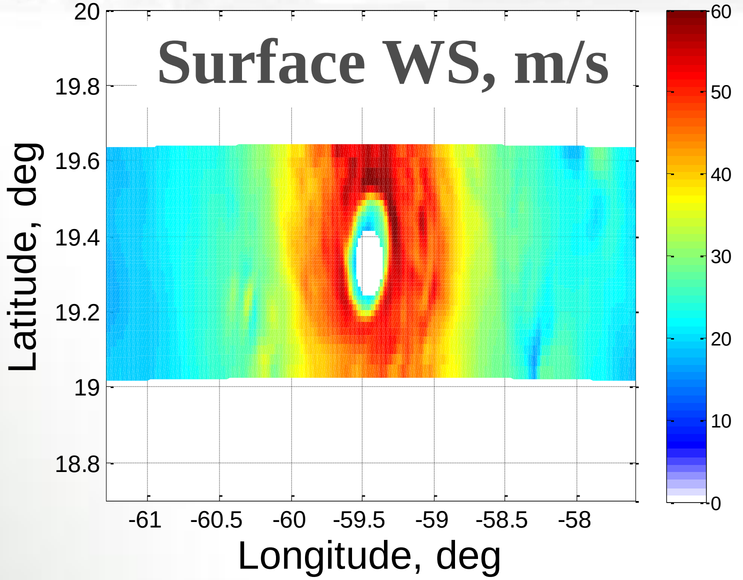
Error Sources Assessment

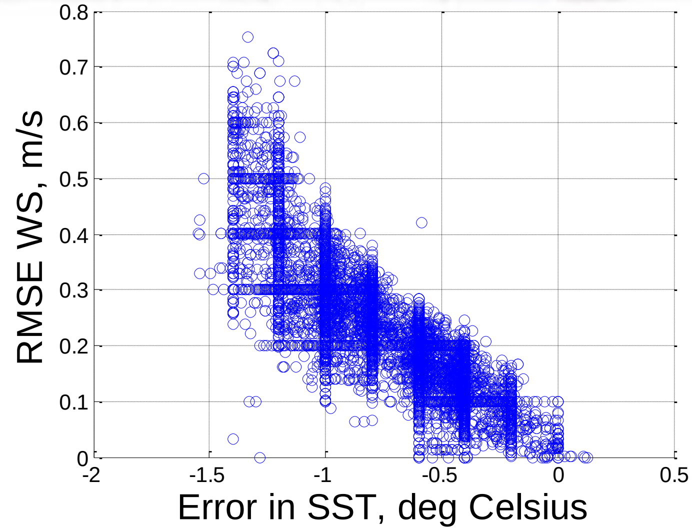
Case 1 → Incorrect SST in retrieval

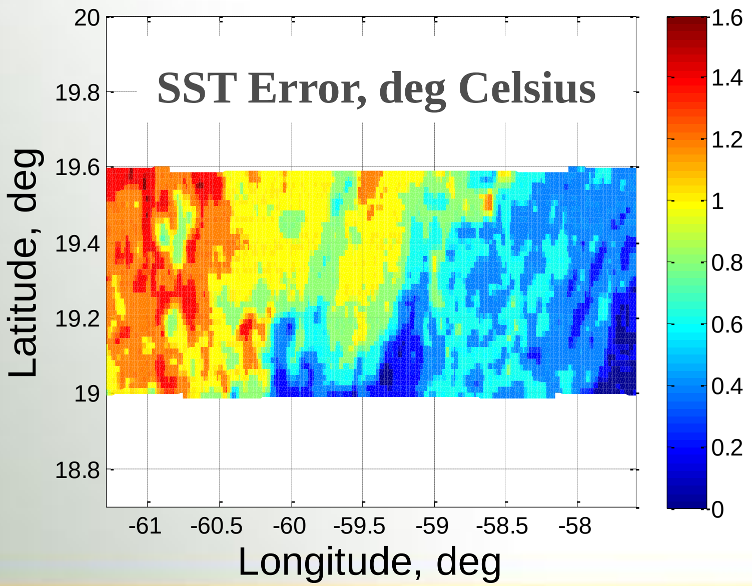
- In FWD Model:
  - Rain-free
  - No Atmosphere
  - **Variable SST**
- In Retrieval Algorithm:
  - No Atmosphere
  - No Random Errors
  - Perfect Antenna Correction
  - **Constant SST = 28 C**

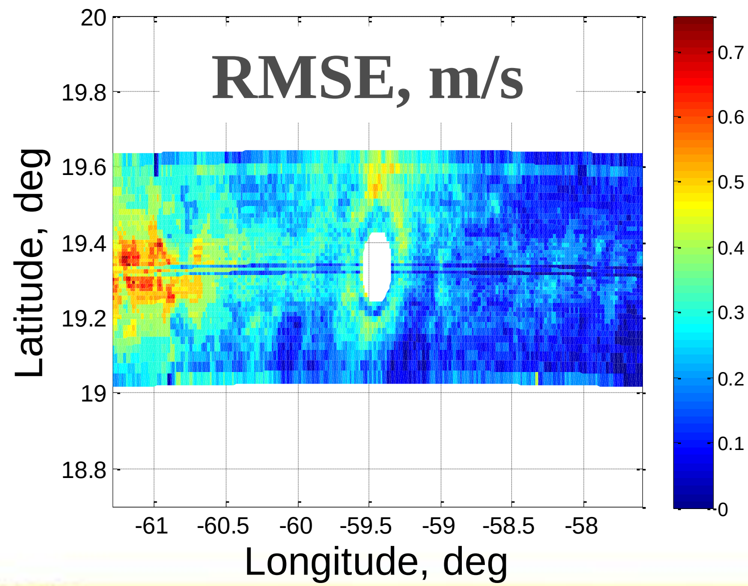
RMS Wind Speed Retrieved Errors

SST Component







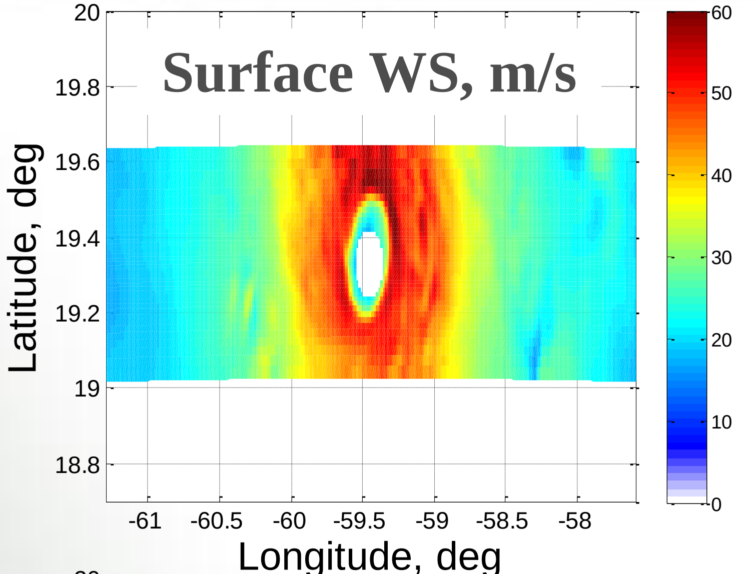


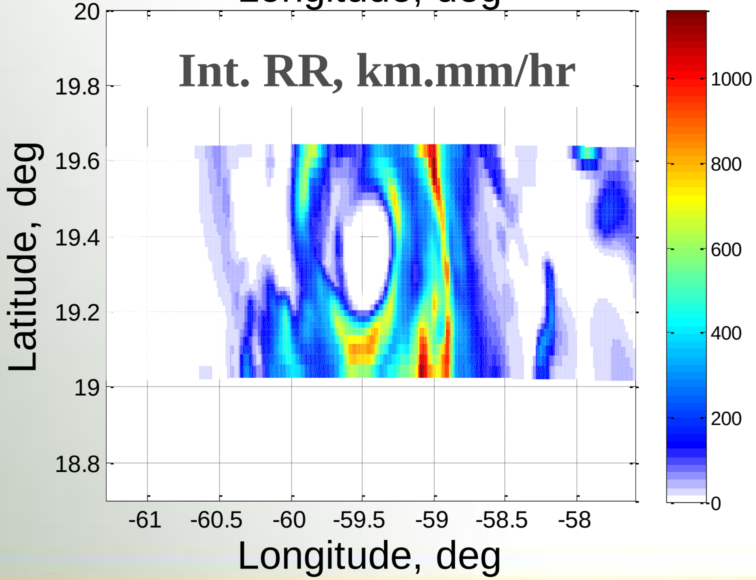
Case 2 → Constant Rain Rate in retrieval

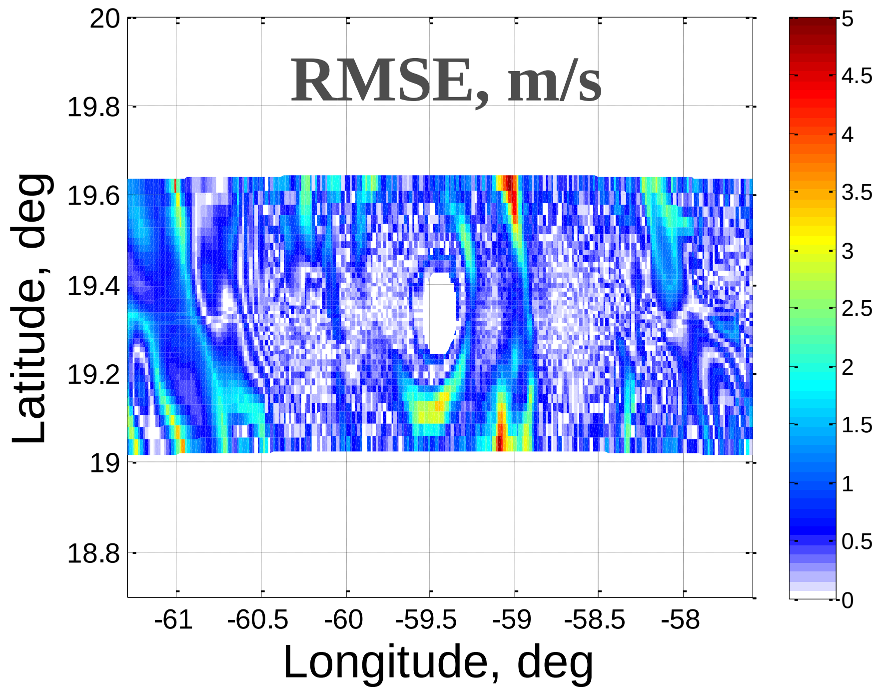
- In FWD Model:
  - **Variable 3D RR**
  - No Atmosphere
  - Constant SST = 28 deg Celsius
- In Retrieval Algorithm:
  - No Atmosphere
  - No Random Errors
  - **0.8 mm/hr RR step size**
  - Perfect Antenna Correction

RMS Wind Speed Retrieved Errors

Rain Rate Component







Error Sources Assessment

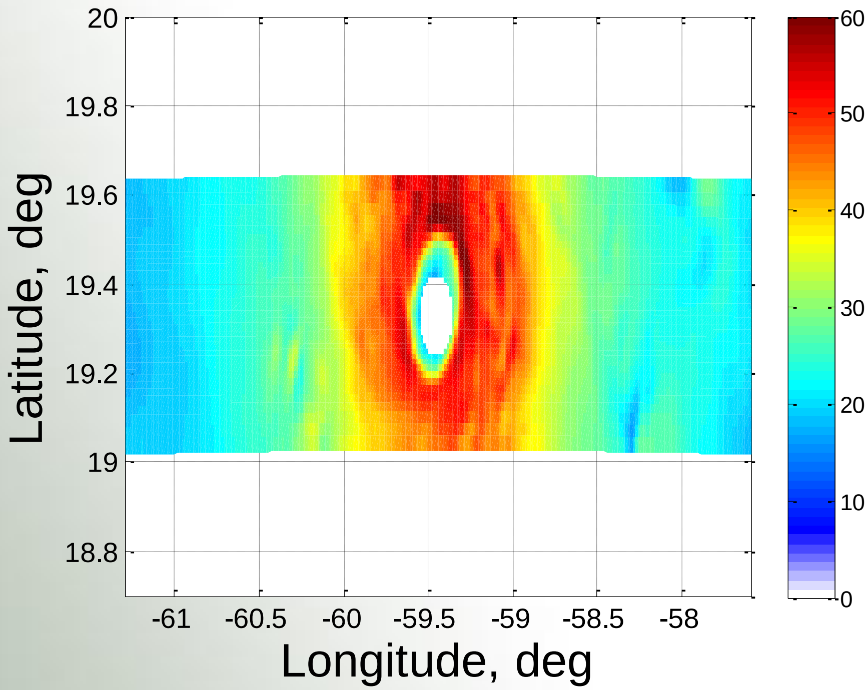
Case 3 → Incorrect atmos. in retrieval

- In FWD Model:
  - Rain-free
  - **3D Atmosphere**
  - Constant SST = 28 deg Celsius
- In Retrieval Algorithm:
  - **Hurricane Atmosphere climatology**
  - No Random Errors
  - Perfect Antenna Correction

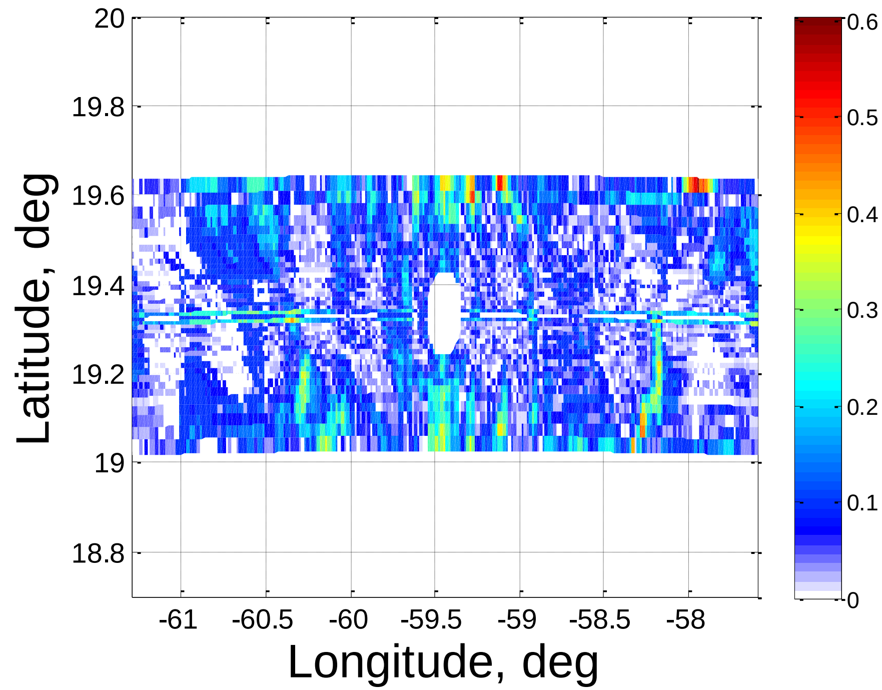
RMS Wind Speed Retrieved Errors

Atmospheric Correction Component

Surface WS, m/s



RMSE, m/s



Error Sources Assessment

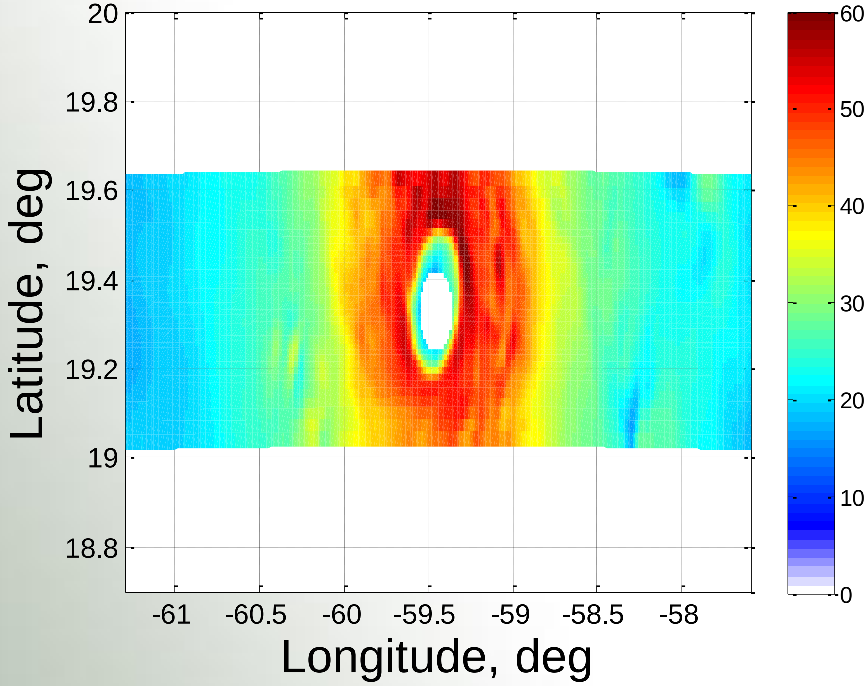
Case 4 → Imperfect antenna pattern correction

- In FWD Model:
  - Rain-free
  - No Atmosphere
  - Constant SST = 28 deg Celsius
- In Retrieval Algorithm:
  - No Atmosphere
  - No Random Errors
  - **Assumed antenna pattern correction**

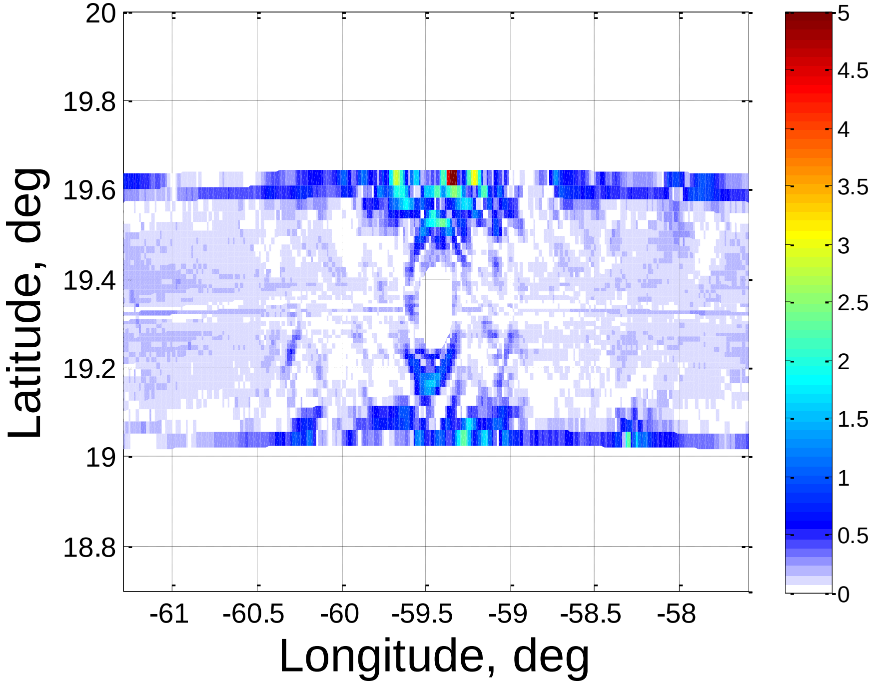
RMS Wind Speed Retrieved Errors

Antenna Pattern Correction Component

Surface WS, m/s



RMSE Surface, m/s

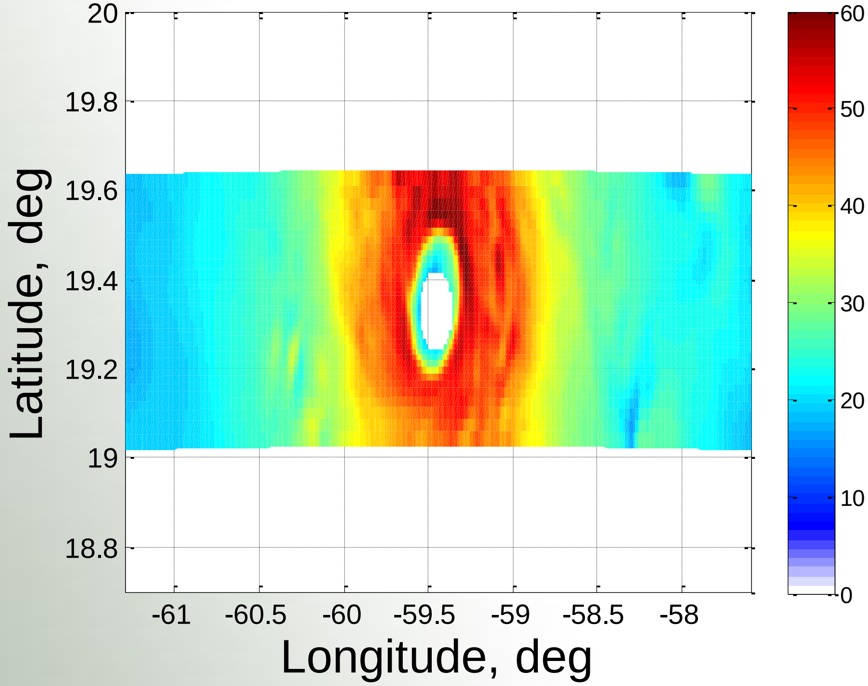


Case 5 → Random Error Effect

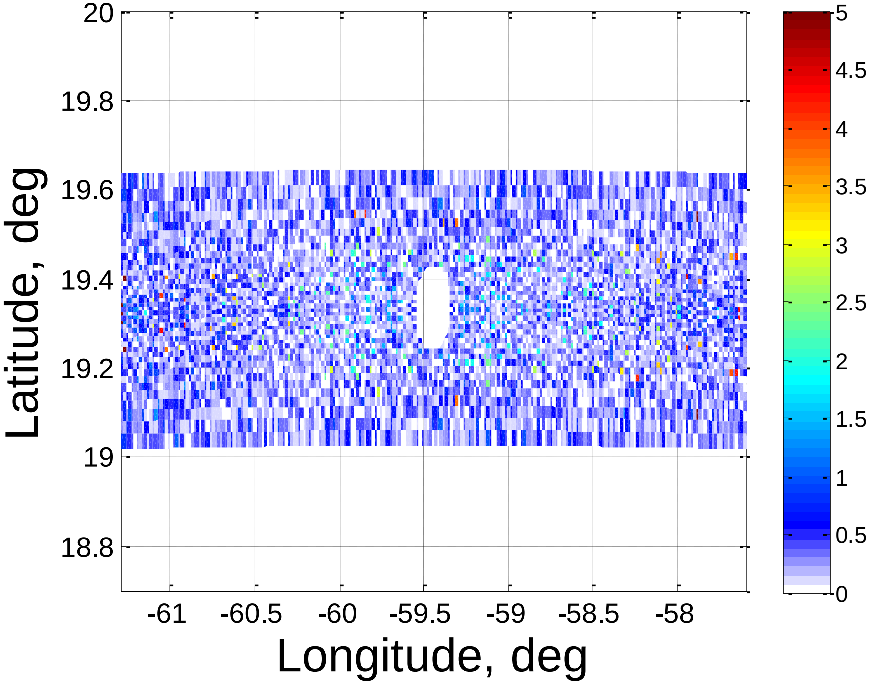
- In FWD Model:
  - Rain-free
  - No Atmosphere
  - Constant SST = 28 deg Celsius
- In Retrieval Algorithm:
  - No Atmosphere
  - **Random Errors Included**
  - Perfect Antenna Correction

RMS Wind Speed Retrieved Errors
1 Kelvin Random Error

Surface WS, m/s



RMSE Surface, m/s



Summary

- An end-to-end simulation of HIRAD measurements of hurricane surface wind and tropical rainfall has been developed
- Simulation has been extensively validated
- Preliminary results of Monte Carlo simulations for Hurricane Frances demonstrate that high resolution, wide swath imaging are feasible under realistic aircraft operating conditions
- Simulations in progress to characterize the wind speed and rain rate retrieval errors as a *f(WS, RR, EIA)*
  - Multiple hurricanes
  - Rotating Fig-4 aircraft flight tracks

Future Work

- Improve rain rate retrieval to account for climatologically hurricane rain vertical profiles

- Develop dual polarized MLE wind speed/rain rate retrieval algorithm to reduce errors due to polarization mixing at larger incidence angles

- Increase simulation data base of hurricane cases

Publications - Journal

[1] Ruba Amarin, Christopher Ruf, W. Linwood Jones , 'Impact of Spatial Resolution on Wind Field Derived Estimates of Air Pressure Depression in the Hurricane Eye', Molecular Diversity Preservation International Journal (*MDPI*), Volume 2, Issue 3, PP 665-672, March 2010.

[2] M. C. Bailey, R. A. Amarin, J. Johnson, P. Nelson, M. James, D. Simmons, C. Ruf, W. L. Jones, and X. Gong, "Multi-Frequency Synthetic Thinned Array Antenna for the Hurricane Imaging Radiometer," *IEEE AP-S Transactions on Antennas and Propagation*, 2010.

[3] Boon H. Lim, Ruba Amarin, Salem El-Nimri, James Johnson, Linwood Jones and Christopher S. Ruf, '' Synthetic Aperture Pattern Considerations For An Under Sampled 1-D Synthetic Thinned Aperture Radiometer'', *submitted for publication in the IEEE Geoscience and Remote Sensing Letters*, 2008.

Publications - Conferences

[1] Johnson, James W., **Amarin, Ruba A.**, El-Nimri, Salem F., and W. Linwood Jones, "A Wide Swath, Imaging Microwave Radiometer for Hurricane Observations", 60th InterDepartmental Hurricane Conference, Mobile, AL, Mar. 21-24, 2006

[2] **Amarin, Ruba A.**, Johnson, James and W. Linwood Jones, "Signal Analysis of Microwave Radiometric Emissions in Hurricanes: Part 2 – Oceanic rain Rate Dependence", Proc. IEEE SoEastCon, Memphis, TN, Mar. 31-Apl. 1, 2006

[3] Johnson, James W., **Amarin, R. A.**, El-Nimri, Salem F., and W. Linwood Jones, "A Wide-Swath, Hurricane Imaging Radiometer for Airborne Operational Measurements", Proc. IEEE IGARSS-06, Aug. 28 - Sept. 1, 2006, Denver, CO.

[4] **Ruba A. Amarin**, Salem F. El-Nimri, James W. Johnson, W. Linwood Jones, Boon H. Lim and Christopher S. Ruf, "Instrument Design Simulations for Synthetic Aperture Microwave Radiometric Imaging of Wind Speed and Rain Rate in Hurricanes", presented at IEEE Intrn. Geosci. Remote Sens. Symp., Barcelona, SP., 2007.

[5] C. S. Ruf, **R. Amarin**, M. C. Bailey, B. H. Lim, R. Hood, M. James, J. Johnson, W. L. Jones, "The Hurricane Imaging Radiometer - An Octave Bandwidth Synthetic Thinned Array Radiometer," presented at IEEE Intrn. Geosci. Remote Sens. Symp., Barcelona, SP., 2007.

[6] B. H. Lim, **R. A. Amarin**, S. F. El-Nimri, J. Johnson, L. Jones, and C. S. Ruf, "Restrictions on the Field of View for an Undersampled 1-D Synthetic Thinned Aperture Radiometry," presented at IEEE Intrn. Geosci. Remote Sens. Symp, Barcelona, SP., 2007.

Publications - Conferences

[7] Ruba Amarin, Chris Ruf, W. Linwood Jones, James W. Johnson and Shuyi Chen, "Improved Microwave Radiometric Imaging of Surface Wind Speed Dynamics in the Hurricane Eye-Wall", Submitted to The 28th Conference on Hurricanes and Tropical Meteorology, special session on "Advances in Remote Sensing of Tropical Cyclones",2008

[8] Ruba Amarin, Christopher Ruf, James Johnson, and W. Linwood Jones, "Performance Simulations for a Synthetic Aperture Radiometer Measuring Peak Surface Wind Speed in Hurricanes", Submitted to IEEE Intrn. Geosci.RemoteSens.Symp.,Boston,2008.

[9] S. F. El-Nimri, S. Alsweiss, J. Johnson, L. Jones, **R. Amarin**, and E. Uhlhorn, "HURRICANE IMAGING RADIOMETER WIDE SWATH SIMULATION FOR WIND SPEED AND RAIN RATE", IGARSS Conference, Boston,2008.

[10] **Ruba A. Amarin**, W. Linwood Jones, Salem El-Nimri and James W. Johnson, "A Wide-Swath Hurricane Imaging Radiometer for Imaging of Wind Speed and Rain Rate in Hurricanes", *2010 USNC URSI Radio Science Meeting*, 6-10 January, 2010, Boulder, CO.

[11] Timothy Miller, Robert Atlas, Peter Black, Shuyi Chen, Linwood Jones, Chris Ruf, Eric Uhlhorn, John Gamache, **Ruba Amarin**, Salem El-Nimri, Courtney Buckley, T. N. Krishnamurti, and Cerese Inglish , " Simulation of the impact of new aircraft- and satellite-based ocean surface wind measurements on wind analyses and numerical forecasts", *Submission to AMS 14th Conference on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (IOAS-AOLS)*, 17-21 January 2010, Atlanta, Georgia.

Publications - Conferences

[12] **Ruba A. Amarin**, Linwood Jones, James Johnson, Chris Ruf, Tim Miller and Shuyi Chen, "Hurricane Imaging Radiometer Wind Speed and Rain Rate Retrieval: Part-2. Analysis of Retrieval Accuracy", *to be submitted to the 11th Specialist Meeting on Microwave and Remote Sensing of the Environment*, 1-4 March, 2010, Washington DC.

[13] **Ruba A. Amarin**, Salem El-Nimri, Suleiman Alsweiss, James Johnson, and Linwood Jones, "Simulations for A Wide Swath Synthetic Aperture Microwave Radiometric Imaging of Wind Speed and Rain Rate in Hurricanes", *to be submitted to SPIE*, 5-9 April, 2010, Orlanod, FL.

[14] **Ruba A. Amarin**, W. Linwood Jones, James W. Johnson, Christopher Ruf, Timothy Miller and Shuyi Chen, 'Estimates of Hurricane Wind Speed Measurement Accuracy using the Airborne Hurricane Imaging Radiometer', *to be submitted to AMS 29th Conference on Hurricanes and Tropical Meteorology*, 10-14 May 2010, Tucson, Arizona.

[15] **Ruba Amarin**, Linwood Jones, James Johnson, Chris Ruf, Timothy Miller and Eric Uhlhorn, 'The Hurricane Imaging Radiometer Wide Swath Simulation And Wind Speed Retrievals', *to be submitted to IGARSS*, 25-30 May, 2010, Honolulu.

[16] Timothy Miller, **Ruba Amarin**, Robert Atlas, M.C. Bailey, Peter Black, Courtney Buckley, Mark James, James Johnson, Linwood Jones, Christopher Ruf, David Simmons and Eric Uhlhorn, 'Capabilities And Impact On Wind Analyses Of The Hurricane Imaging Radiometer (HIRAD)' *to be submitted to IGARSS*, 25-30 May, 2010, Honolulu.

CFRSL

Back Up Slides

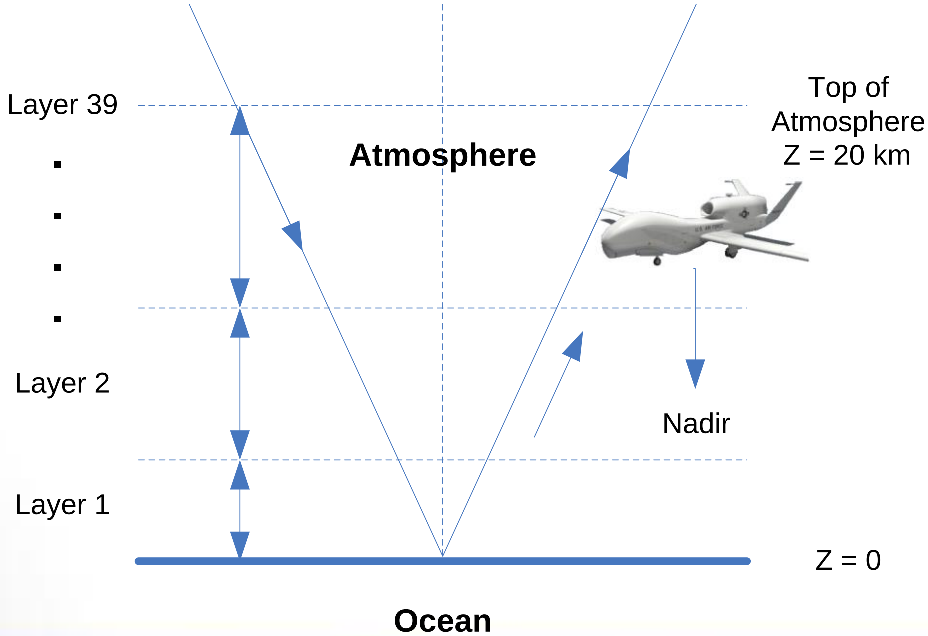
Parameters in Atmosphere

Effect on Tb ↑

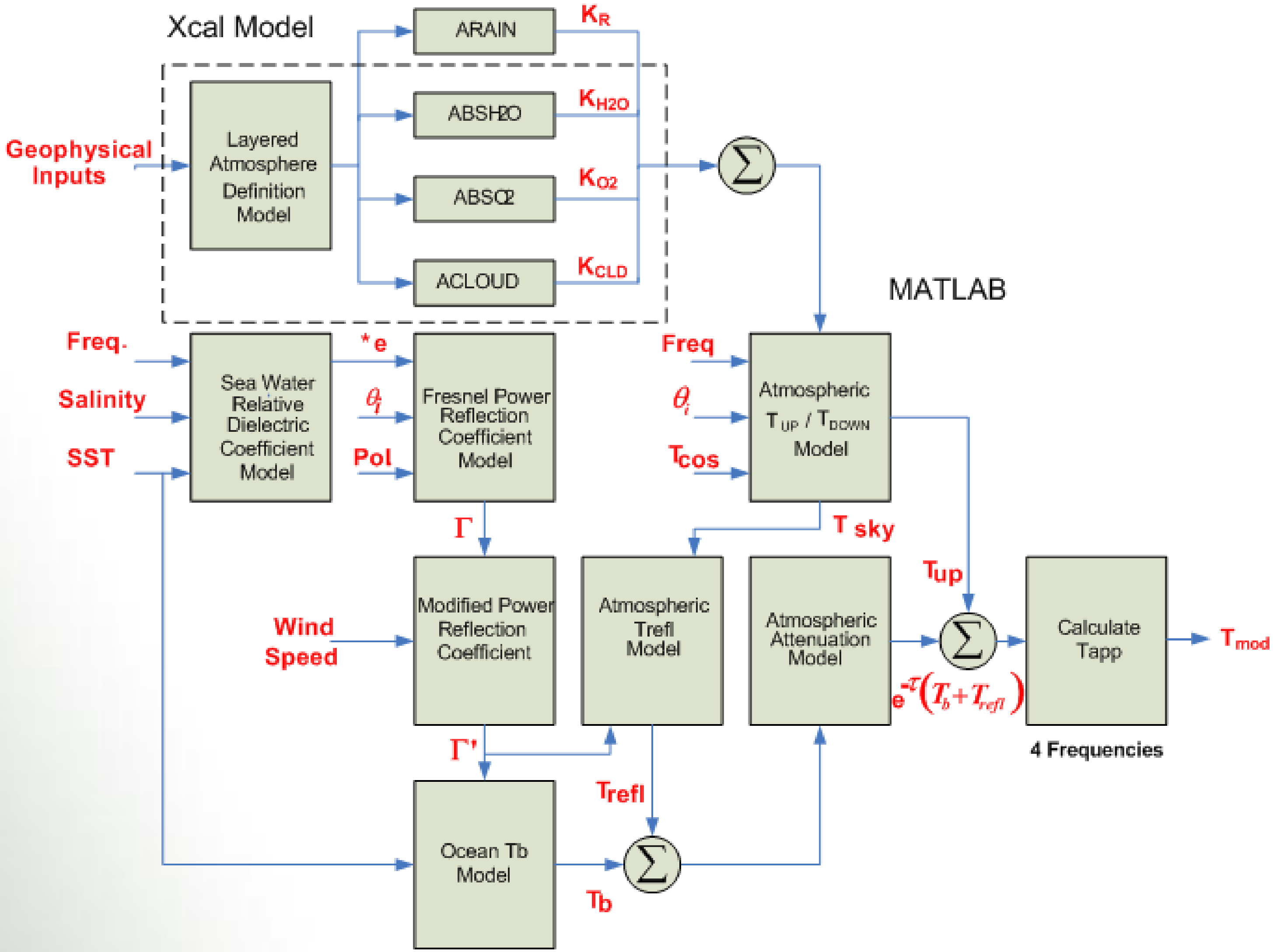
Parameter	Included	Source
Rain Rate	3-D	• MM5 data available
Water Vapor	3-D	• MM5 data available
Cloud Liquid Water	3-D	• MM5 data available
Super-cooled Water	3-D	• Included in cloud liquid water
Oxygen	2-D	• MM5 data available
SST	2-D	• Data available from NSSTC
Nitrogen	✗	• Not included
Graupel	✗	• MM5 data not available

Forward RTM (RadTb) Atmospheric Model

- RadTb is a μ-wave RTM used to compute atmospheric absorption coefficients
  - O2, WV & CLW
  - 39 layers of 20 Km total thickness

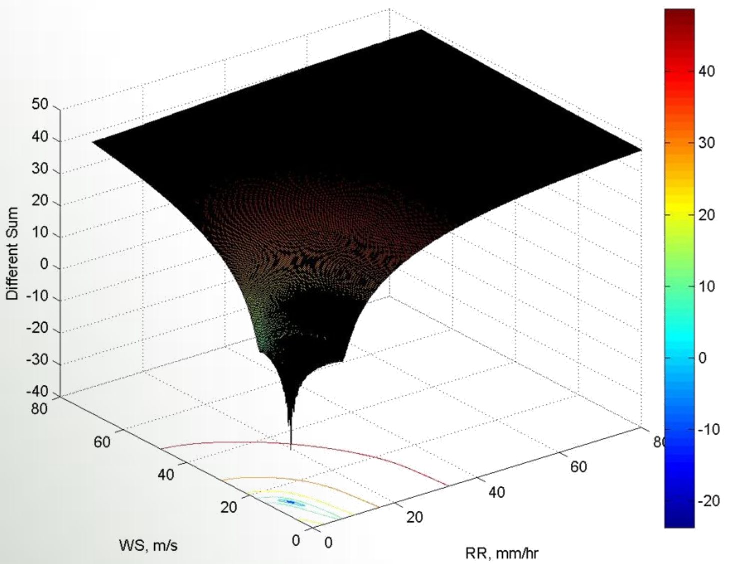


FWD Model - RTM

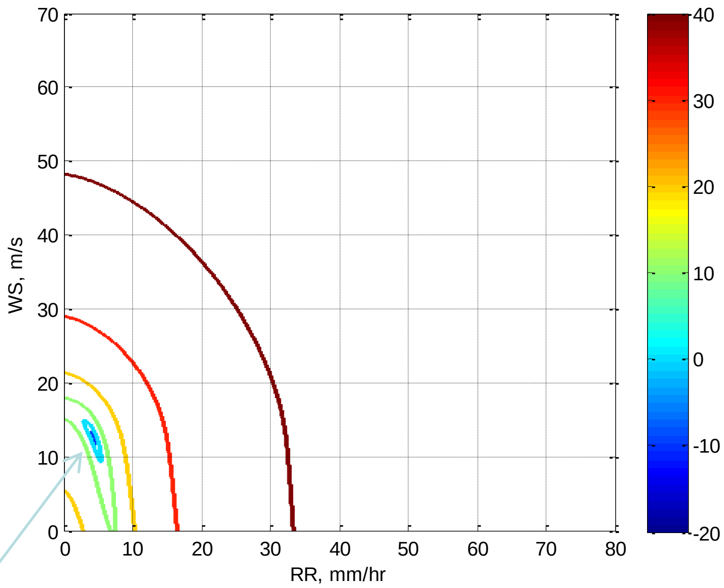


Verification
Hurricane Eye

Sum of Difference Surface



Contour Plot of the Surface



One Local Minimum

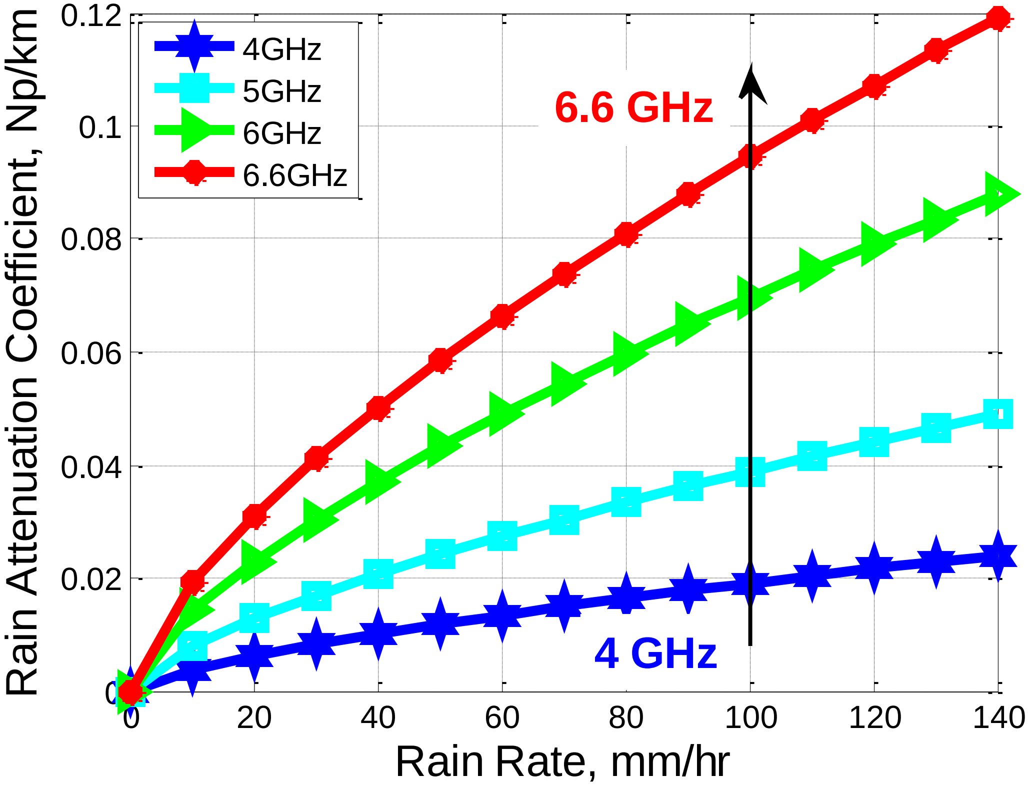
WS=12.6 m/s
RR=4.25 mm/hr

Rain Absorption Model

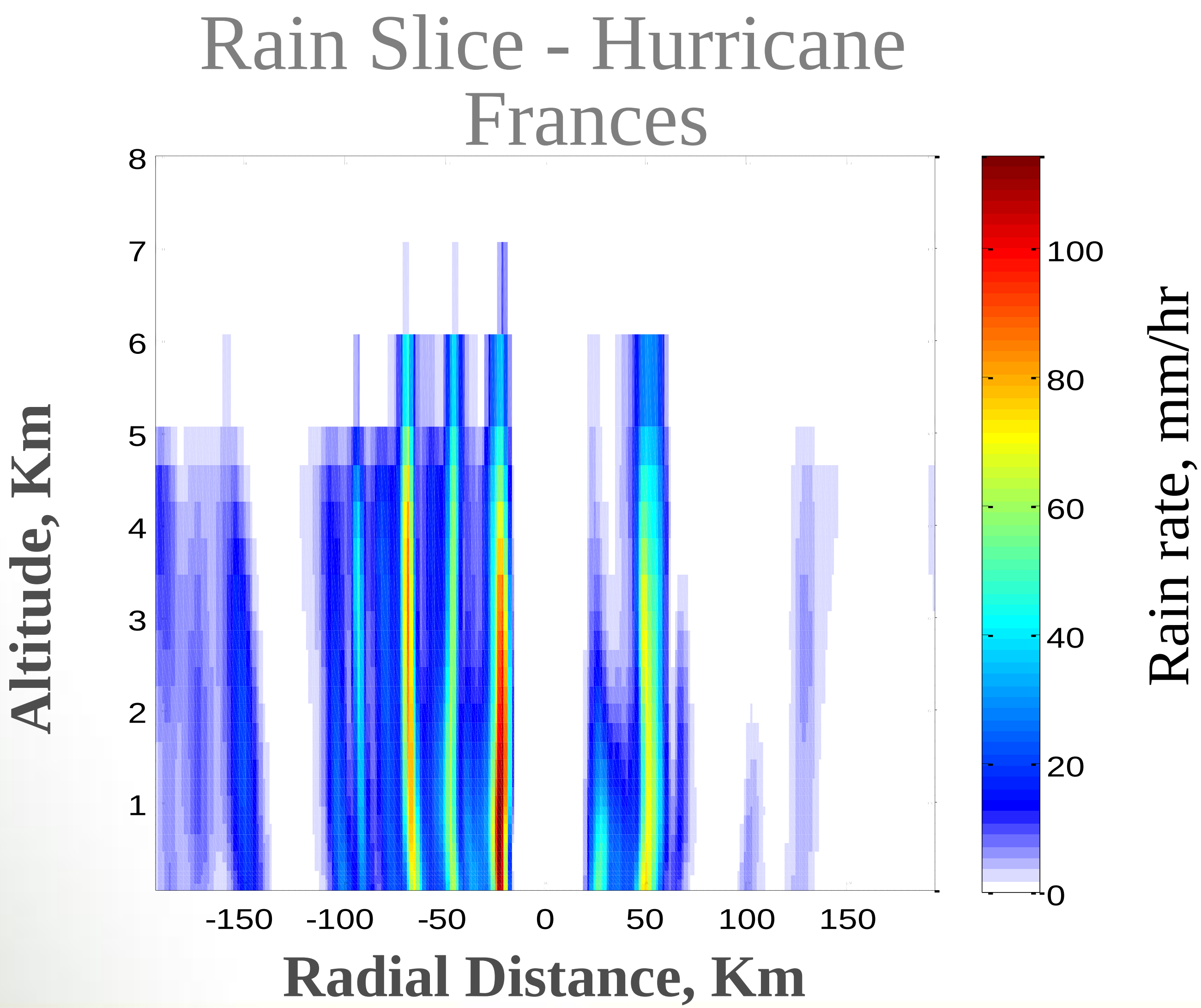
from NOAA HRD SFMR Algorithm

- Uses empirical power-law relationship to calculate rain absorption coefficient (Uhlhorn)

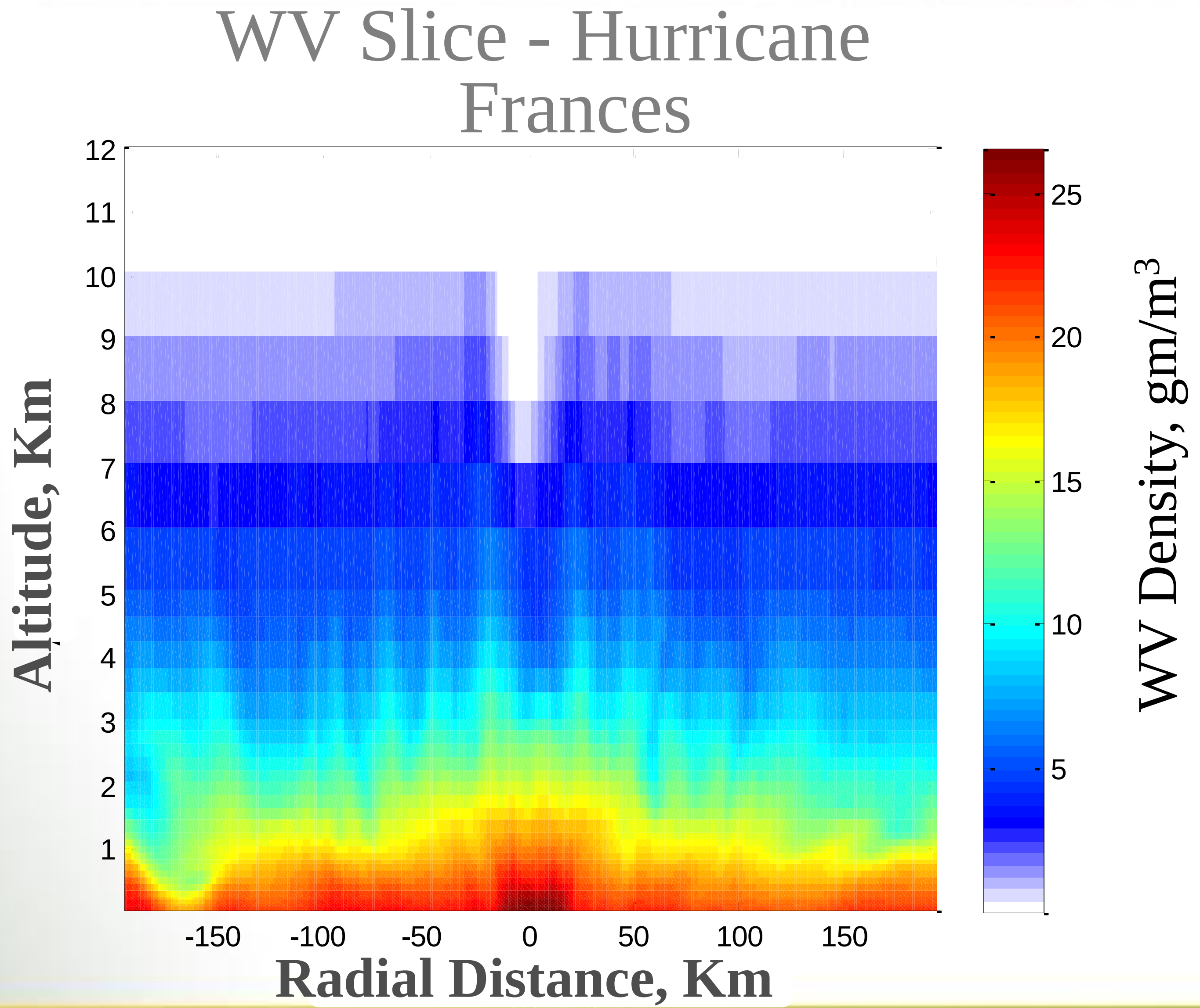
$$K_R = aR^b$$



Rain Rate Distribution 2-D Slice

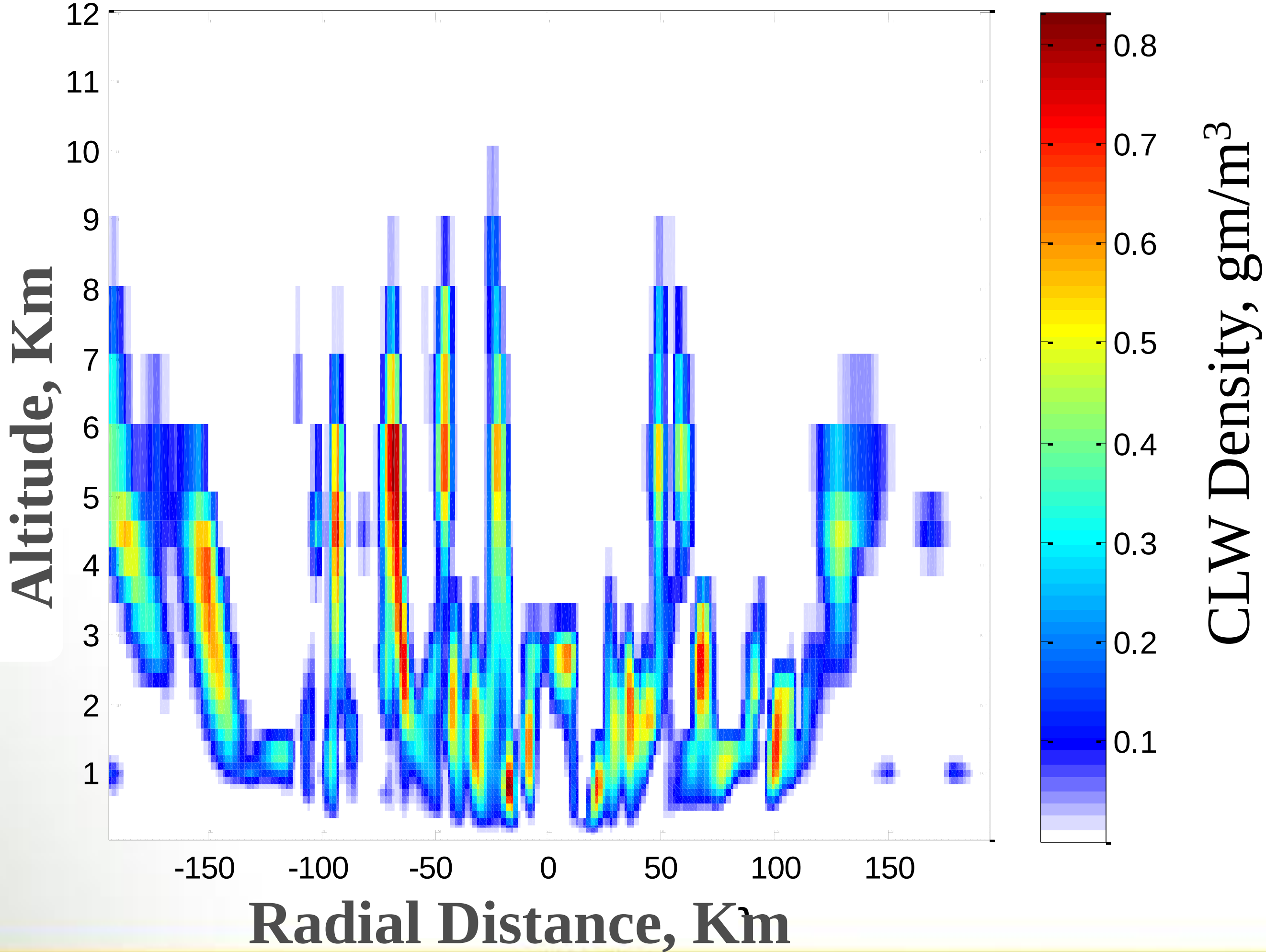


WV Density, gm/m^3

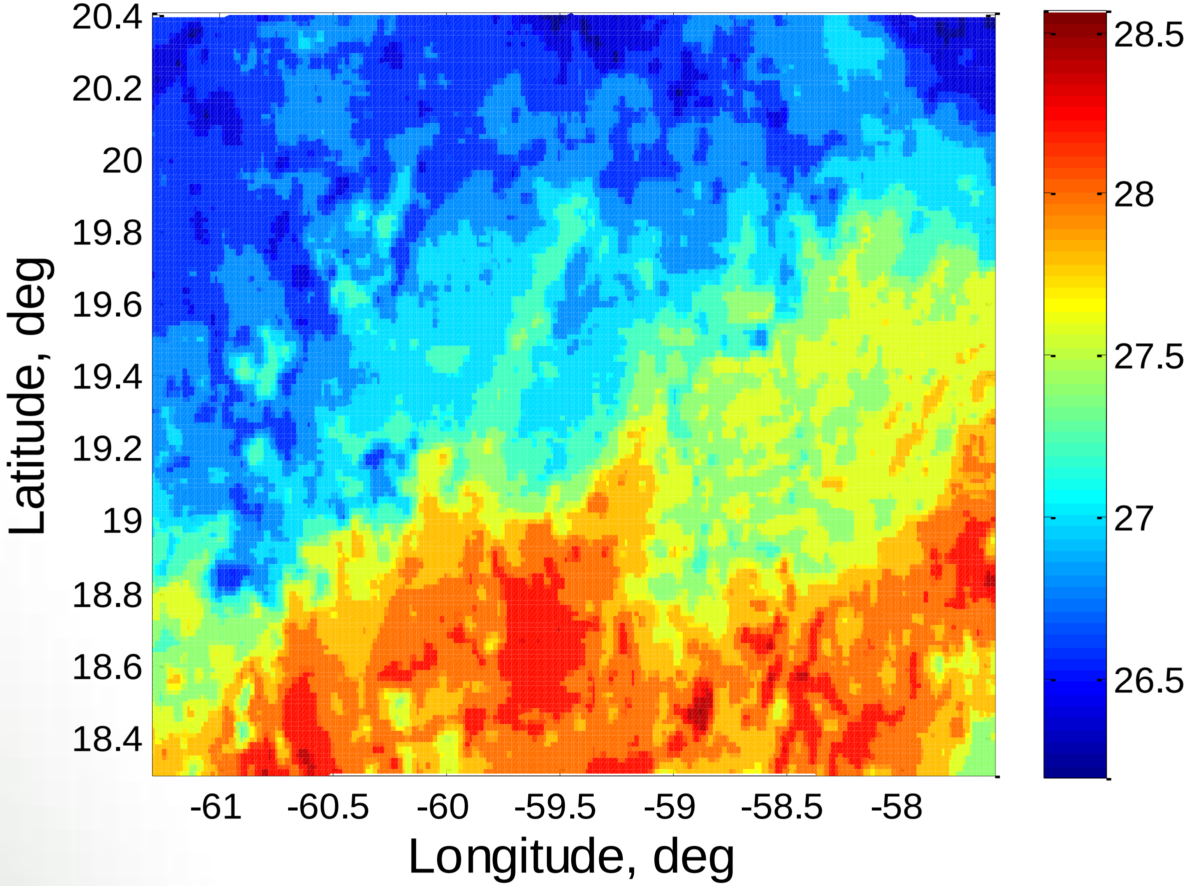


CLW Density, gm/m^3

CLW Slice - Hurricane Frances



SST, deg Celsius

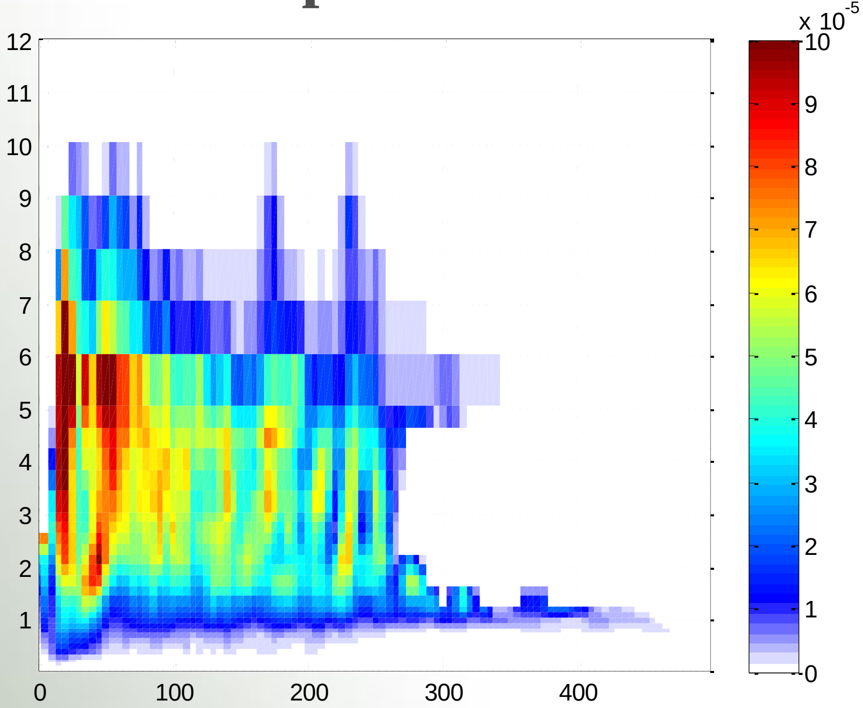


- Retrievals
  - SST assumed constant = 28 deg Celsius

CLW and WV Profiles in Retrievals
5Km Averaged Rings

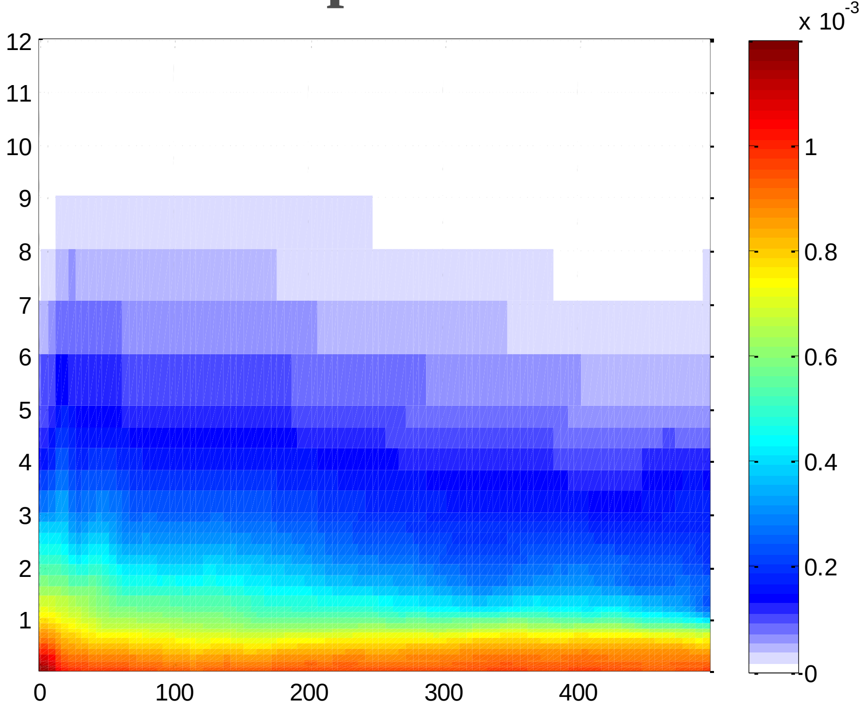
Cloud Liquid Water Profiles

Np/km



Water Vapor Profiles

Np/km

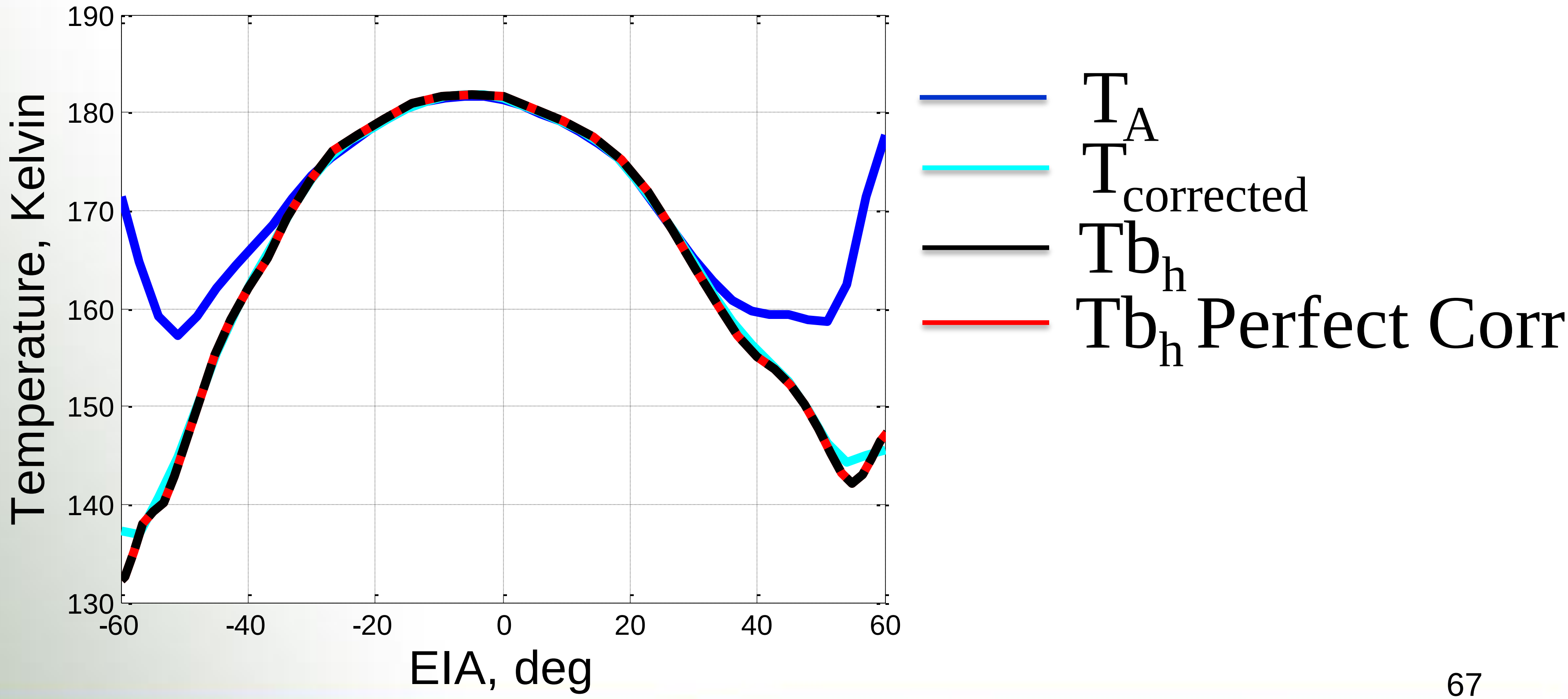


Altitude, Km

Radial Distance, Km

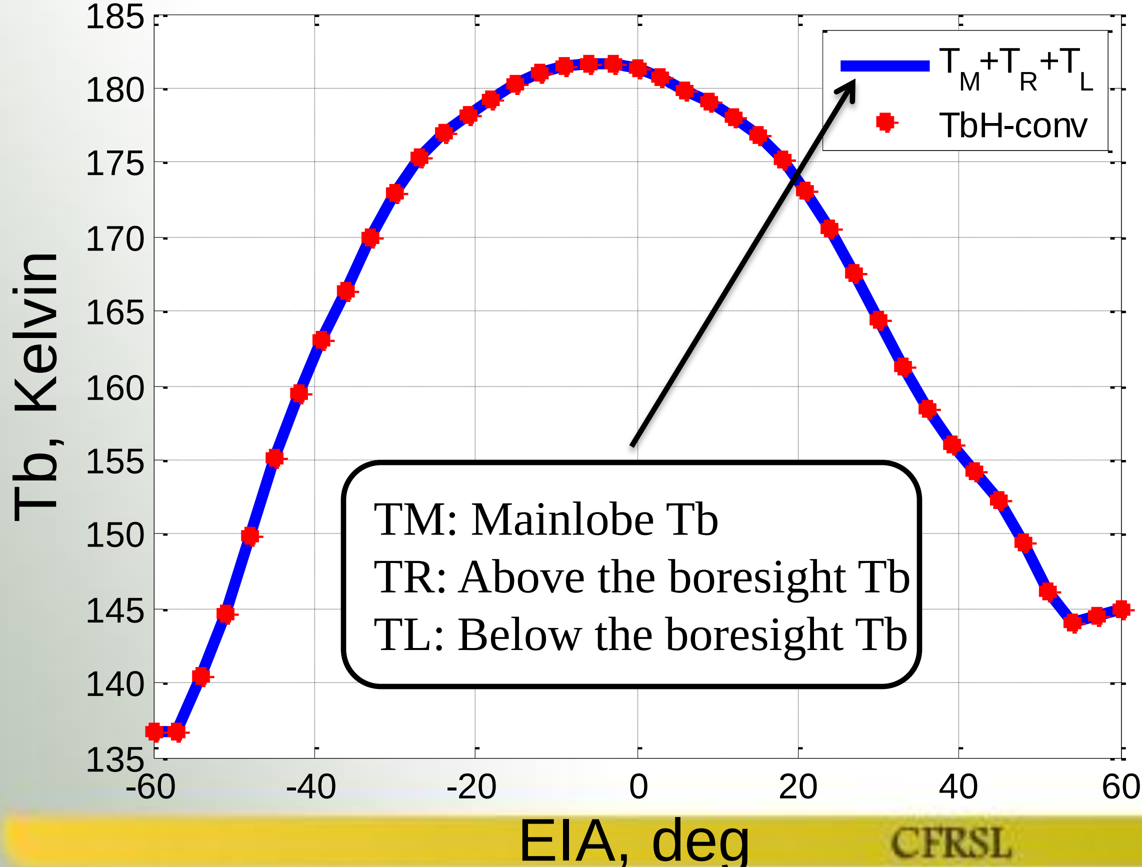
Model Validation – Example

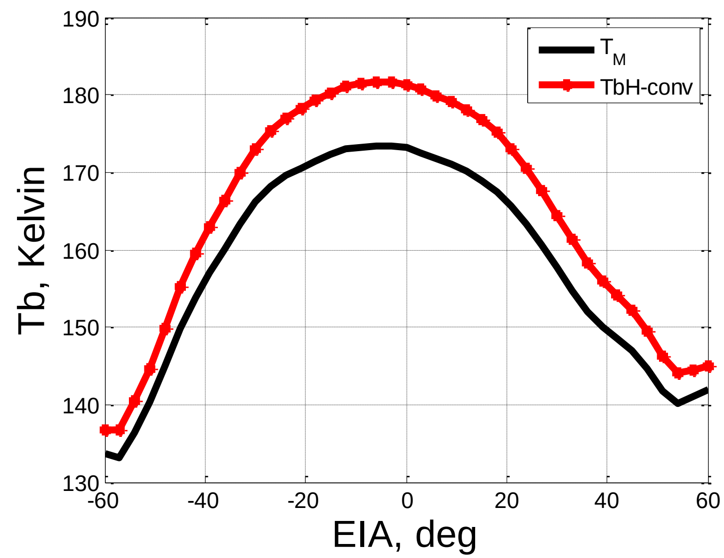
- Antenna Pattern Correction
  - Perfect knowledge of the sidelobe Tb contribution yields negligible error

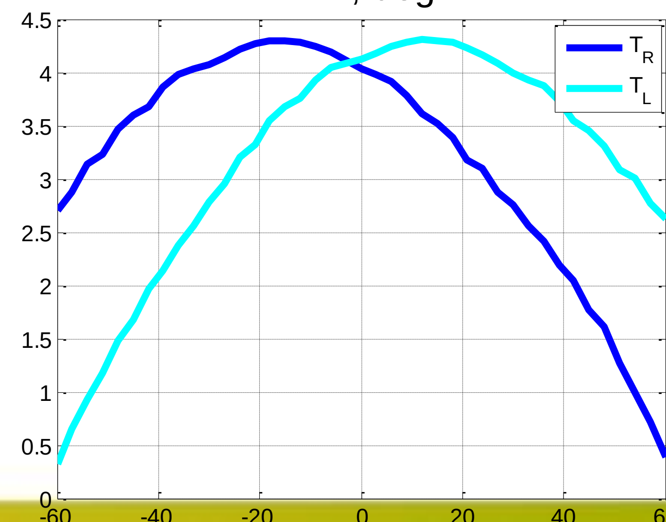


No Issues in Applying Antenna Pattern

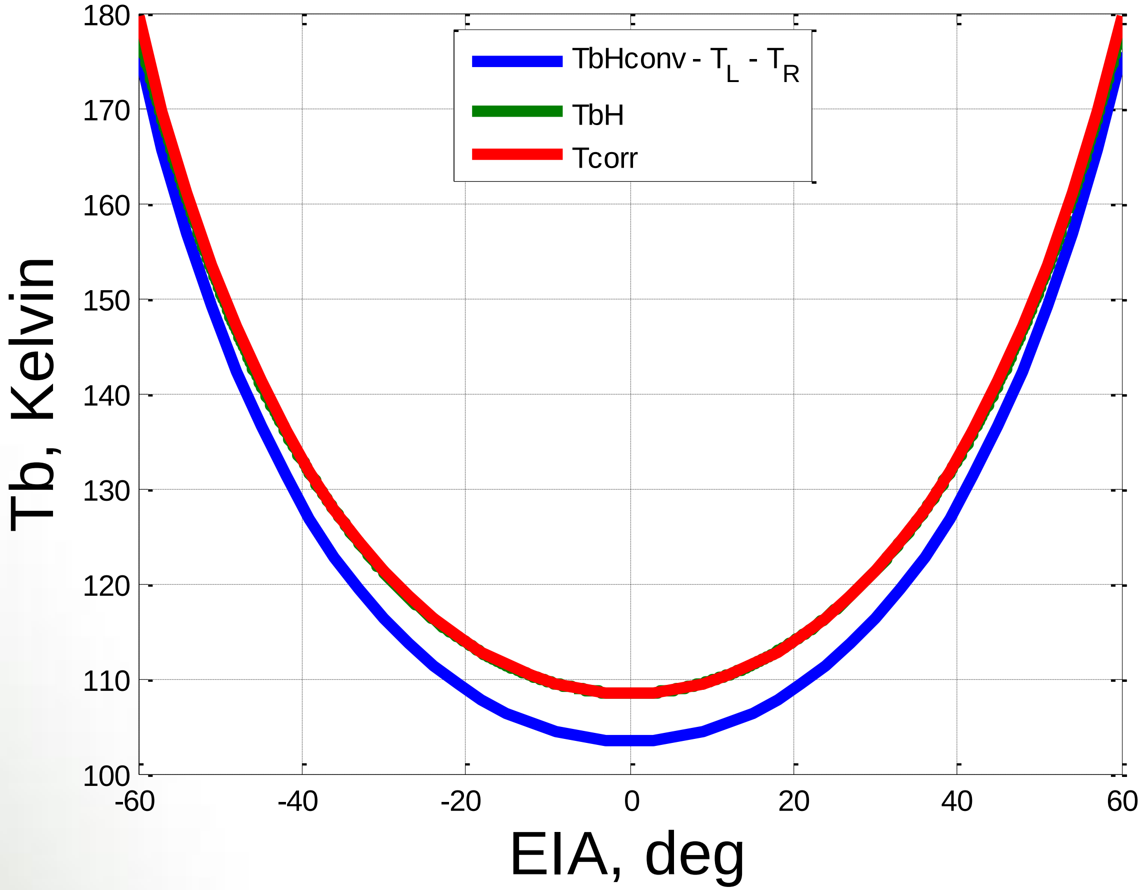
$$T_{bH\_conv} = \frac{\int_0^{2\pi} \int_{-\theta_1}^{\theta_1} T_{aph}(\theta, \Phi) \times F_{Co-Pol}(\theta, \Phi) \times sin\theta d\theta d\Phi}{\int_0^{2\pi} \int_{-\theta_1}^{\theta_1} F_{Co-Pol}(\theta, \Phi) \times sin\theta d\theta d\Phi}$$





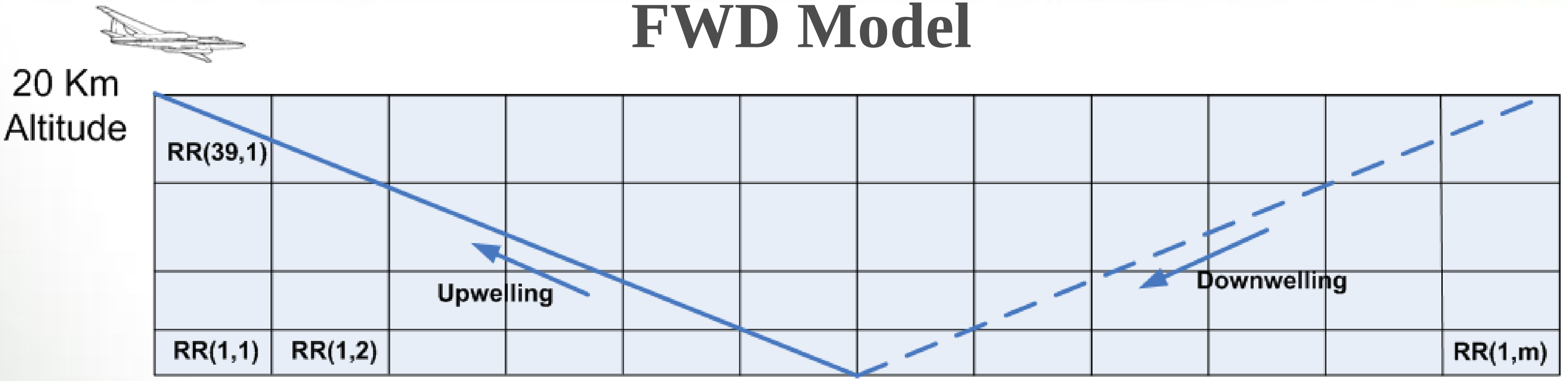


Fixing the Issue



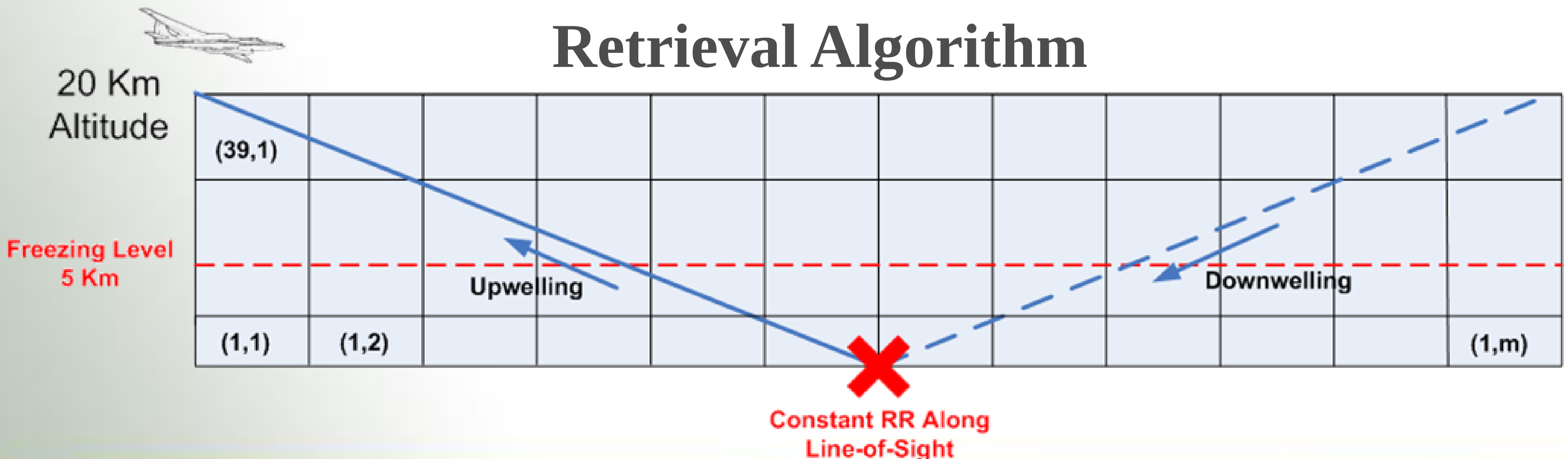
Rain Simulation

FWD Model



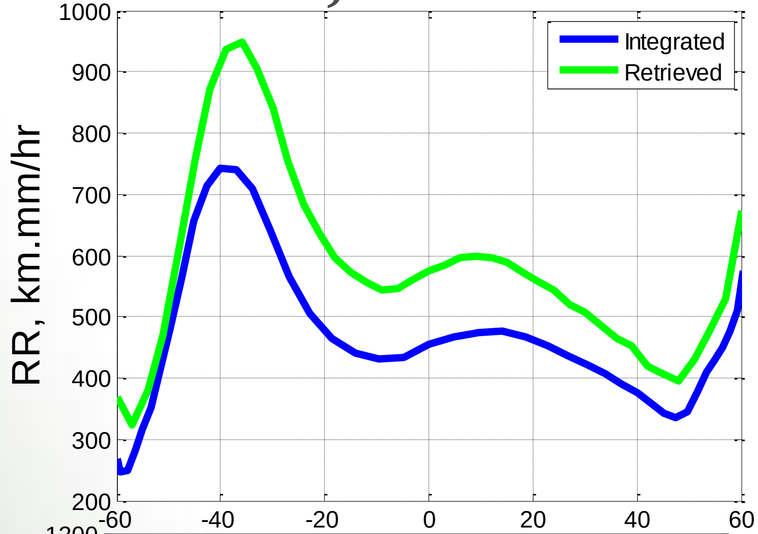
Beyond HIRAD Swath

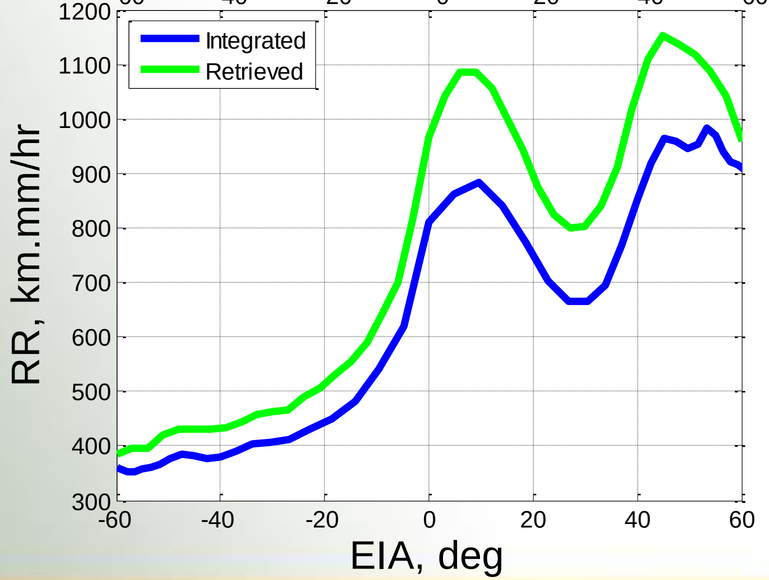
Retrieval Algorithm



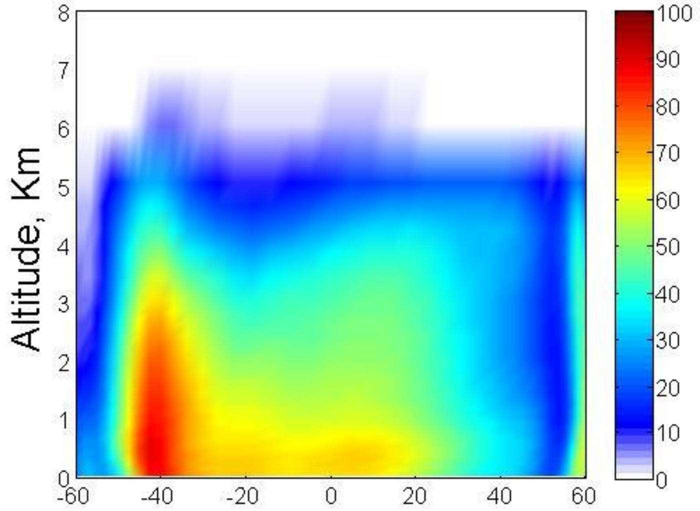
Scans in Eye Wall Region

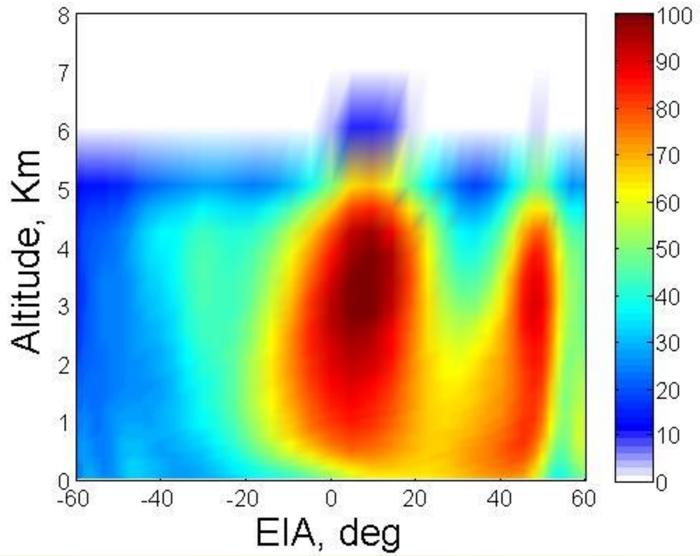
RR, mm/hr





2D RR Slice



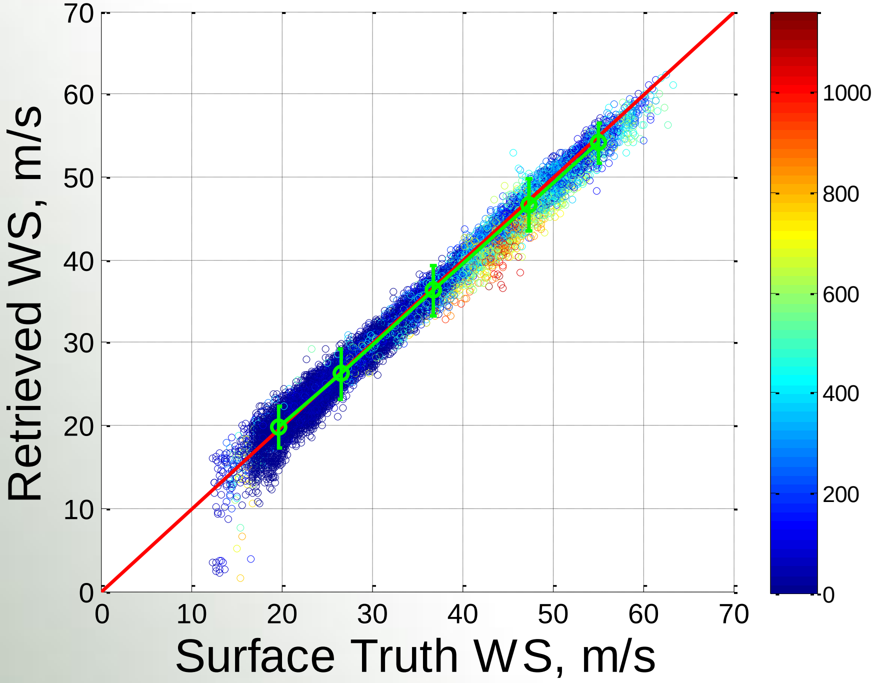


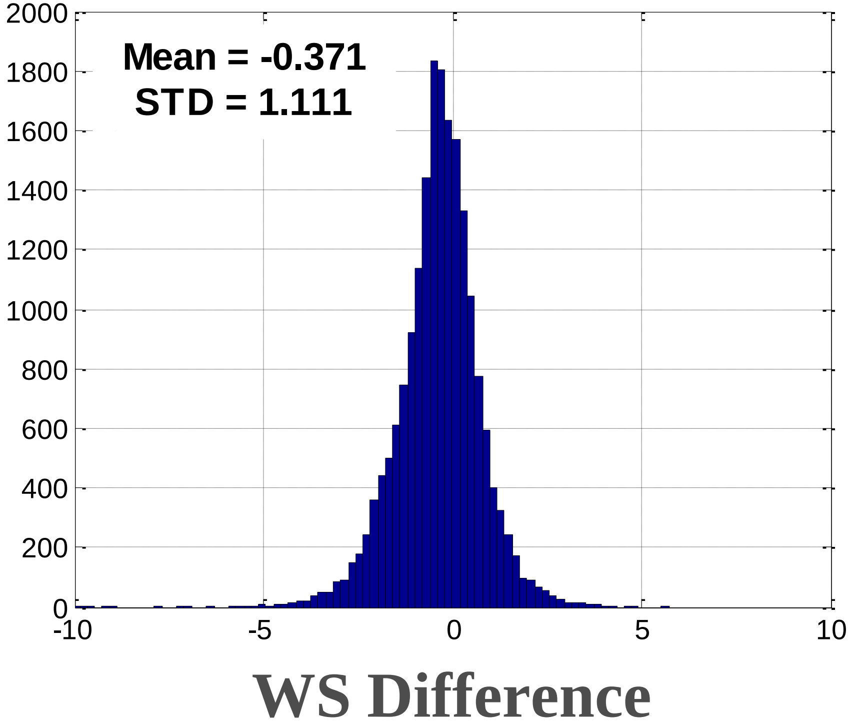
Results - Retrieved Wind Speed

1 Kelvin Random Errors

Fig-4 A

Two Legs (IP 90, 180) → 480 Cross-track Scans



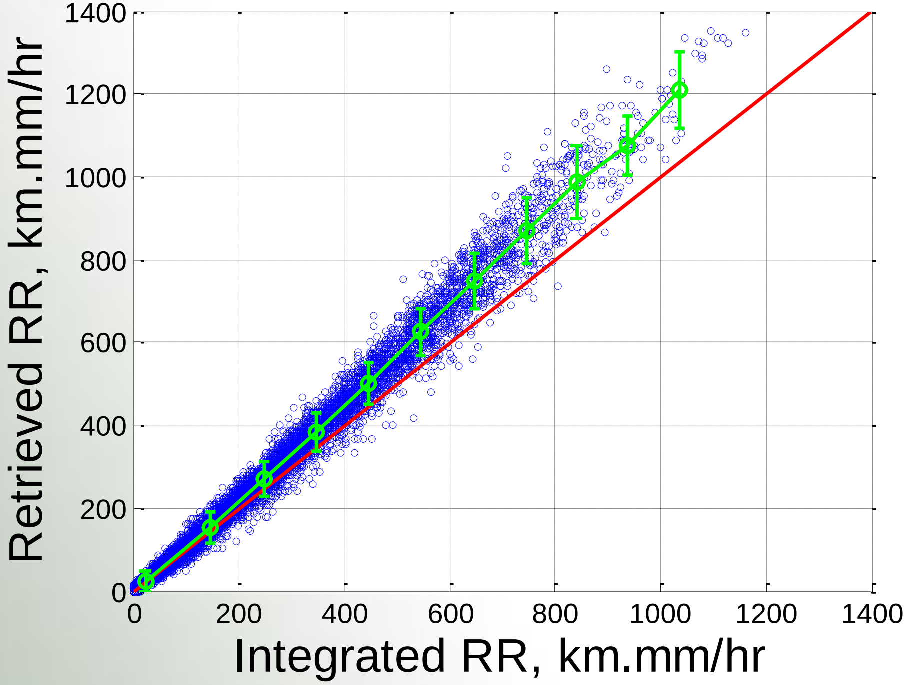


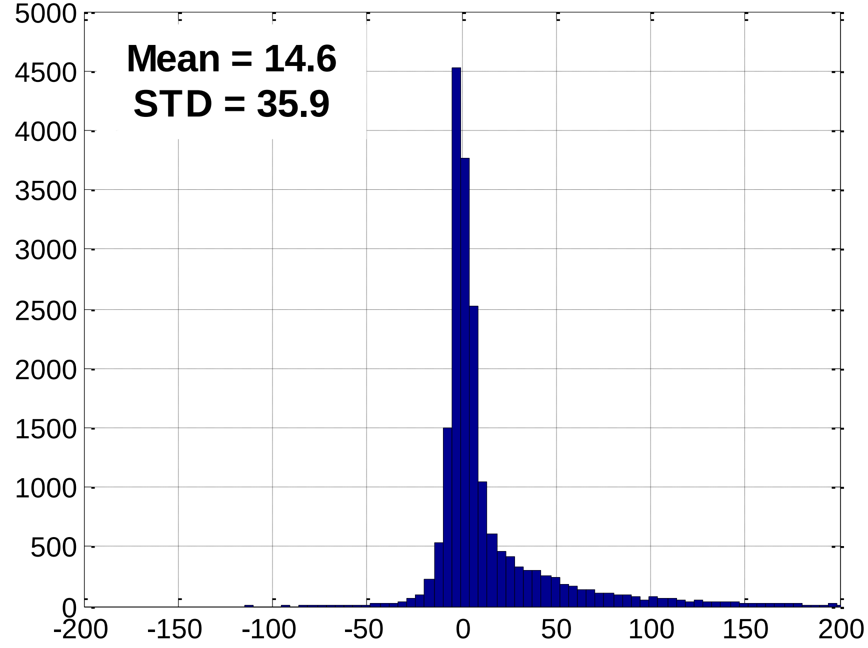
Results - Retrieved Rain Rate

1 Kelvin Random Errors

Fig-4 A

Two Legs (IP 90, 180) → 480 Cross-track Scans





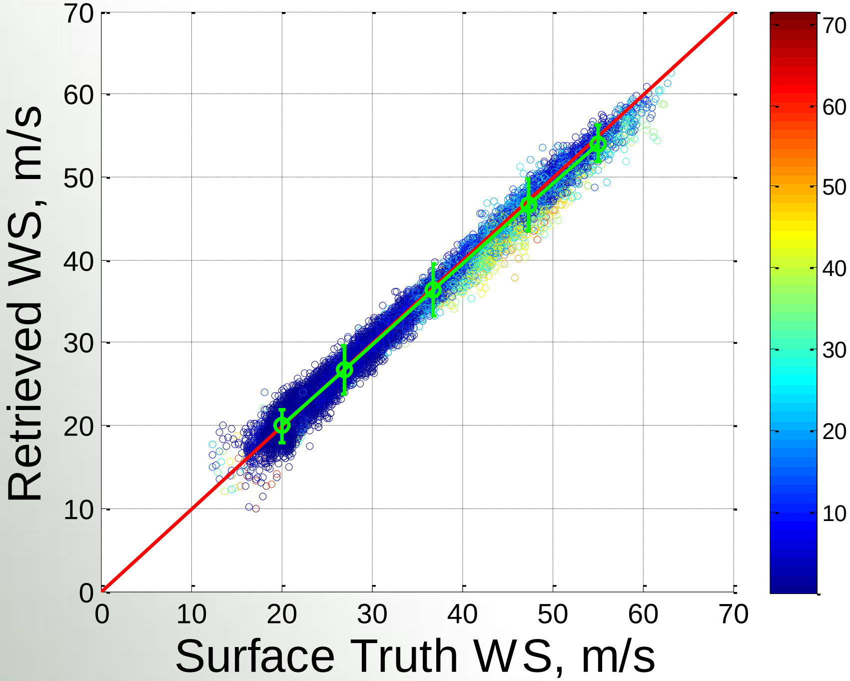
WS Difference

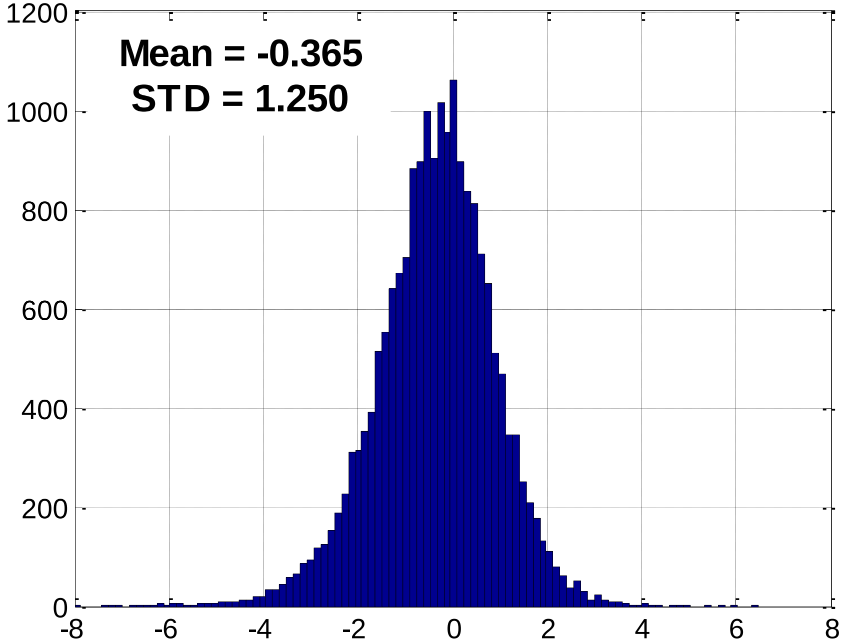
Results - Retrieved Wind Speed

1 Kelvin Random Errors

Fig-4 B

Two Legs (IP 30, 120) → 480 Cross-track Scans





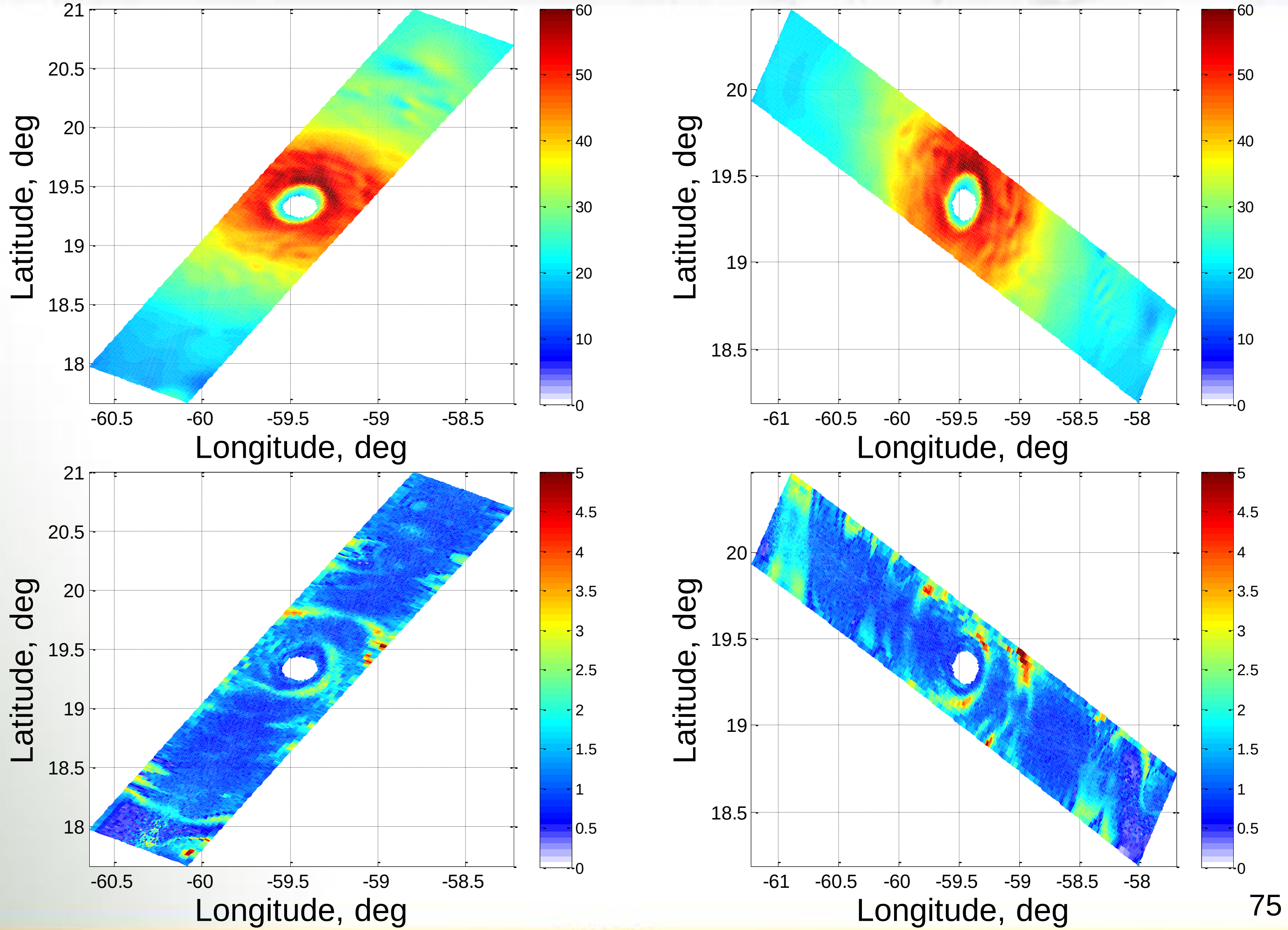
WS Difference

RMS Wind Speed Retrieved Errors

1 Kelvin Random Errors

Surface Truth WS

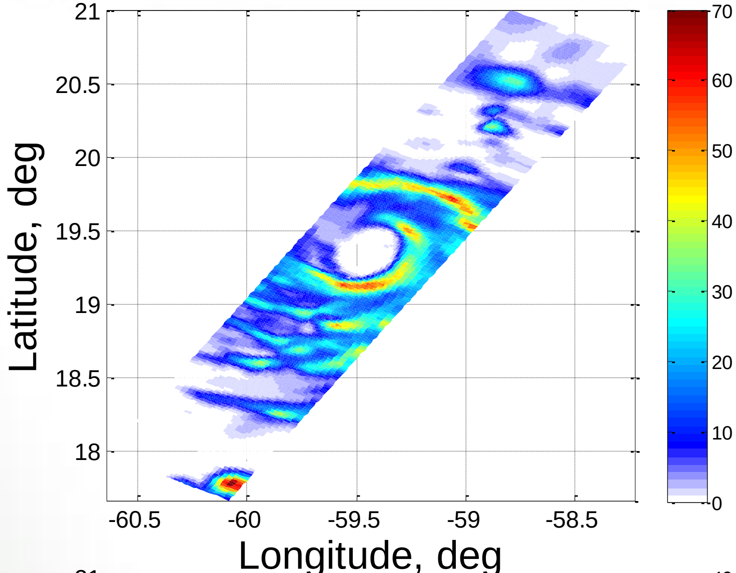
WS Error

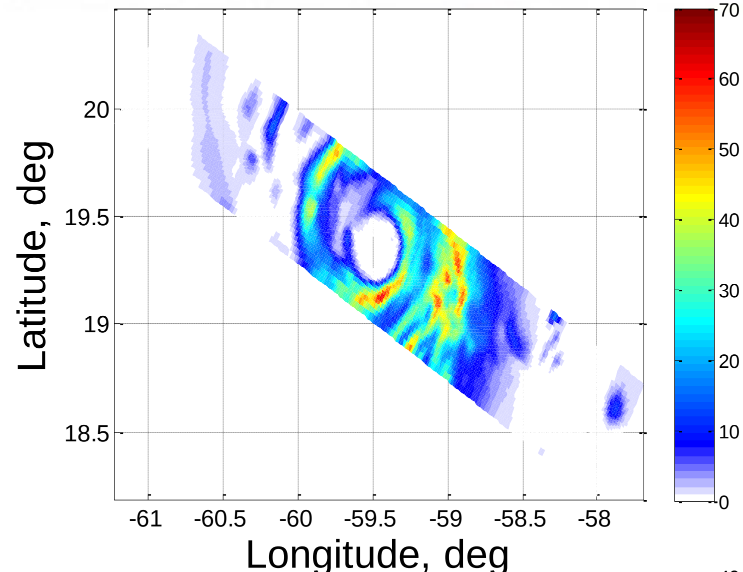


RMS Rain Rate Retrieved Errors

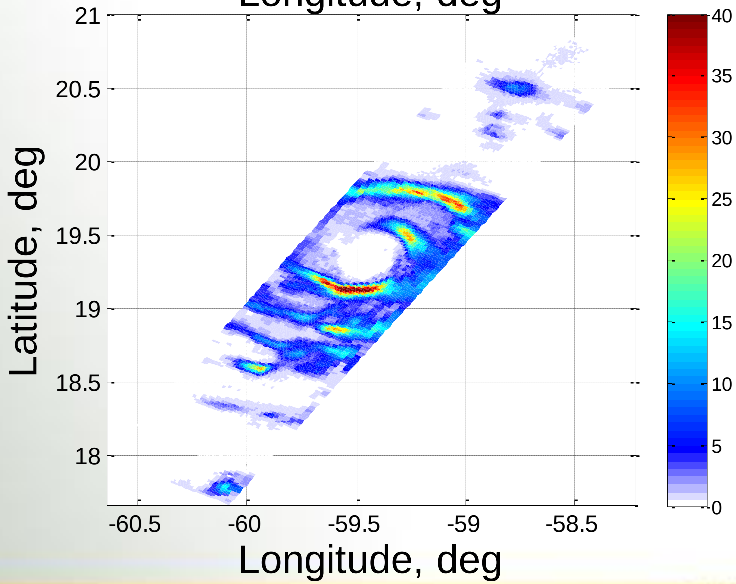
1 Kelvin Random Errors

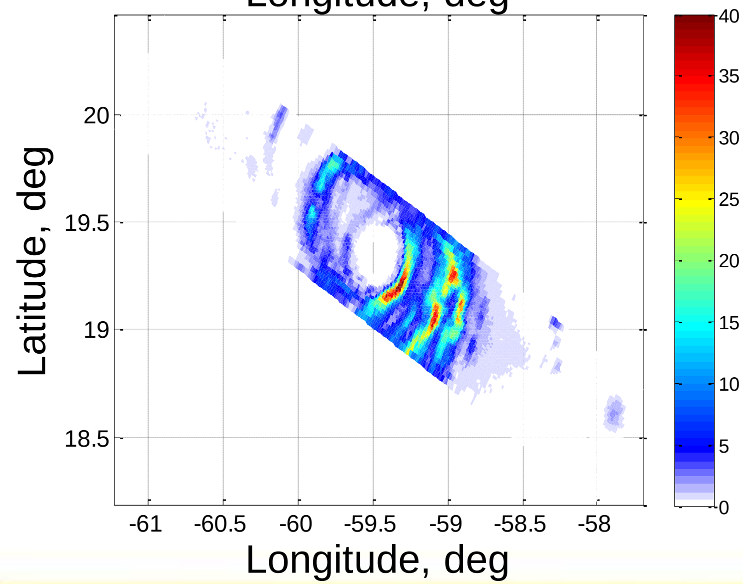
Path Avg. RR





RR Error



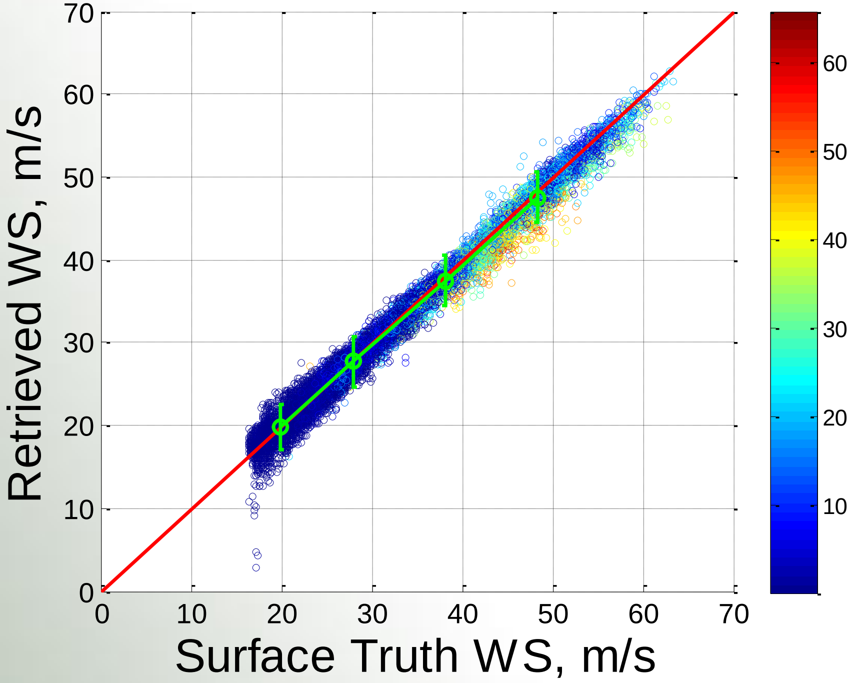


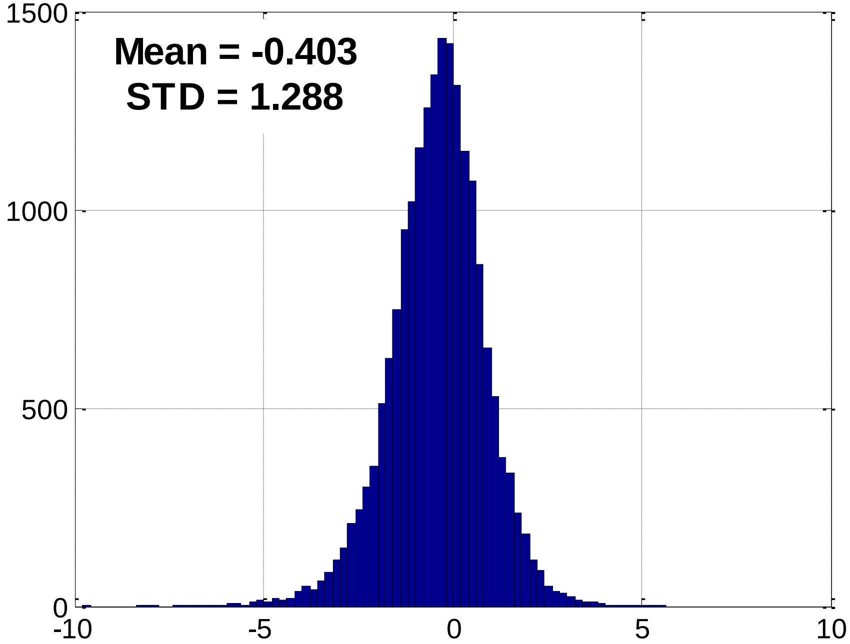
Results - Retrieved Wind Speed

1 Kelvin Random Errors

Fig-4 C

Two Legs (IP 60, 150) → 480 Cross-track Scans





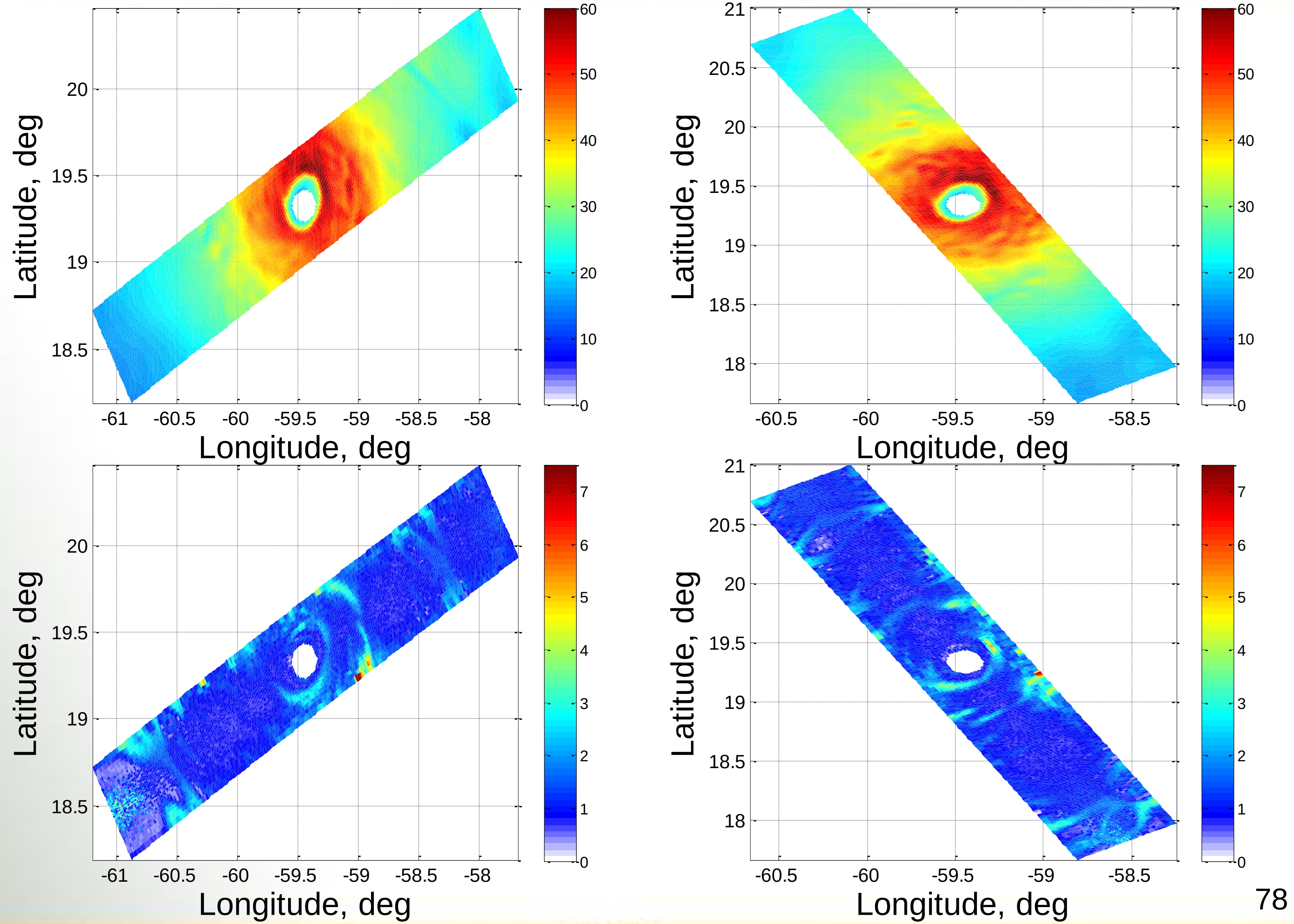
WS Difference

RMS Wind Speed Retrieved Errors

1 Kelvin Random Errors

Surface Truth WS

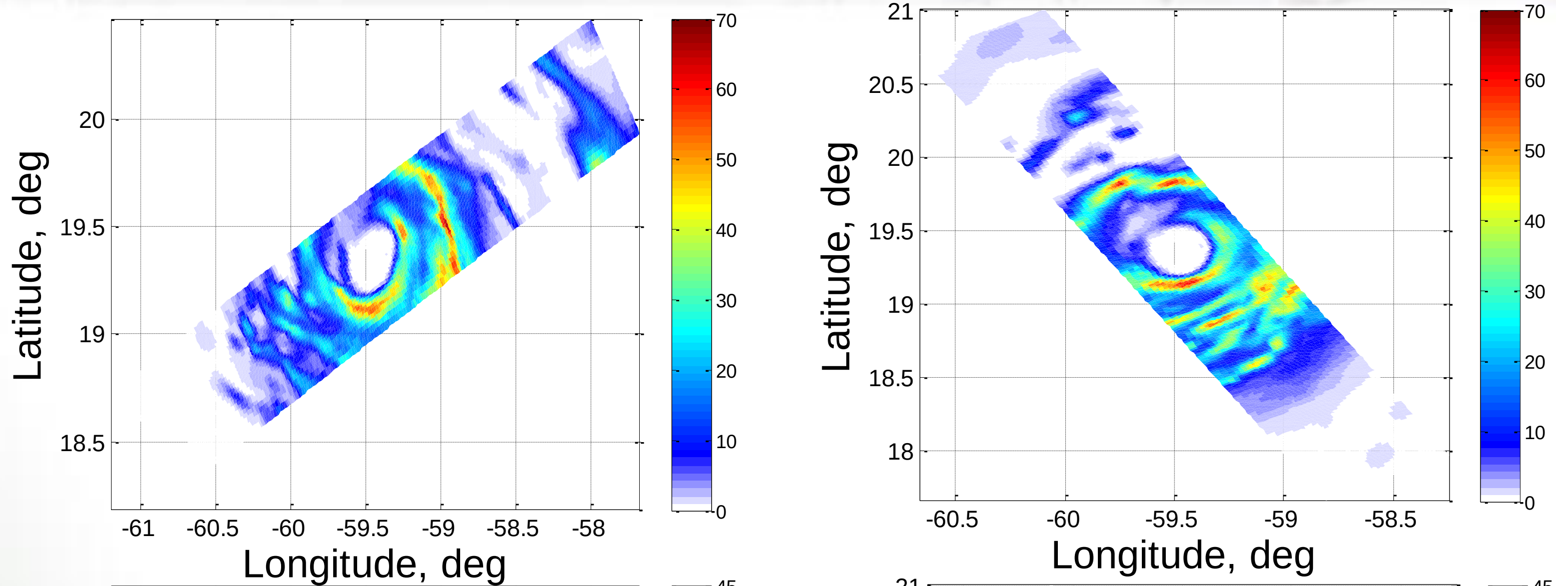
WS Error



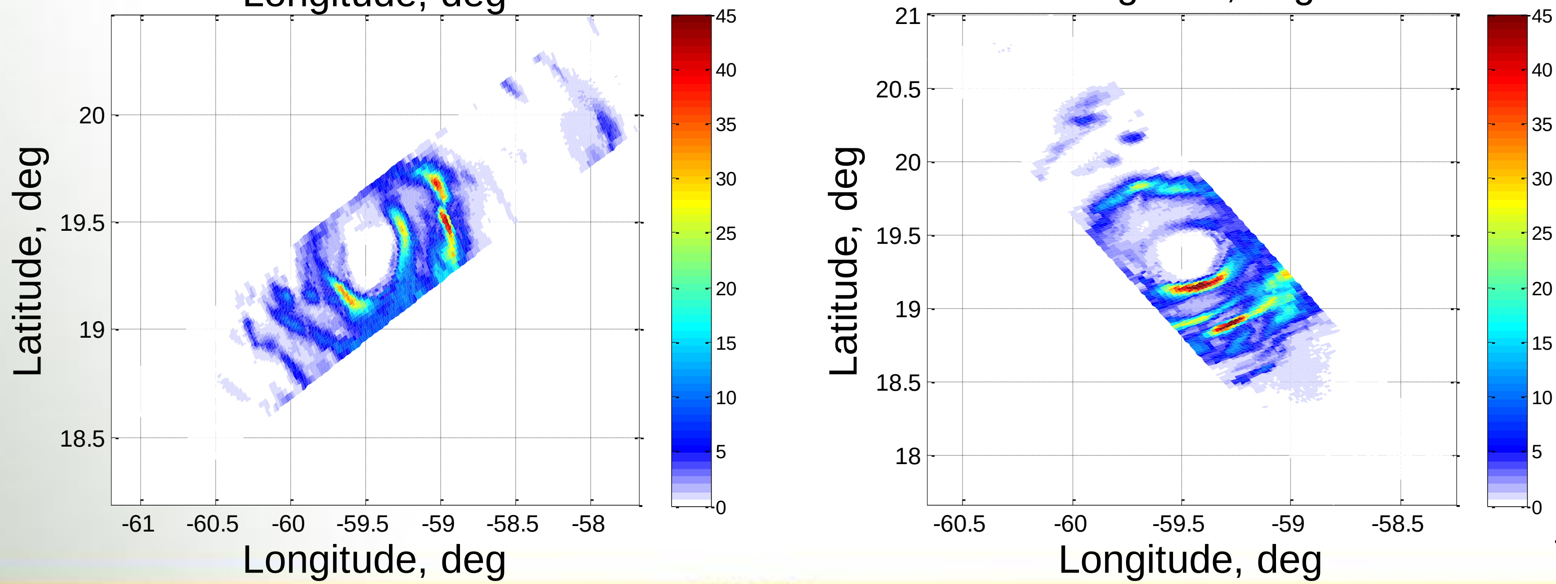
RMS Rain Rate Retrieved Errors

1 Kelvin Random Errors

Path Avg. RR

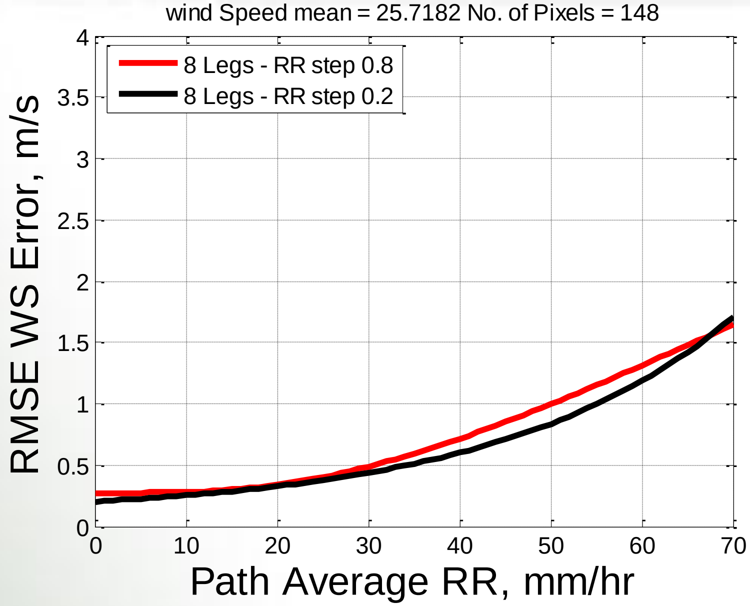


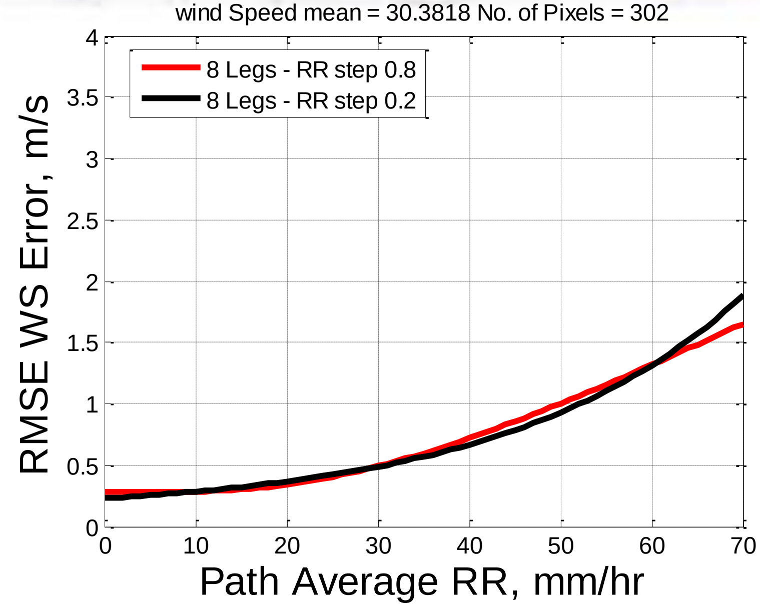
RR Error



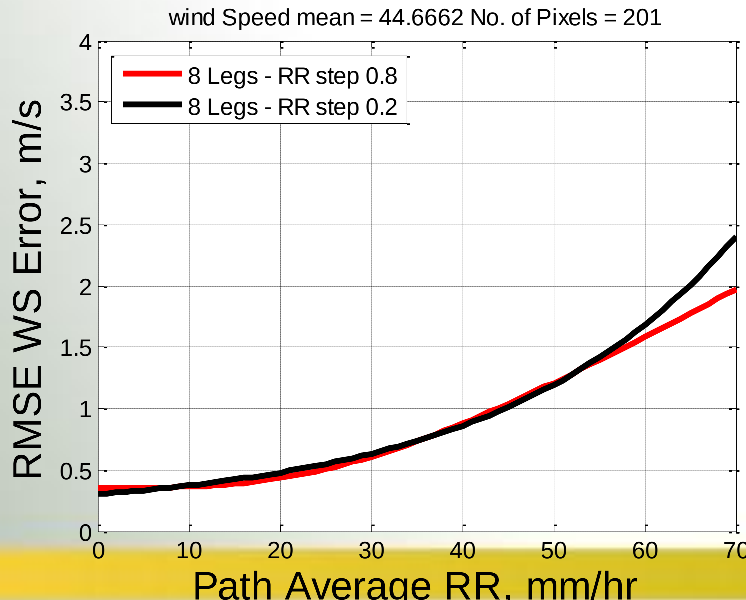
RR Quantization Error

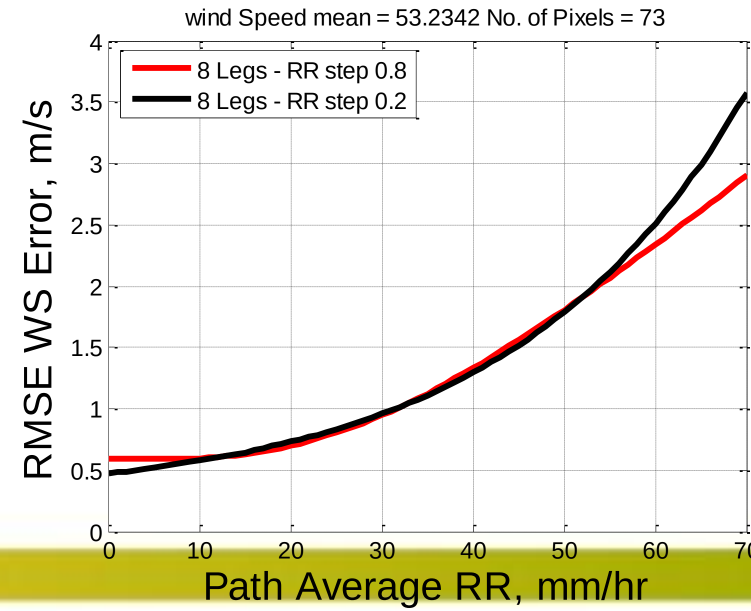
RMSE WS Error vs. RR for WS bins ± 5 m/s





Nadir

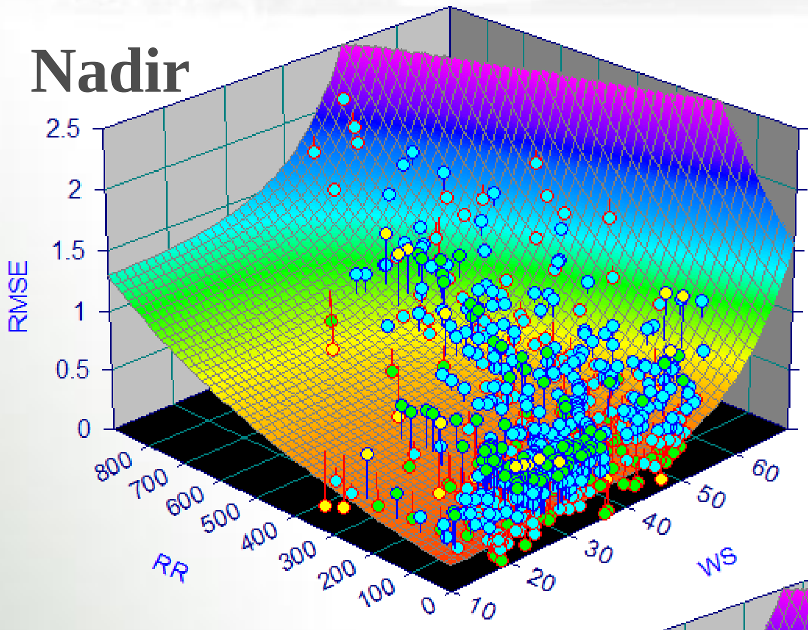




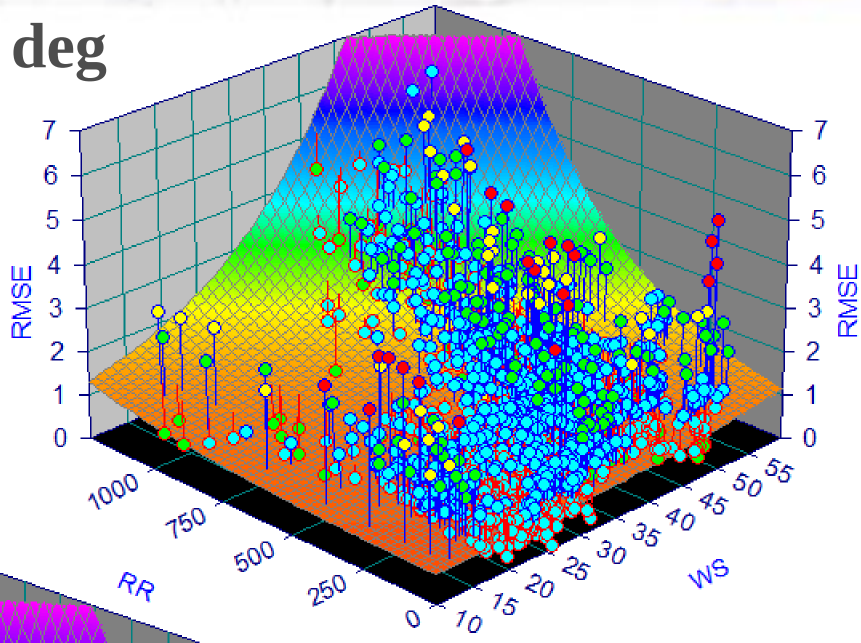
WS Error Surface

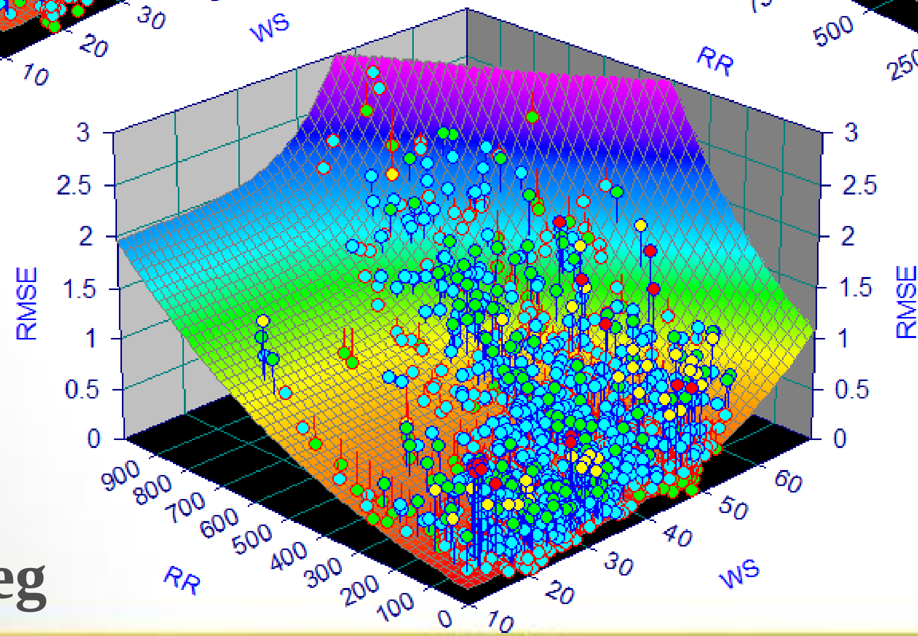
0 Kelvin Random Error - Total of 8 Legs

Nadir



60 deg

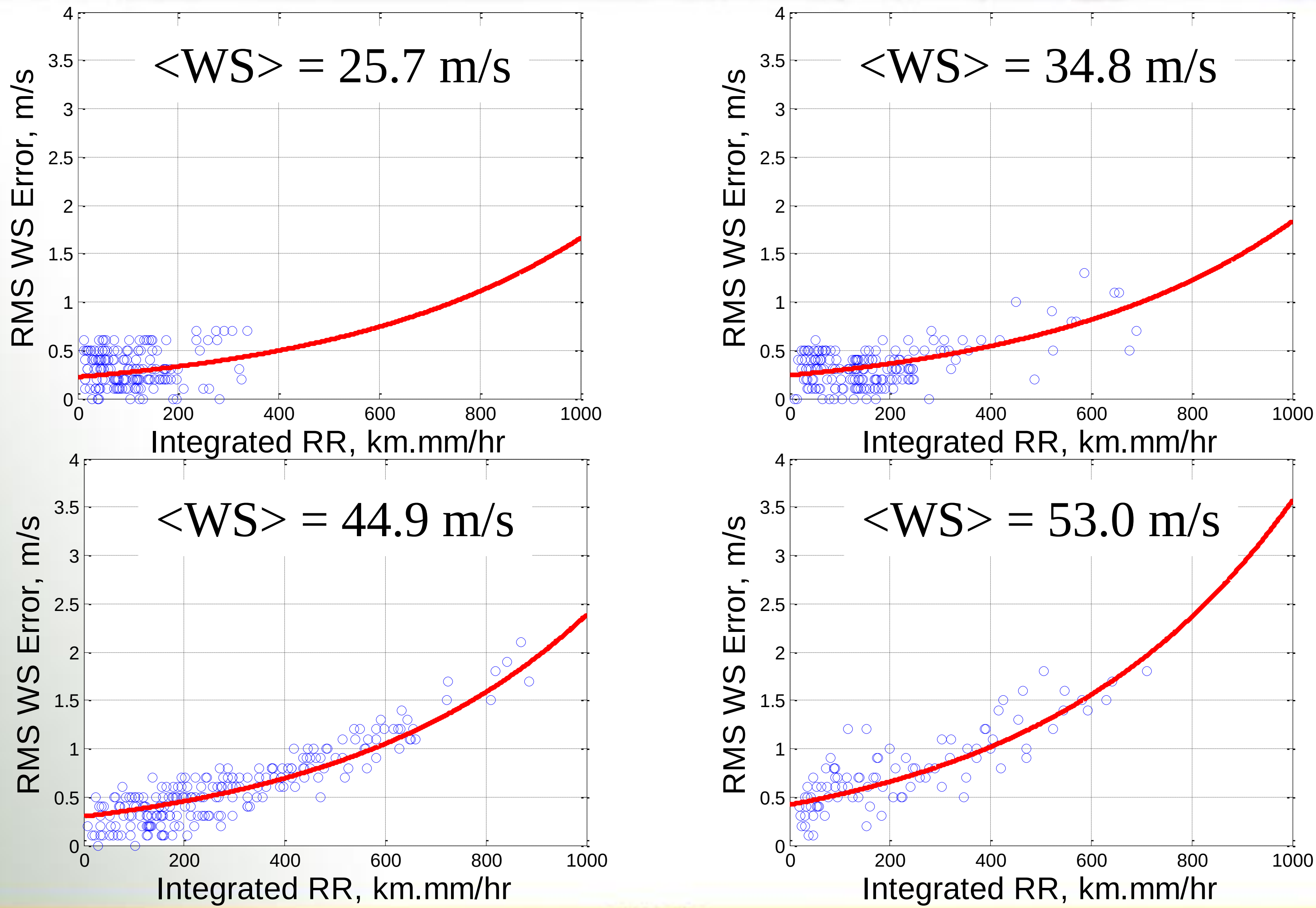




30 deg

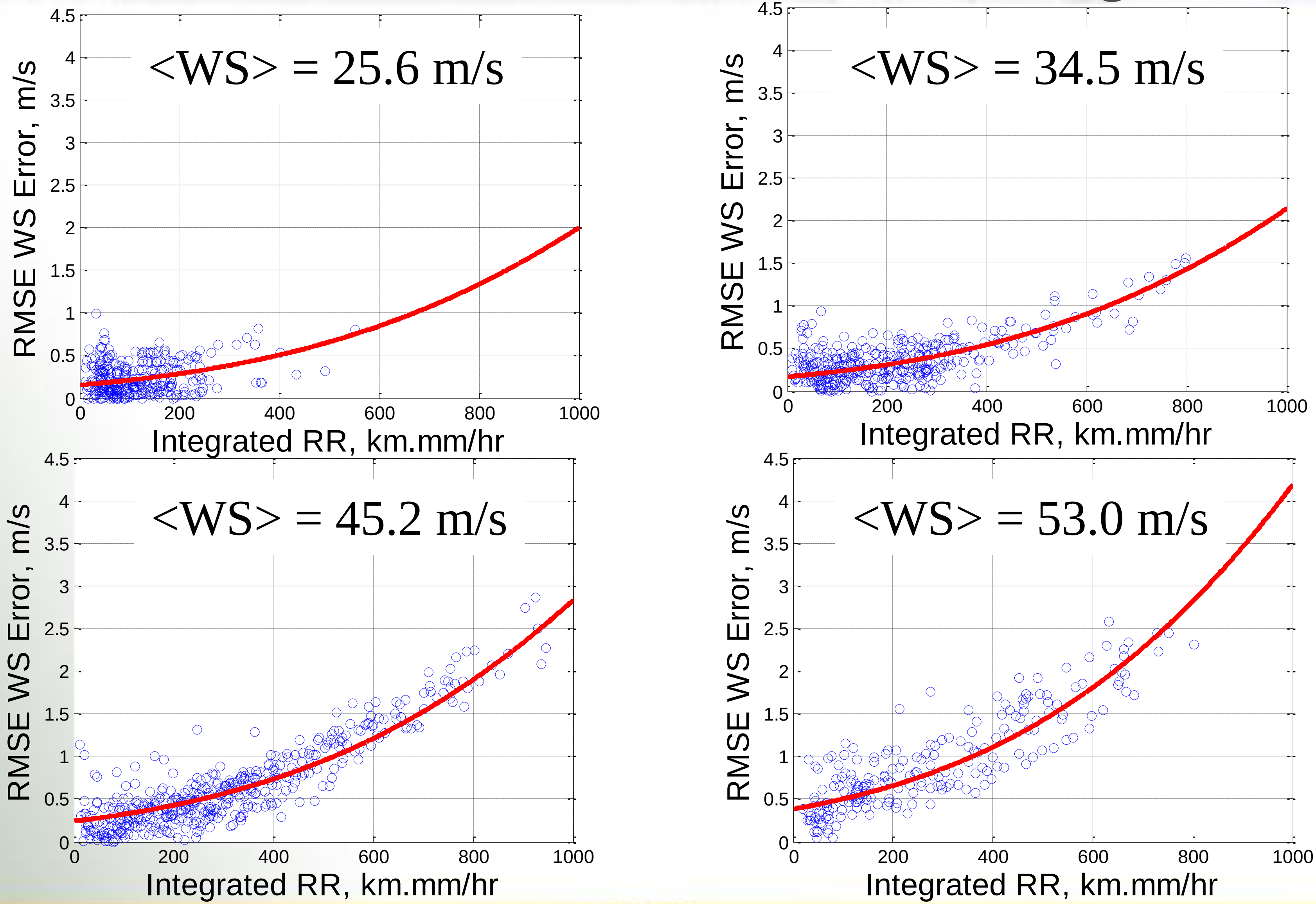
RMS WS Error @ Nadir

0 Kelvin Random Error - Total of 8 Legs



RMS WS Error @ ± 30°

0 Kelvin Random Error - Total of 8 Legs



RMS WS Error @ ± 60°

0 Kelvin Random Error - Total of 8 Legs