Estimation of Oceanic Rainfall using Passive and Active Measurements from SeaWinds Spaceborne Microwave Sensor

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Doctoral Dissertation Defense

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Presentation Outline:

❖ <u>Introduction</u>

- Dissertation objectives
- Why measure rainfall from space ?
- Background
  - Microwave scatterometry
  - Microwave radiometry
  - SeaWinds sensor
  - SeaWinds sampling contribution – GPM mission

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Presentation Outline:

❖ SeaWinds Rain Algorithm

- QRad Rain Rate Algorithm
  - Passive excess brightness – rain rate relationship
  - Validation: TRMM 3B42RT, 2A12
- Modeling SeaWinds backscatter in presence of rain
- Combined passive / active rain retrievals
  - Methodology
  - Performance comparison with QRad
  - Validation: TRMM 2A12, JPL IMUDH flag

❖ Summary & Conclusions

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Dissertation Objectives:

- Utilize the rain sensitivity of passive T_B / active σ^o measurements acquired by SeaWinds sensor to infer global oceanic rainfall
  - Characterize the effects of rain on passive / active measurements
  - Develop a statistical inversion algorithm
- Validate the quality of SeaWinds oceanic rain retrievals

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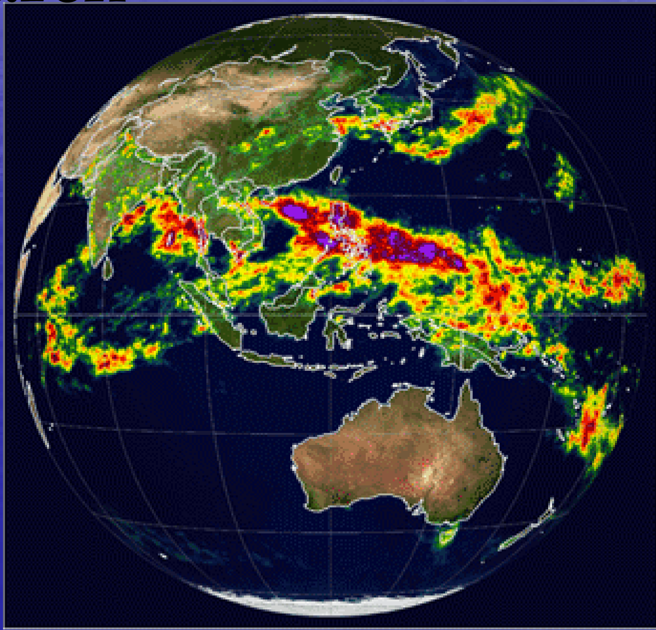
Why measure rainfall from space ?

- Essential source for fresh water
- Valuable for a wide range of research areas and related applications:
  - Earth's hydrological cycle
  - Earth's energy cycle
  - Weather forecasting / climate change



- Rainfall tend to be random in character and also evolve very rapidly

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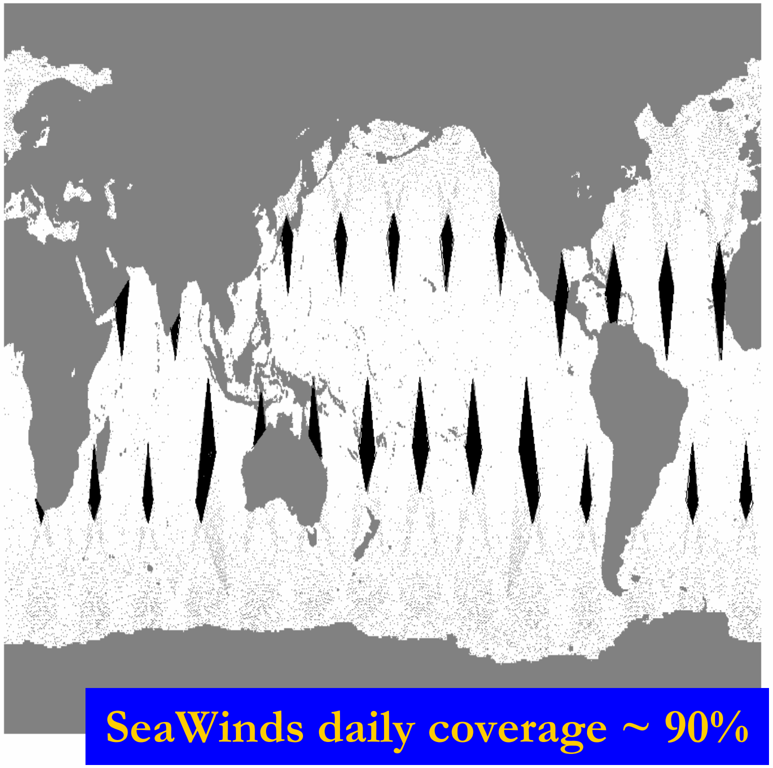
Why measure rainfall from space ?

- Radar / rain gauges can provide reliable measurements over small land areas
  - Difficult to quantify on regional / global scale
  - Impractical over ocean surface
- Space-based microwave remote sensing instruments are indispensable tools in providing useful regional / global scale precipitation measurements
  - Wide (global) coverage
  - Frequent / uniform sampling



Background

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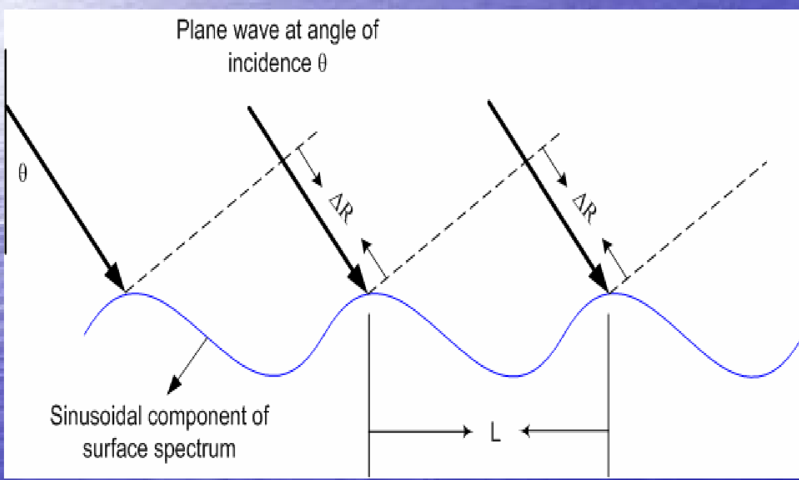
Microwave Scatterometry

- **Scatterometer :** A special purpose radar to measure σ°

Bragg scattering from short waves



$$\frac{2L}{\lambda}\sin\theta = n, \qquad n = 1,2,3,\ldots$$

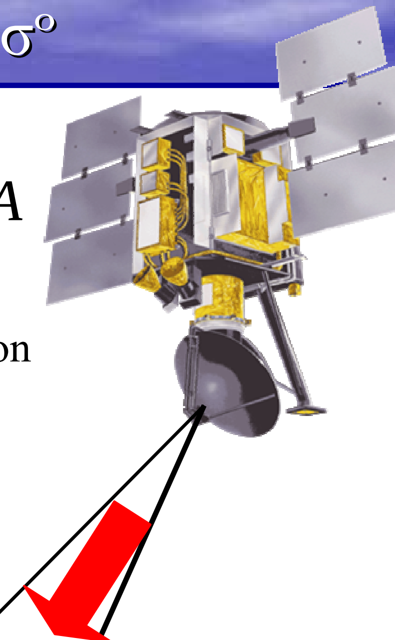
$$P_r = \frac{P_t \lambda^2}{(4\pi)^3} \iint_A \frac{G^2}{R^4} \sigma^o \, dA$$

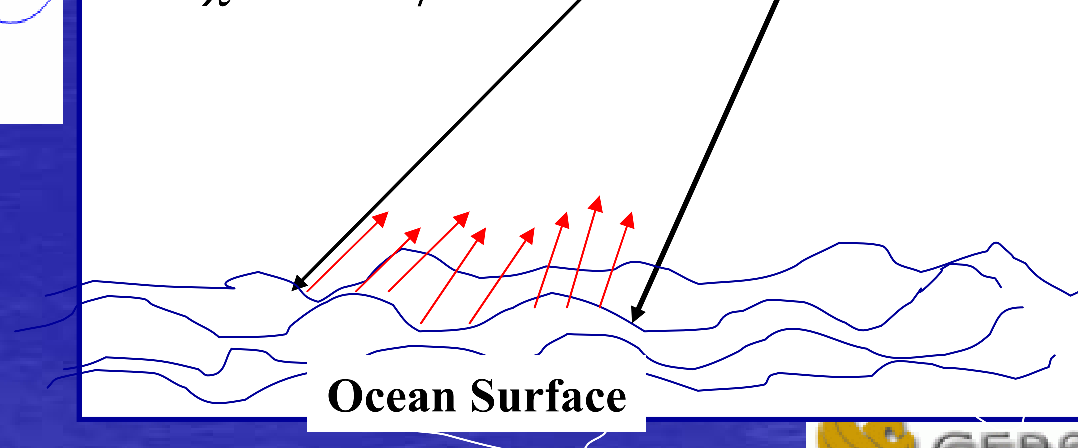
- σ^o: Normalized Radar Cross Section (NRCS) of the ocean surface

$$\sigma^0 = \mathfrak{M}(\upsilon, \chi, \theta, p, \ldots)$$

$\mathfrak{M}$: Geophysical Model Function (GMF)

$$\chi = \alpha - \varphi$$





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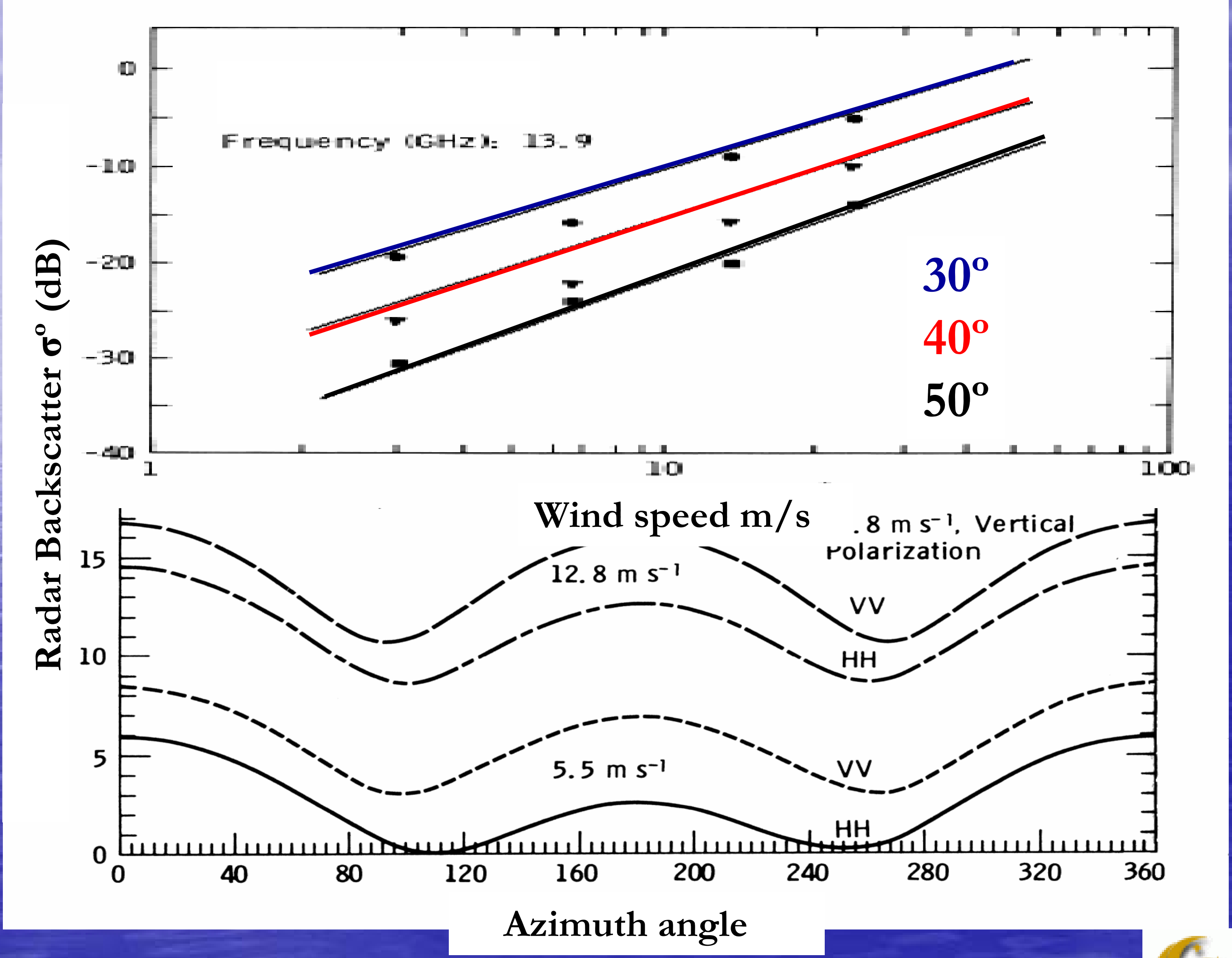
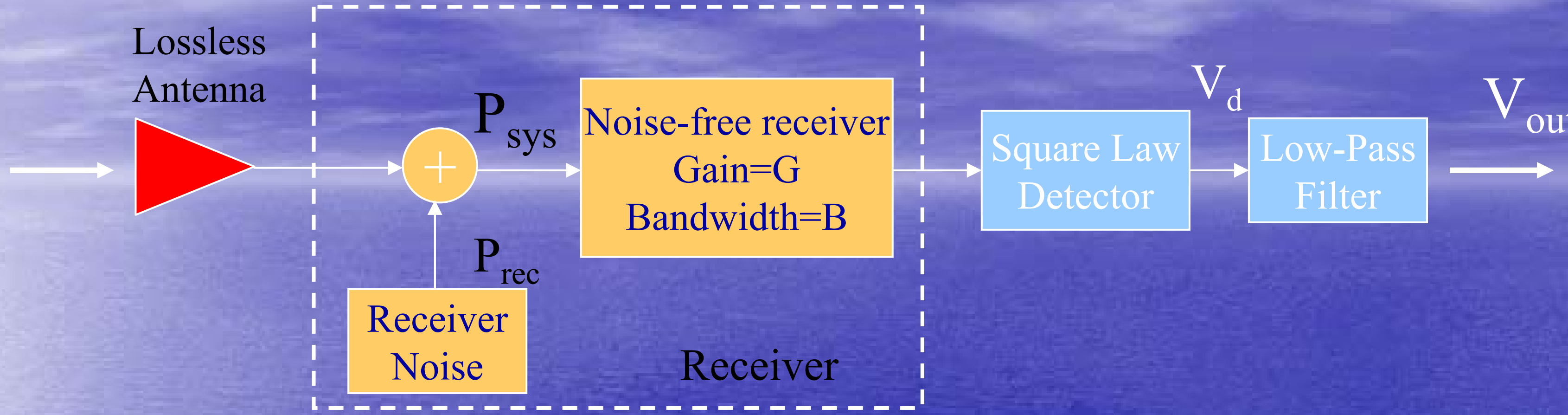
Microwave Scatterometry



Microwave Radiometry



- Power collected by antenna is:

$$P_{out} = k\,T_{ap}\,B$$

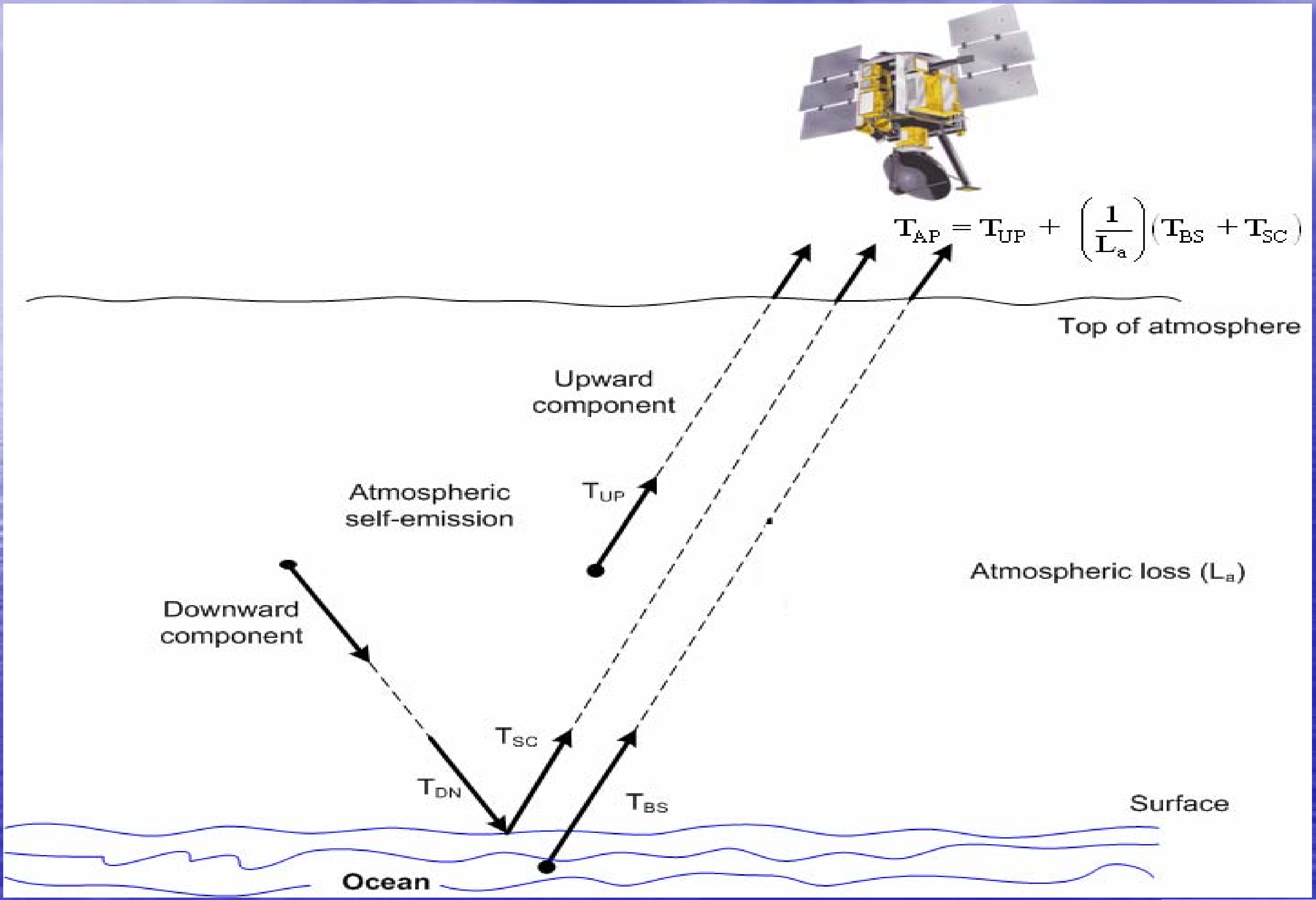
- K is Boltzmann's constant
- B is receiver bandwidth
- T_{AP} is the scene brightness temperature

- Radiometer sensitivity or radiometric resolution (Δ T):

$$\Delta T = \frac{T_{sys}}{\sqrt{B \cdot \tau}}$$

- τ is the integration time

Microwave Radiometry



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SeaWinds Microwave Sensor

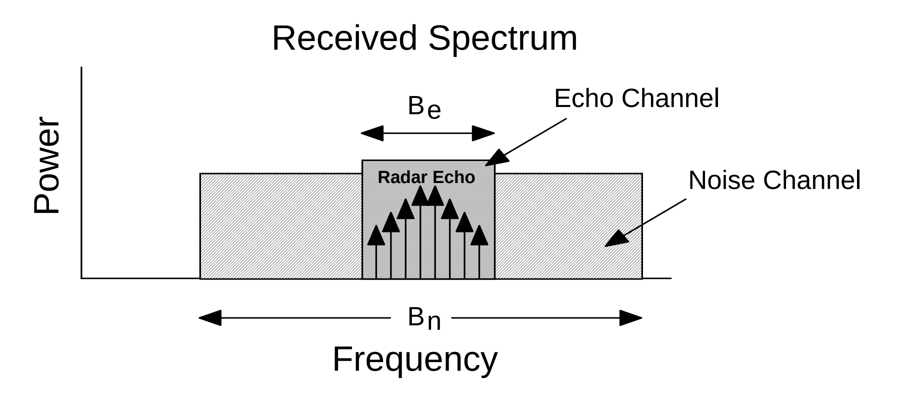
- SeaWinds is a Ku-band microwave scatterometer flown onboard two satellit missions:
  - QuikSCAT (June '99 ~ present)
  - ADEOS-II (Dec. '02 ~ Oct. '03)
- Instrument description:
  - Radar: 13.4 GHz / 110 W pulse / 189 Hz PR
  - Mass / power: 200 kg / 220 W
  - Antenna: 1-meter-diameter parabolic dish
    Dual Pol (H / V)

Parameter	Inner Beam	Outer Beam
Polarization	H	V
Elevation Angle	40°	46°
Surface Incidence Angle	47°	55°
Slant Range	1100 km	1245 km
3 dB Beam Dimensions (az × el)	1.8° × 1.6°	1.7° × 1.4°
3 dB Footprint Dimensions (az × el)	34 × 44 km	37 × 52 km.
Peak Gain	38.5 dBi	39 dBi
Rotation Rate	18 rpm	
Along Track Spacing	22 km	22 km
Along Scan Spacing	15 km	19 km

SeaWinds on QuikSCAT

SeaWinds Microwave Sensor

- Originally designed to measure marine wind vector by relating the measured surface backscatter to a GMF. To get an accurate backscatter measurement the instrument utilizes:
  - Echo channel
  - Noise channel (~ 1 MHz)



- QuikSCAT / SeaWinds Radiometer (QRad / SRad) transforms observed noise into apparent brightness temperature:
  - Implemented through signal processing
  - Calibrated against TMI observations
  - Not an optimum radiometer (ΔT ~ 25 Kelvin /pulse)
  - Improved ΔT by averaging / spatial filtering

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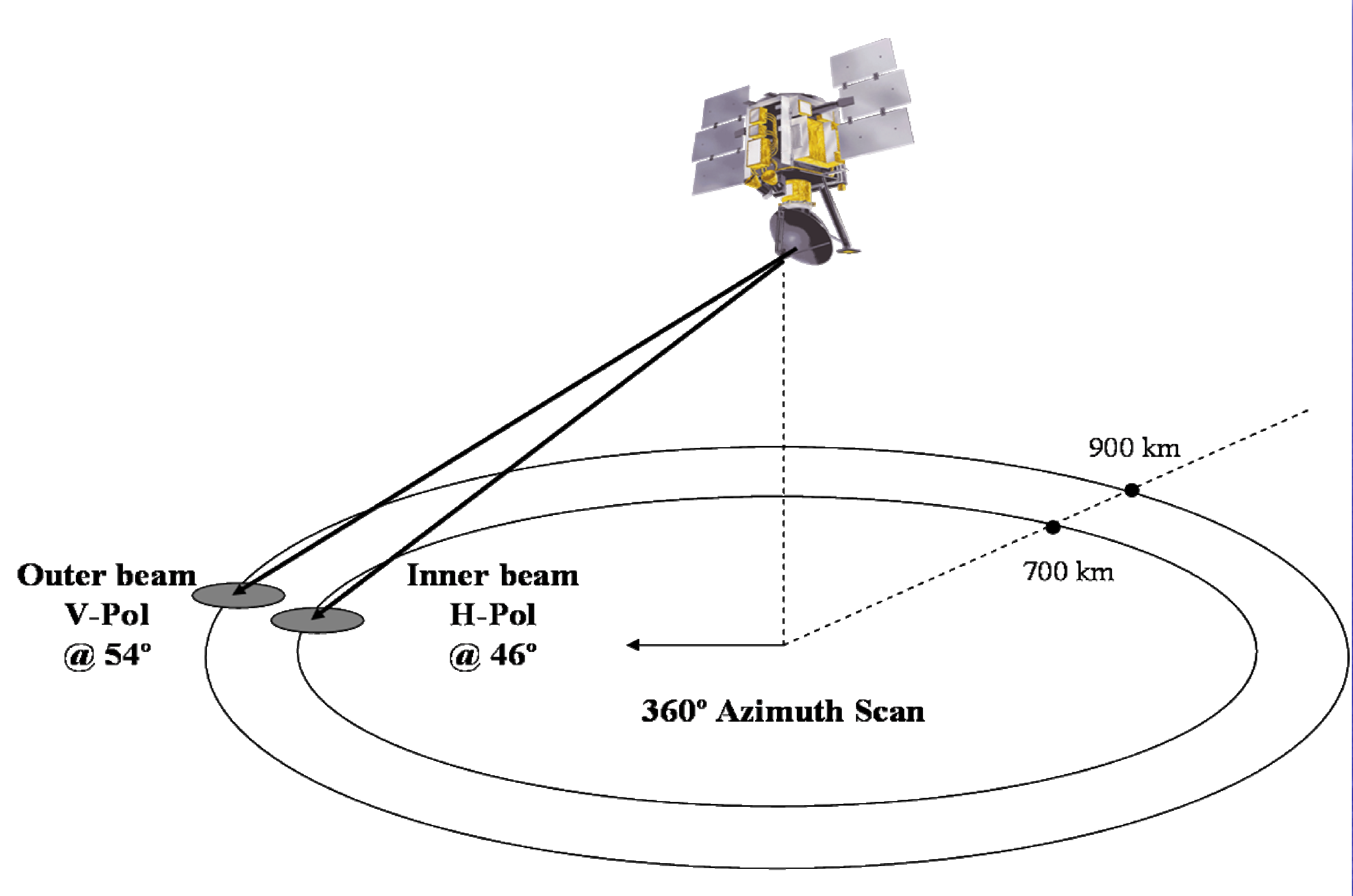
SeaWinds Microwave Sensor



SeaWinds Rain Algorithm

- Introduction

SeaWinds Rain Algorithm

- Oceanic instantaneous integrated rain rate, 25 km resolution on WVC measurement grid
- Data source:
  - Polarized microwave brightness temperatures (L2A)
  - Polarized microwave backscatter (L2A)
  - Collocated NCEP wind speeds (L2B)
- Statistical retrieval algorithm:
  - Empirical T_{ex} vs. IRR relationship
  - Empirical σ^0_{ex} vs. IRR relationship
- Trained using near-simultaneous collocations with TRMM Microwave Imager (TMI) oceanic rain rates

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SeaWinds Rain Algorithm

- Utility of SeaWinds rain product:
  - Provides simultaneous, collocated precipitation measurements with QuikSCAT ocean surface wind vectors for rain-flagging contaminated wind vector retrievals
  - Increase oceanic rain sampling ~10%

- NASA's GPM mission:

OBJECTIVES

- Provide sufficient global sampling to reduce uncertainties in short-term rainfall accumulations.

- Understand horizontal & vertical structure of rainfall, its associated latent heating.

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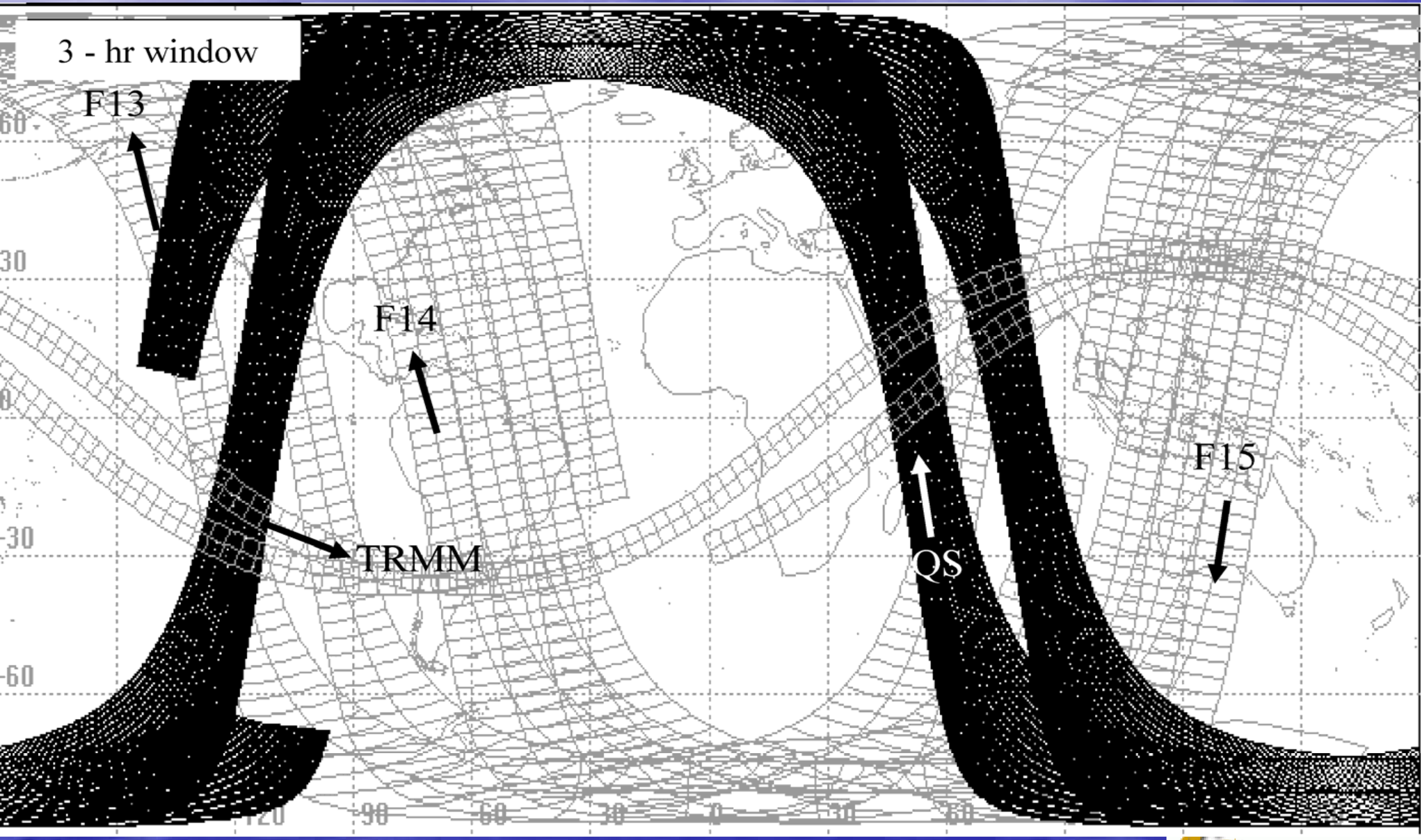
SeaWinds sampling – 3 hr window



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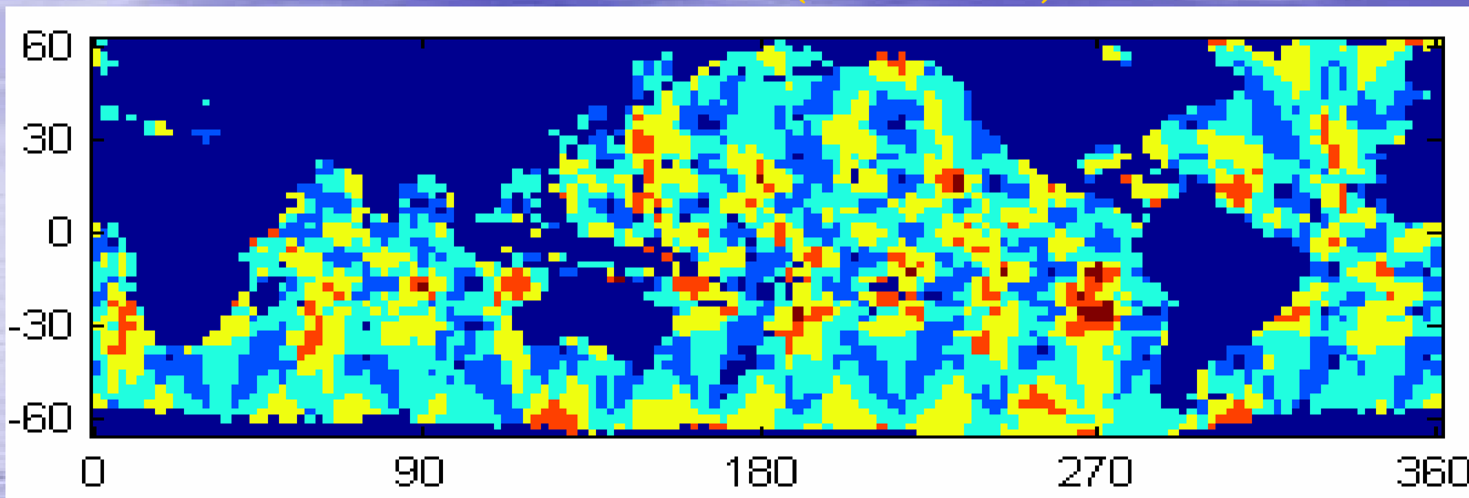
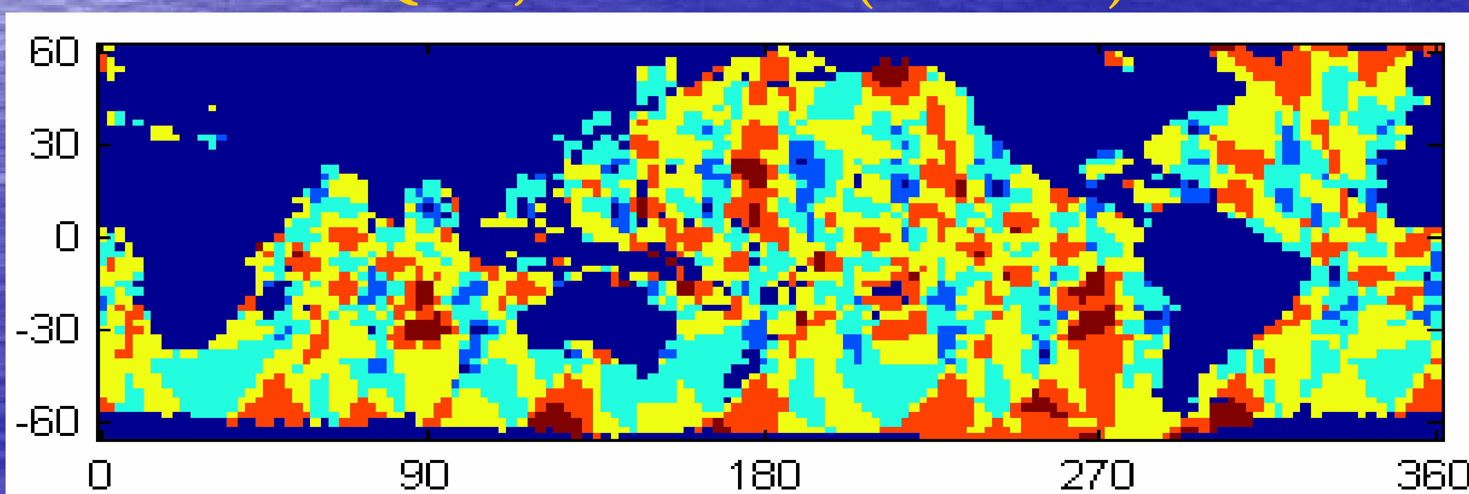
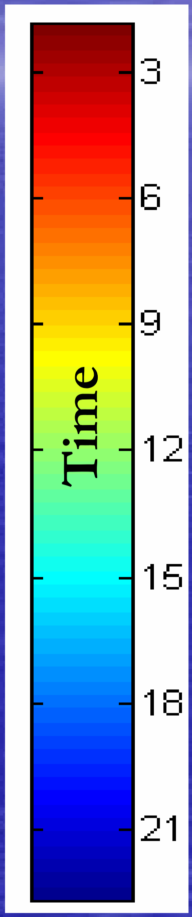
Daily average revisit time – 3 hr window

TMI & SSMI (3 satellites)



QRad, TMI & SSMI (3 satellites)





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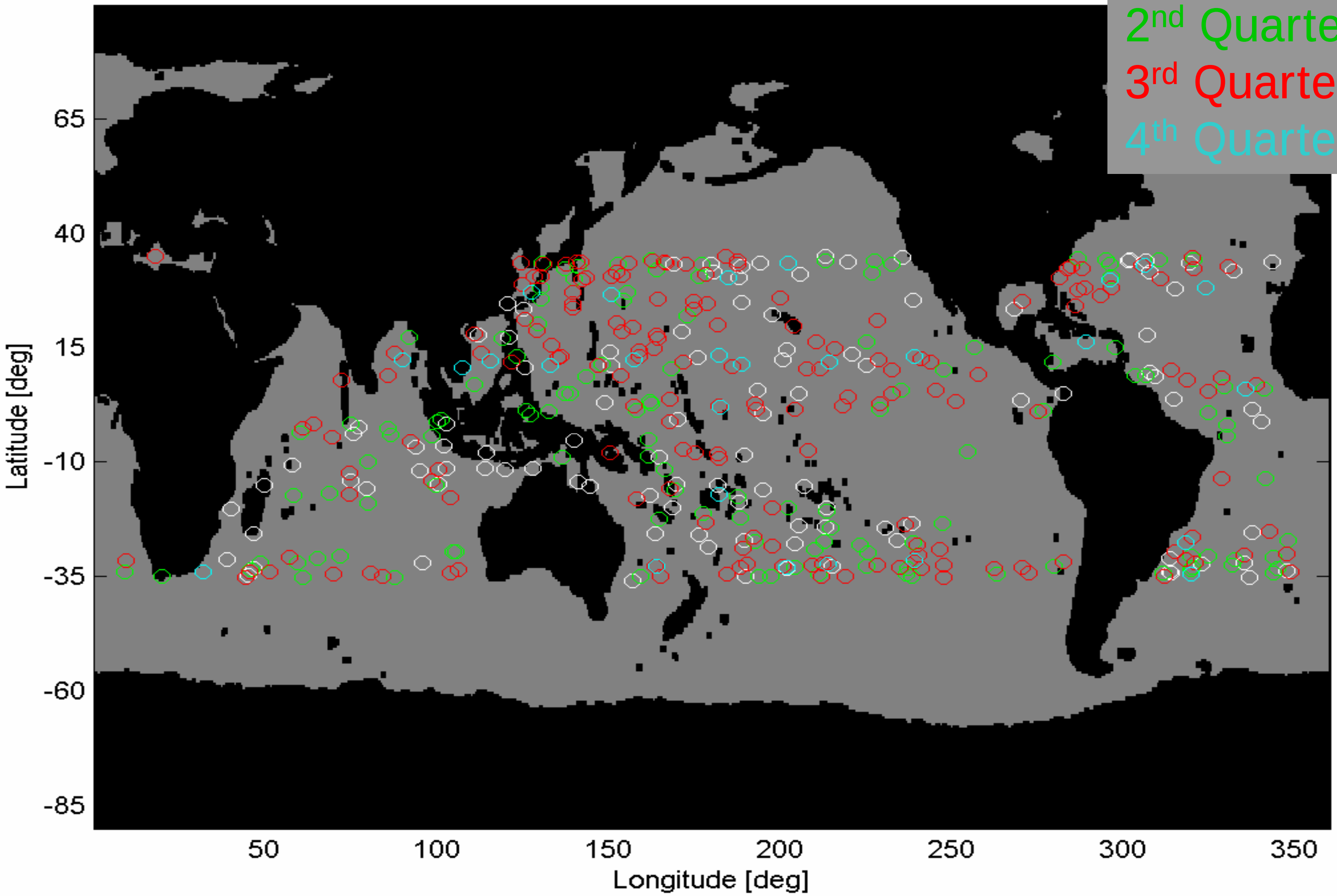
SeaWinds Rain Algorithm

- Passive-only (QRad)

Collocation Database



1st Quarter ~ 106
2nd Quarter~ 121
3rd Quarter~ 167
4th Quarter~ 27

Excess Brightness Temperature Model

- The polarized microwave "excess brightness" (Tex_p) is proportional to the integrated rain rate

$$Tex_p = T_b meas_p - T_b ocean_p - T_b w.speed_p$$

- $T_{b\ ocean}$: Ocean background (includes atmospheric Emissions without rain)
  - based upon 7 year SSMI climatology

- $T_{b\ w.speed}$: Wind speed brightness bias

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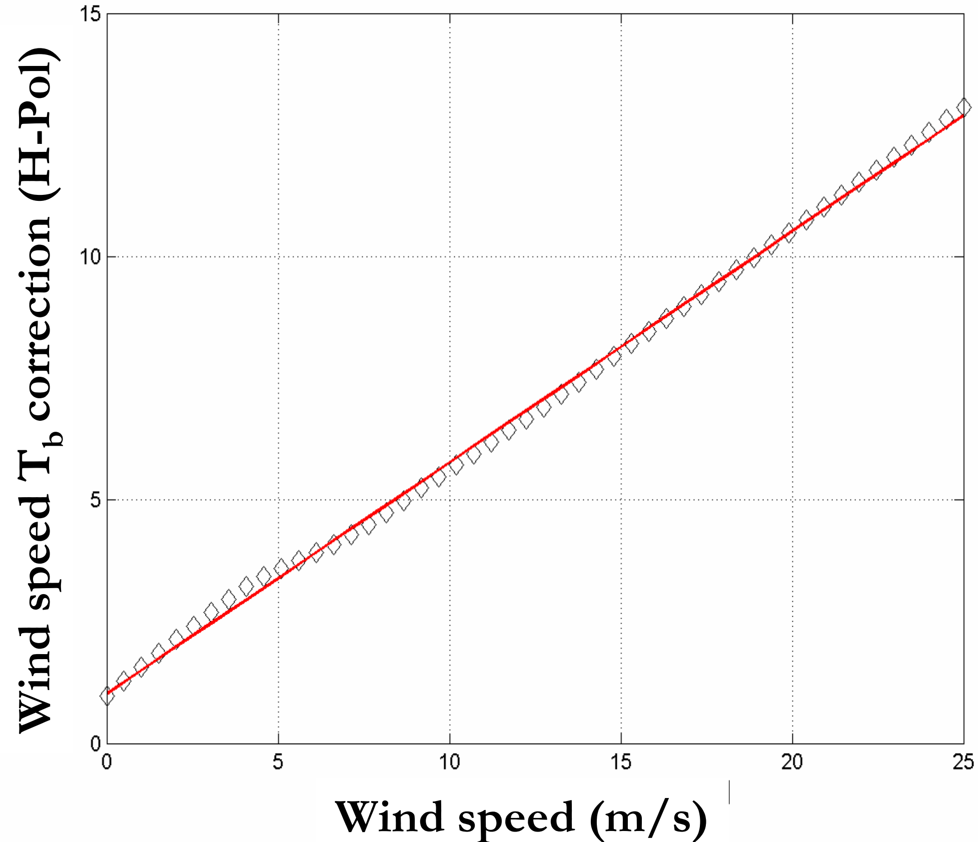
Wind Speed Correction

- Calculate polarized wind speed correction:

$$Tex_p = T_b meas_p - T_b ocean_p$$



- $T_{b\ meas}$: rain free brightness temperature measurements
- $T_{b\ ocean}$: ocean background (includes atmospheric Emissions without rain)
  - based upon 7 year SSMI climatology

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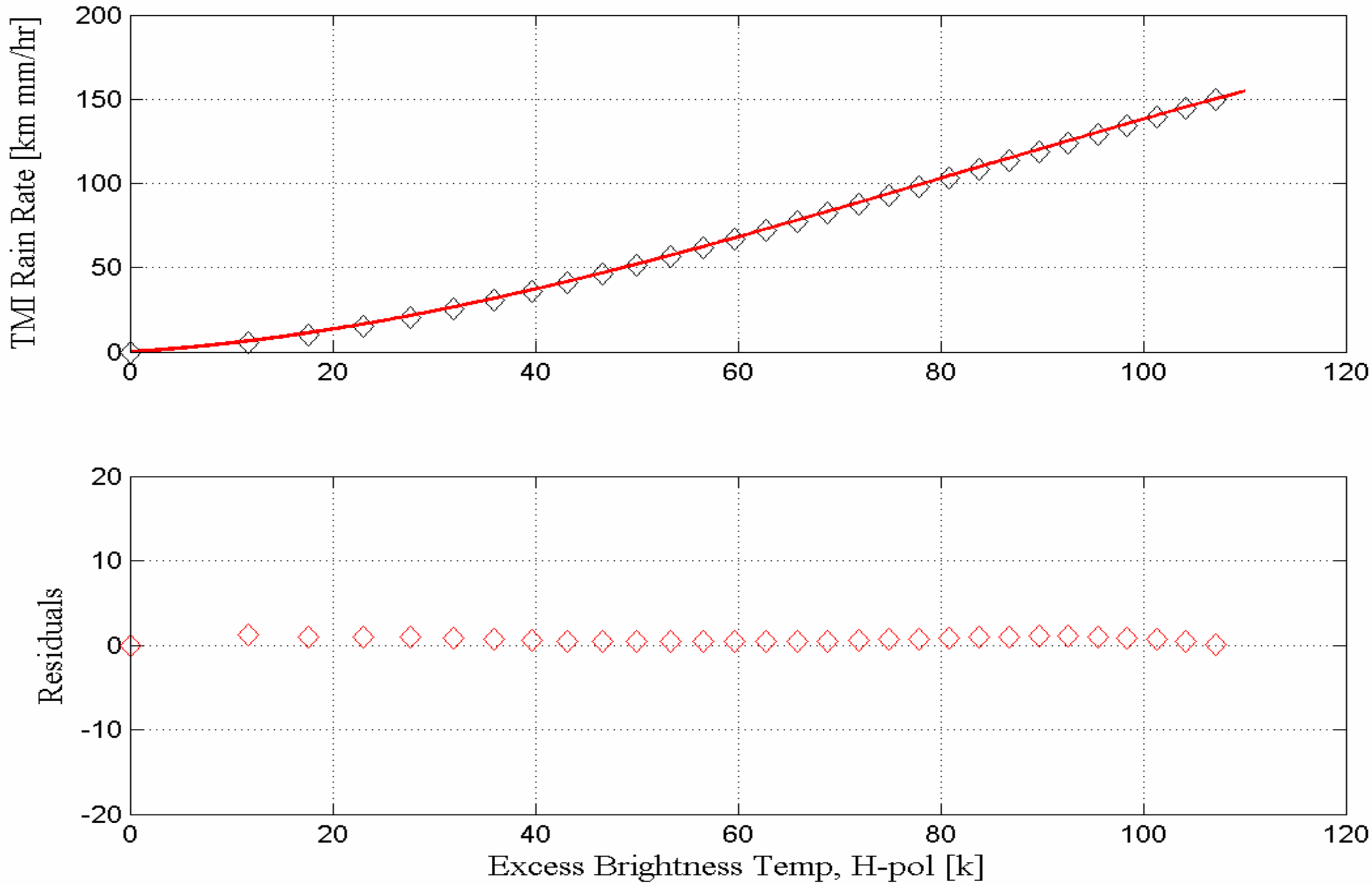
H-Pol “Tex vs. IRR” Transfer Function



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QRad Rain Calculations

- Calculate Polarized Rain Rates:

$$IRR_p = \sum_{i=0}^{n} a_{i,p} \cdot (T_{EX,p})^i \qquad (n = 3)$$

- Calculate Combined Rain Rates:

$$IRR_{QRad} = c_0 + c_1 \left(\alpha \cdot IRR_h + \beta \cdot IRR_v \right)$$

- Calculate Coefficients:

$$\min \sqrt{\frac{\sum_{i=1}^{N} (IRR_{TMI} - IRR_{QRad})^2}{N}}$$

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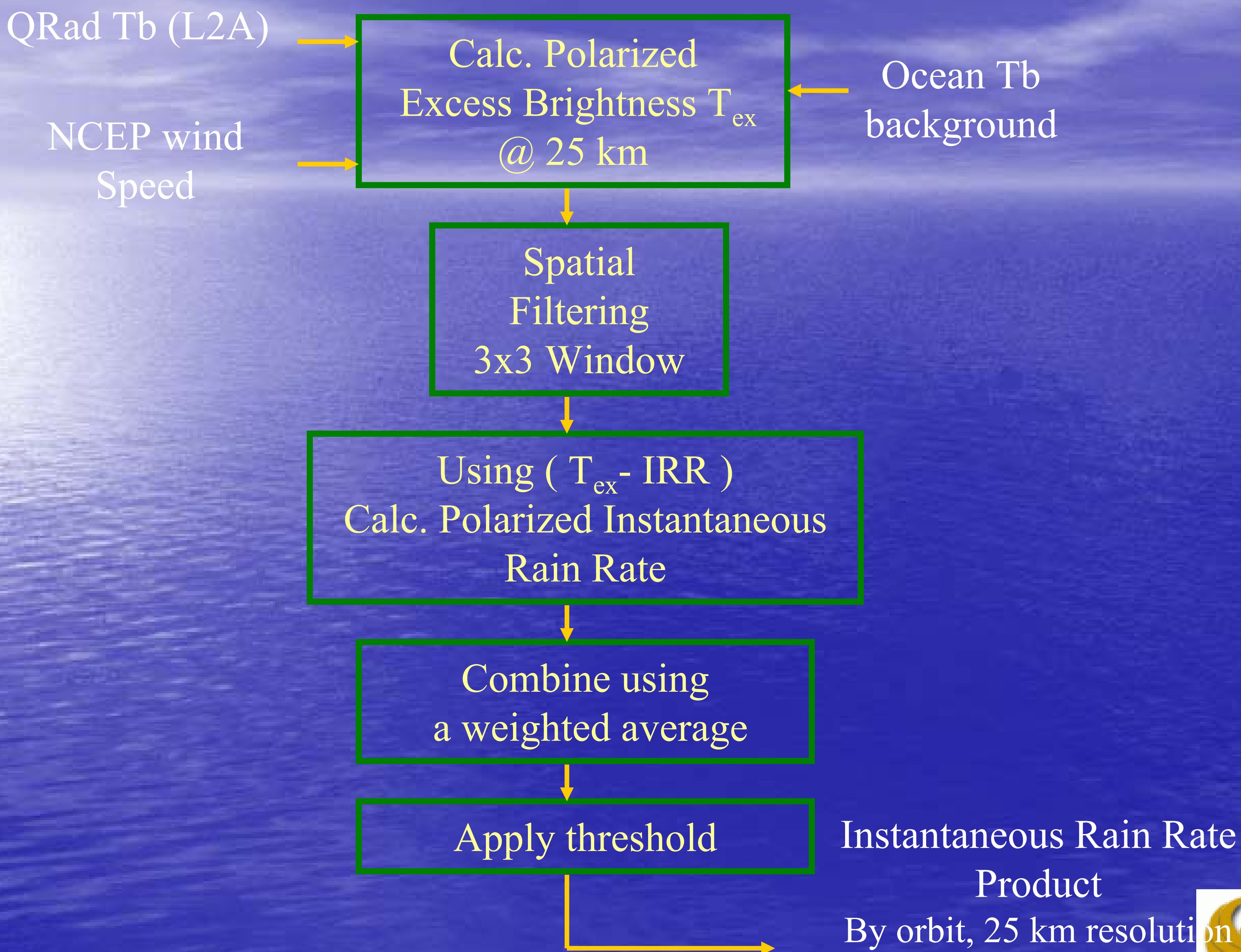
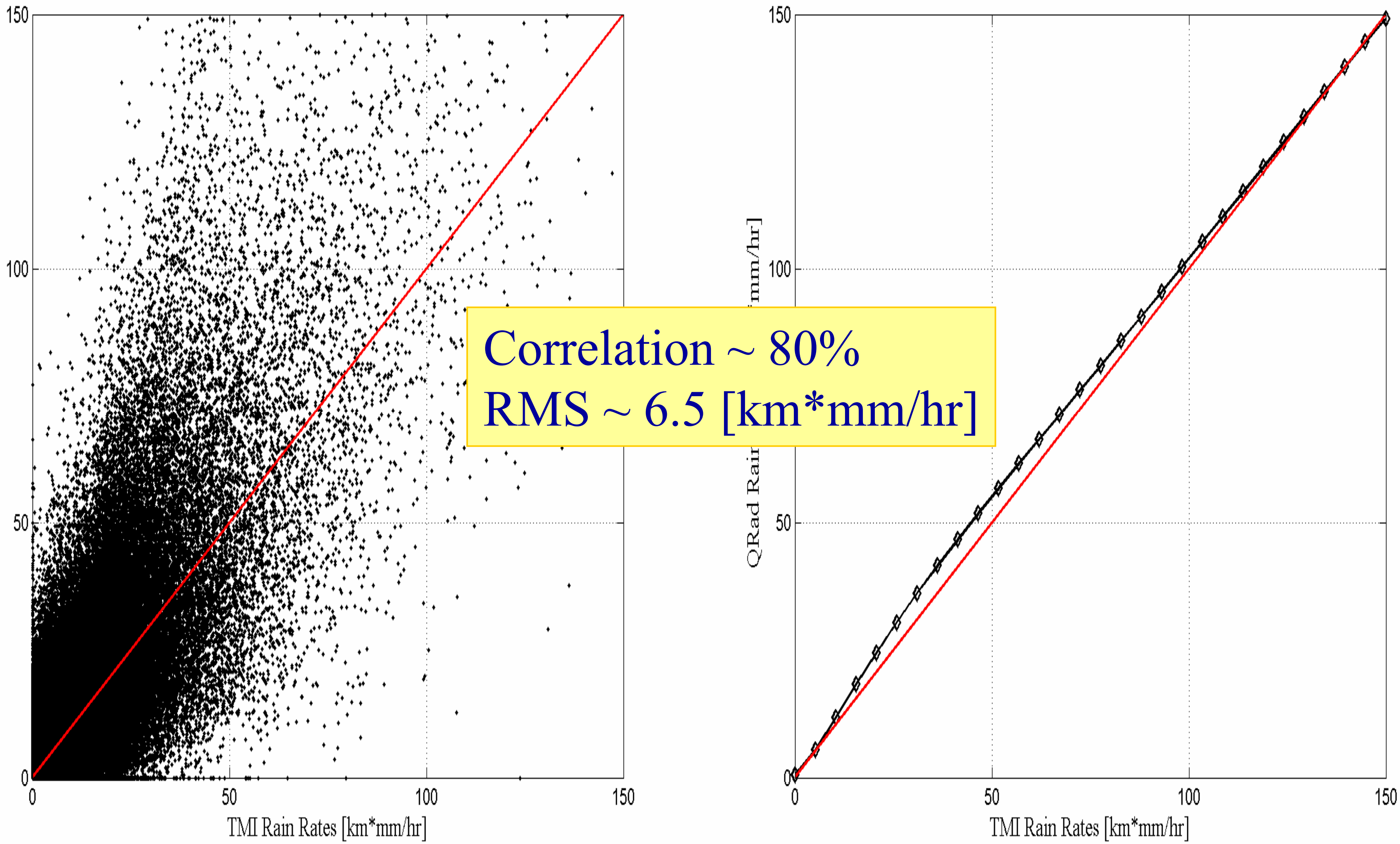
QRad Algorithm Block Diagram



Overall Rain Scatter



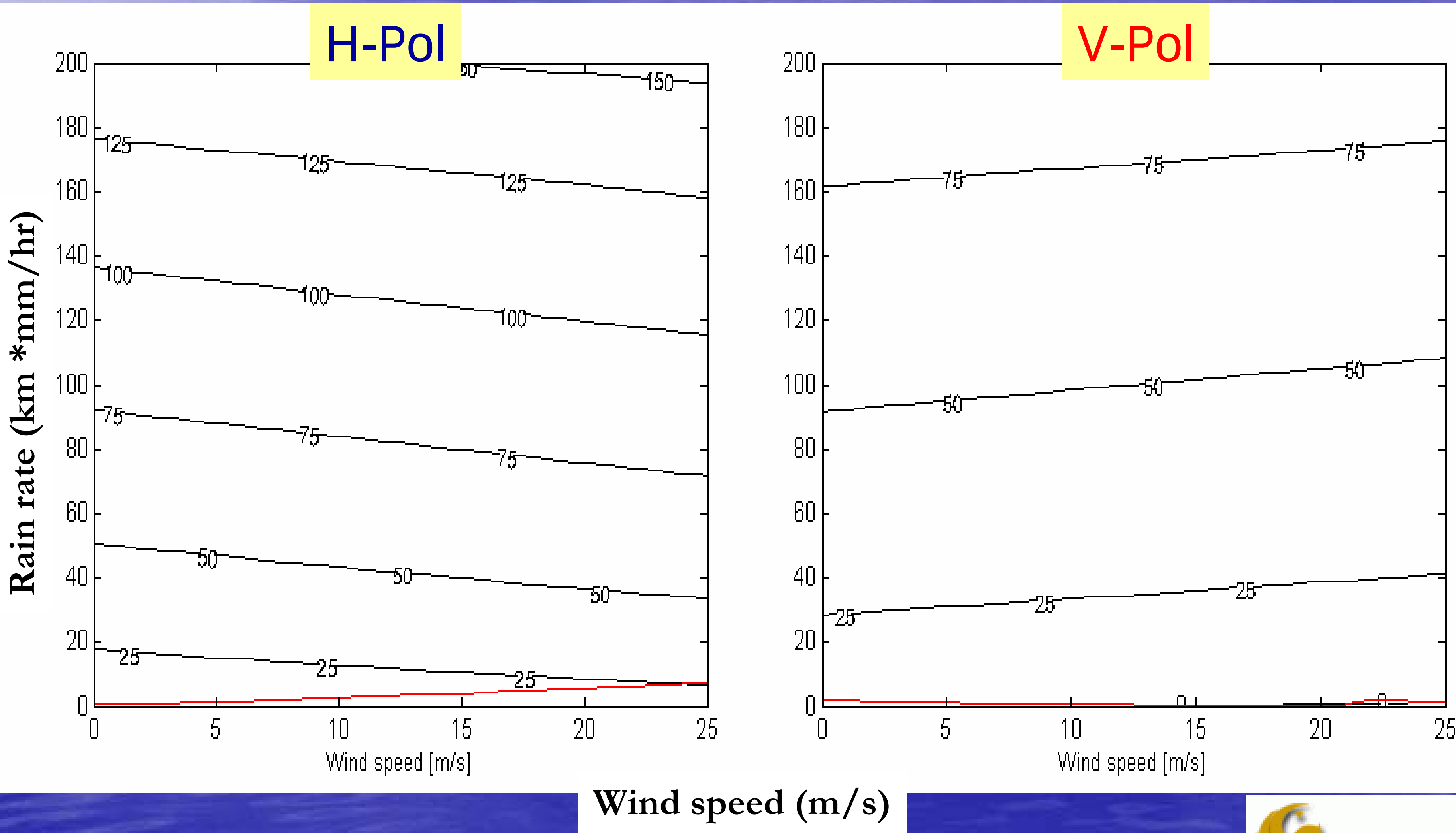
Correlation ~ 80%
RMS ~ 6.5 [km*mm/hr]

QRad IRR [km*mm/hr]

TMI IRR [km*mm/hr]

QRad Radiometric Response

$$T_{ex_{total}} = T_{ex_{rain}} + T_{ex_{wind}}$$



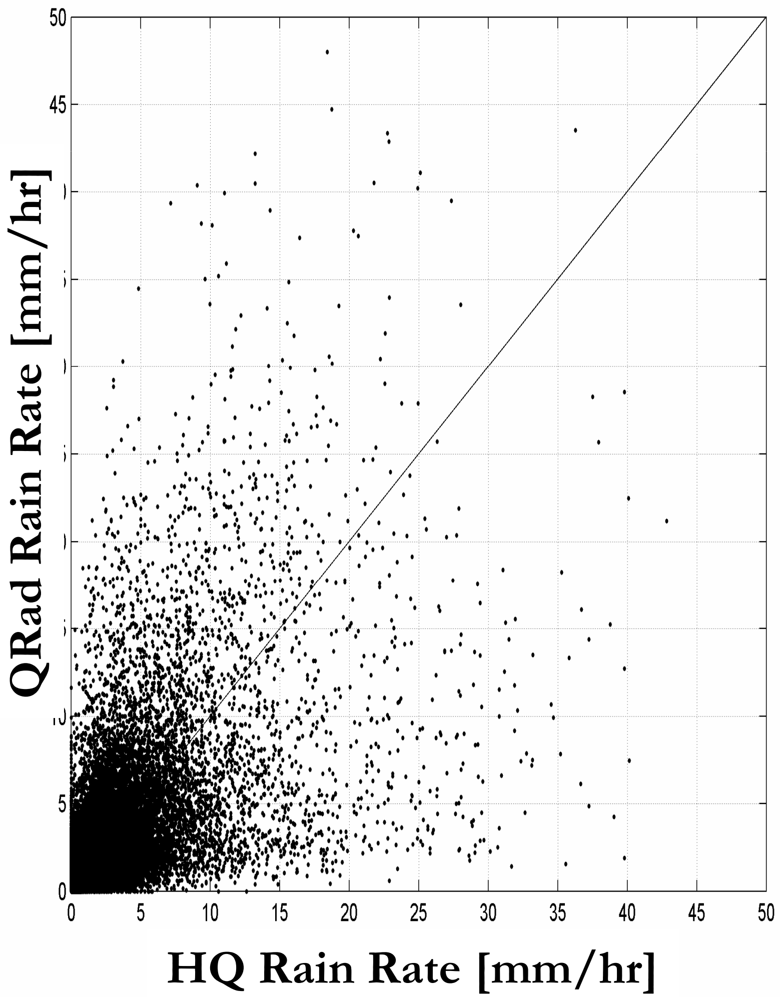
SeaWinds Rain Algorithm

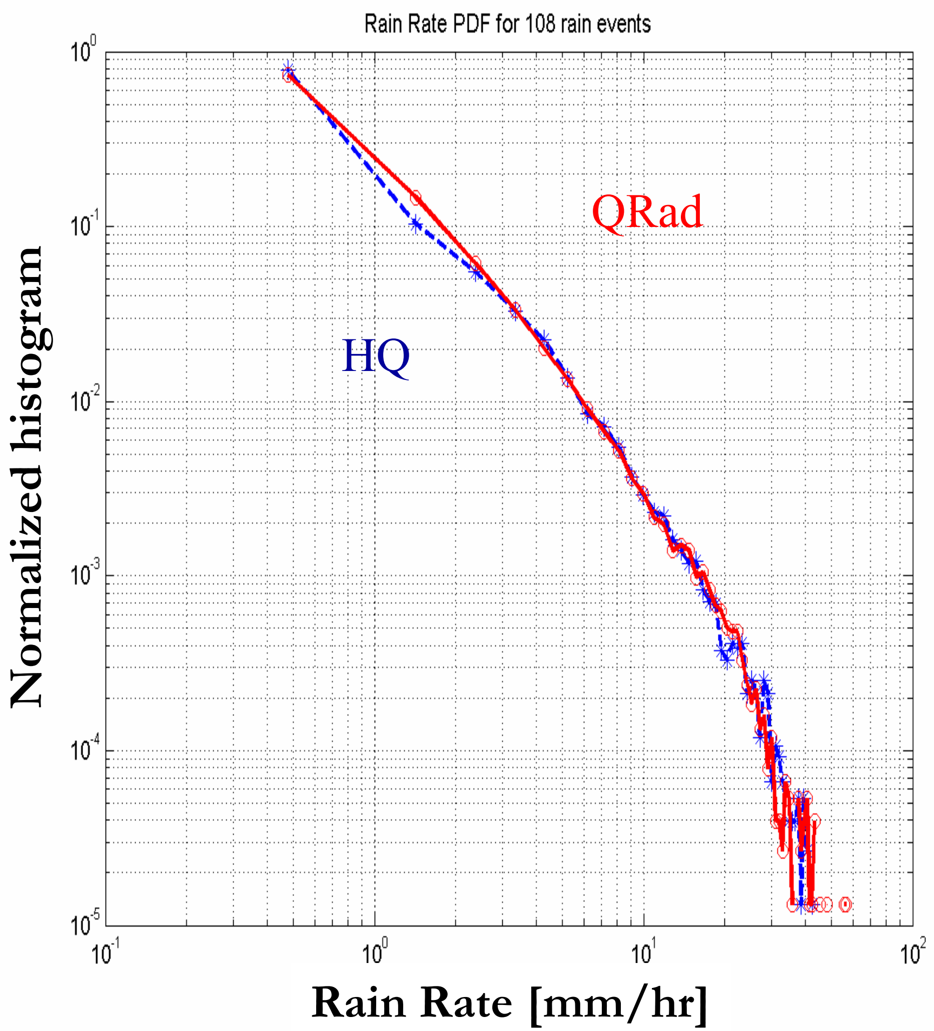
- Validation of QRad

TRMM 3B42RT Data Product

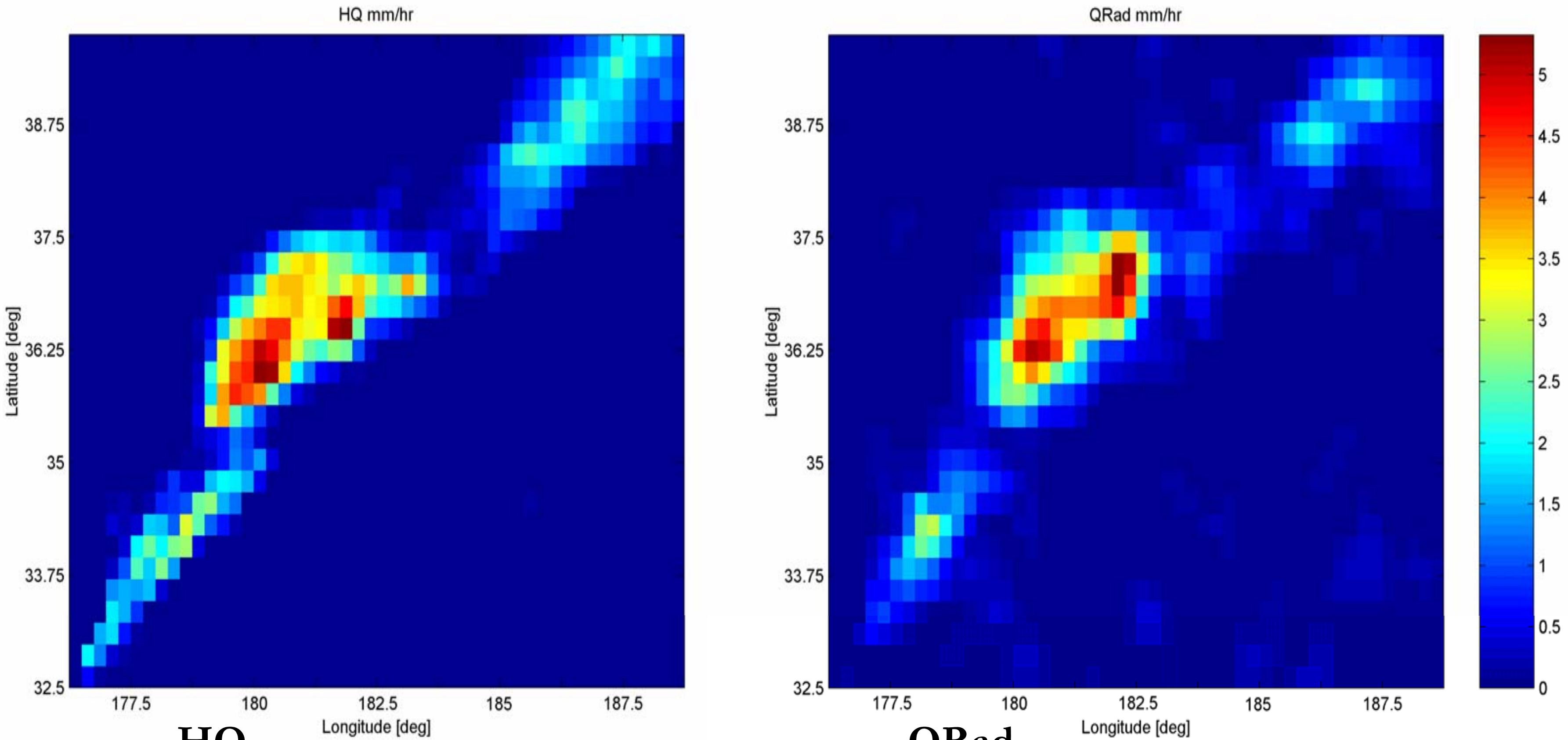
- Provides near real-time global precipitation:
  - 3-hour universal time windows
  - Spatial resolution: 0.25° x 0.25°
- Rain estimates are derived from all available high quality (HQ) microwave merged with visible and infrared rain rate (VAR)
  - VAR estimates obtained from geostationary visible/infrared observations

Comparison of 108 Instantaneous QRad – TRMM 3B42RT HQ Collocated Rain Events



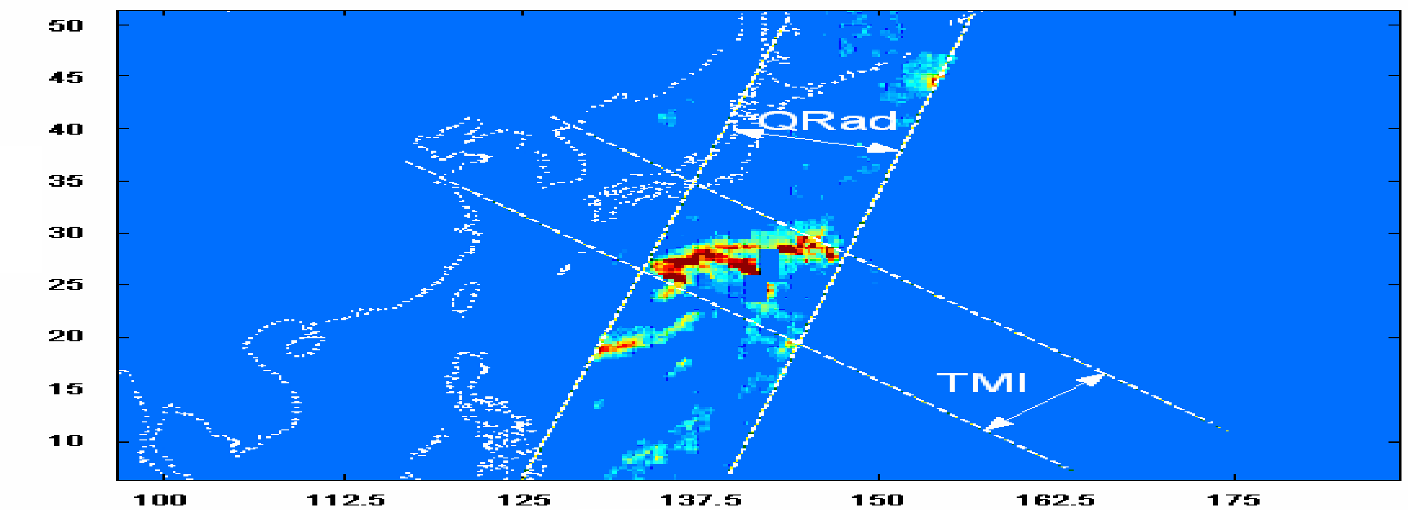


QRad / TRMM 3B42RT HQ Instantaneous Collocated Rain Event

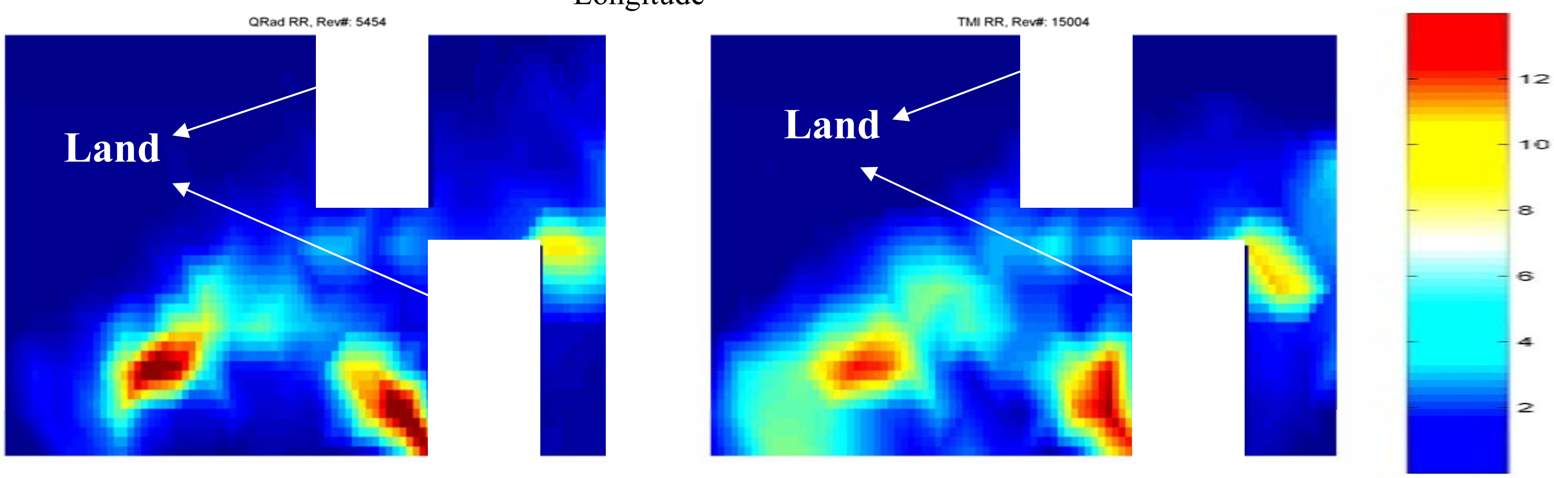


HQ **QRad**

QRad / TRMM 2A12 Instantaneous Rain Rate



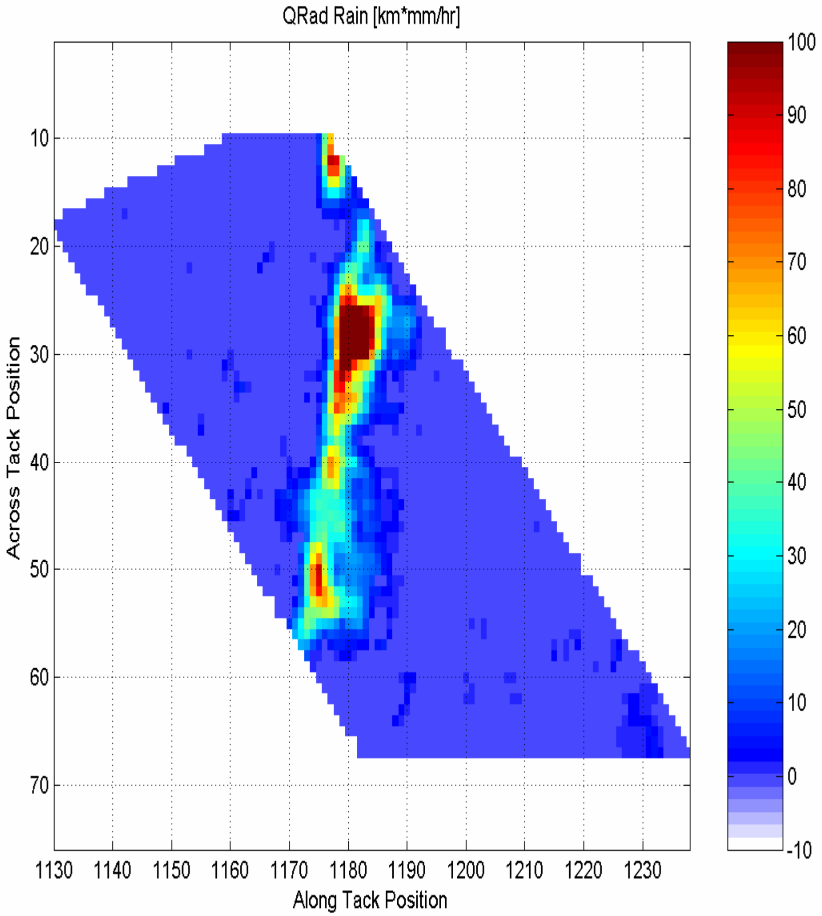
Longitude

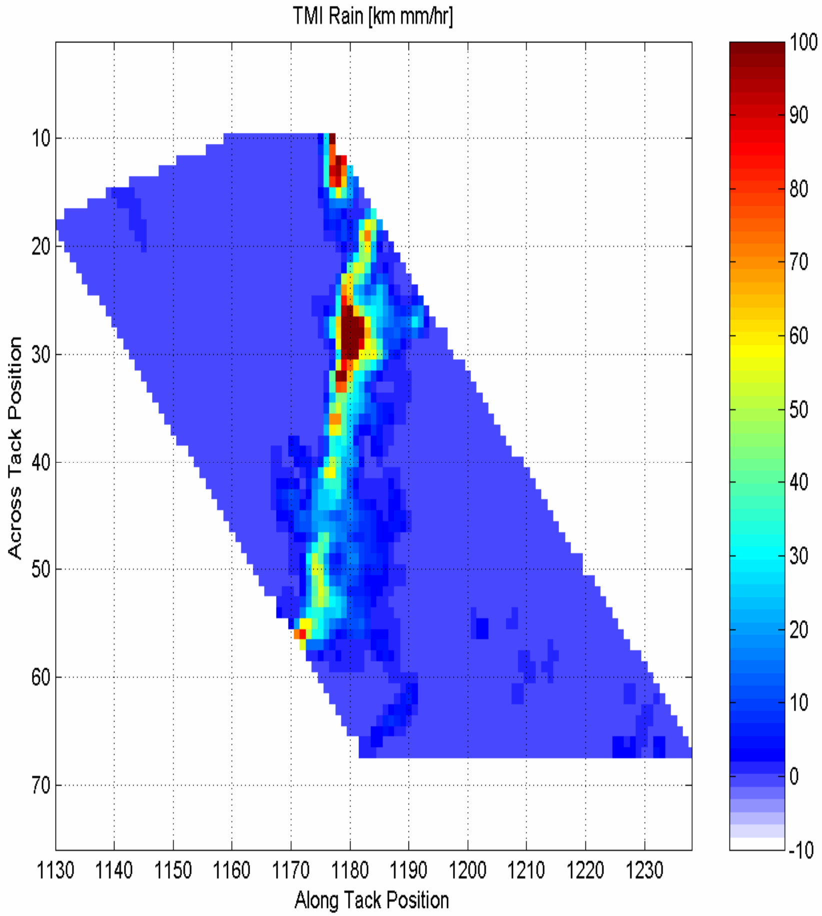


QRad

TMI

Rain Image Comparison





QRad

TMI

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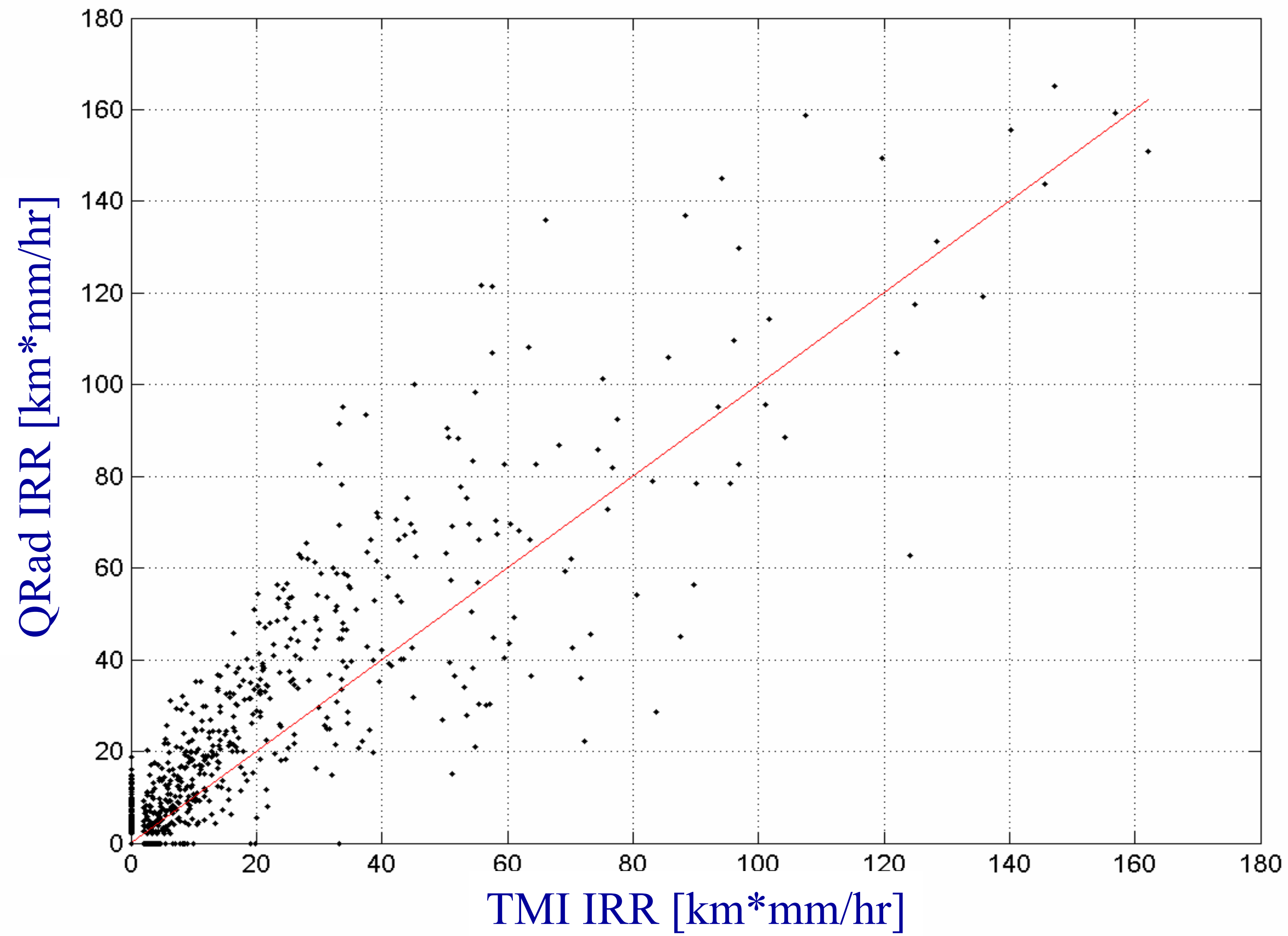
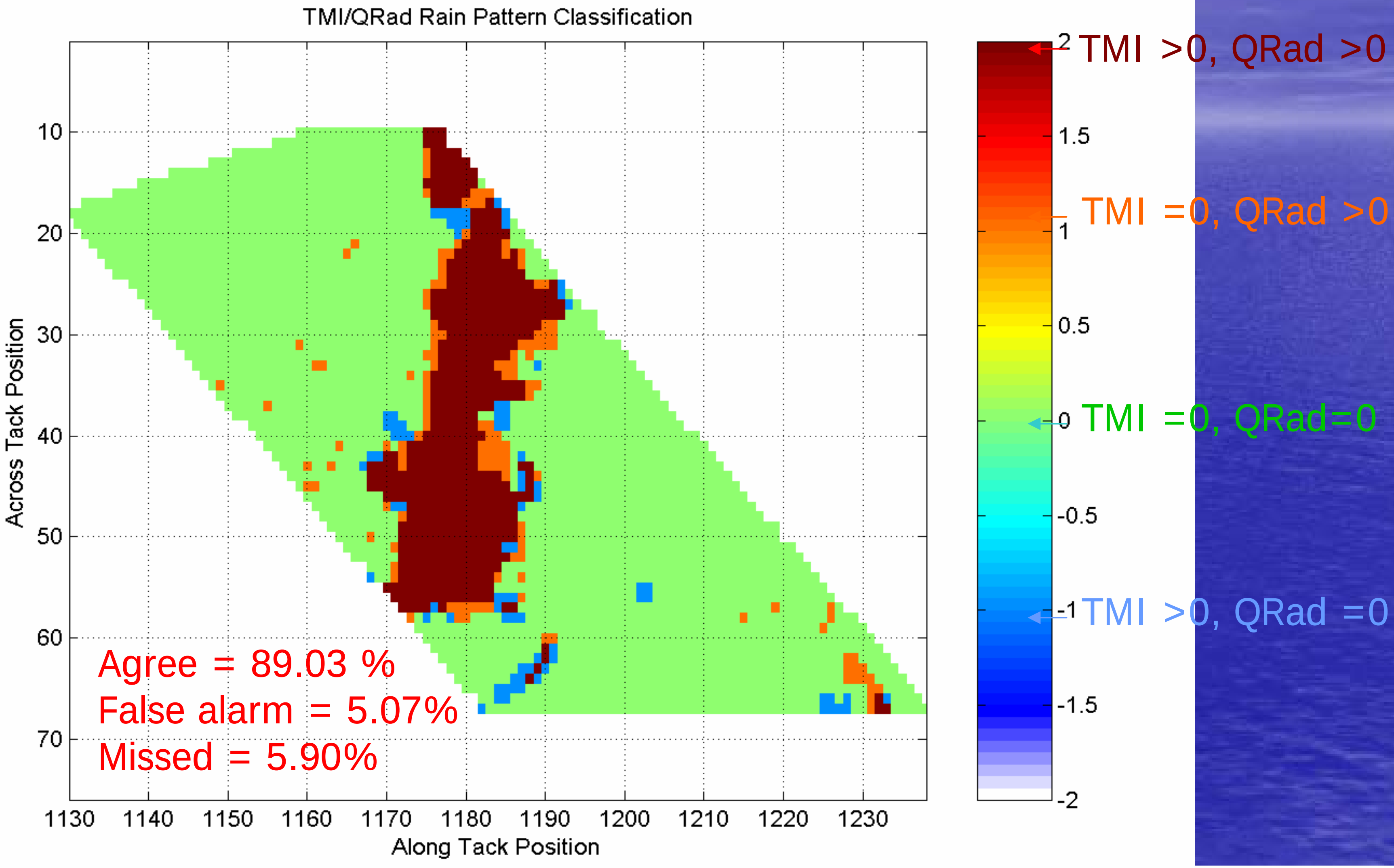
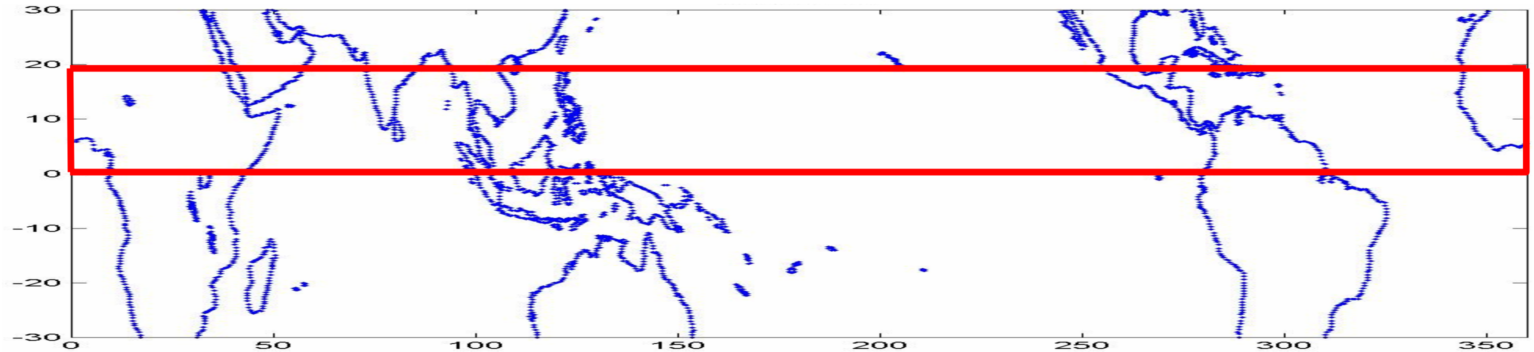
Rain Scatter



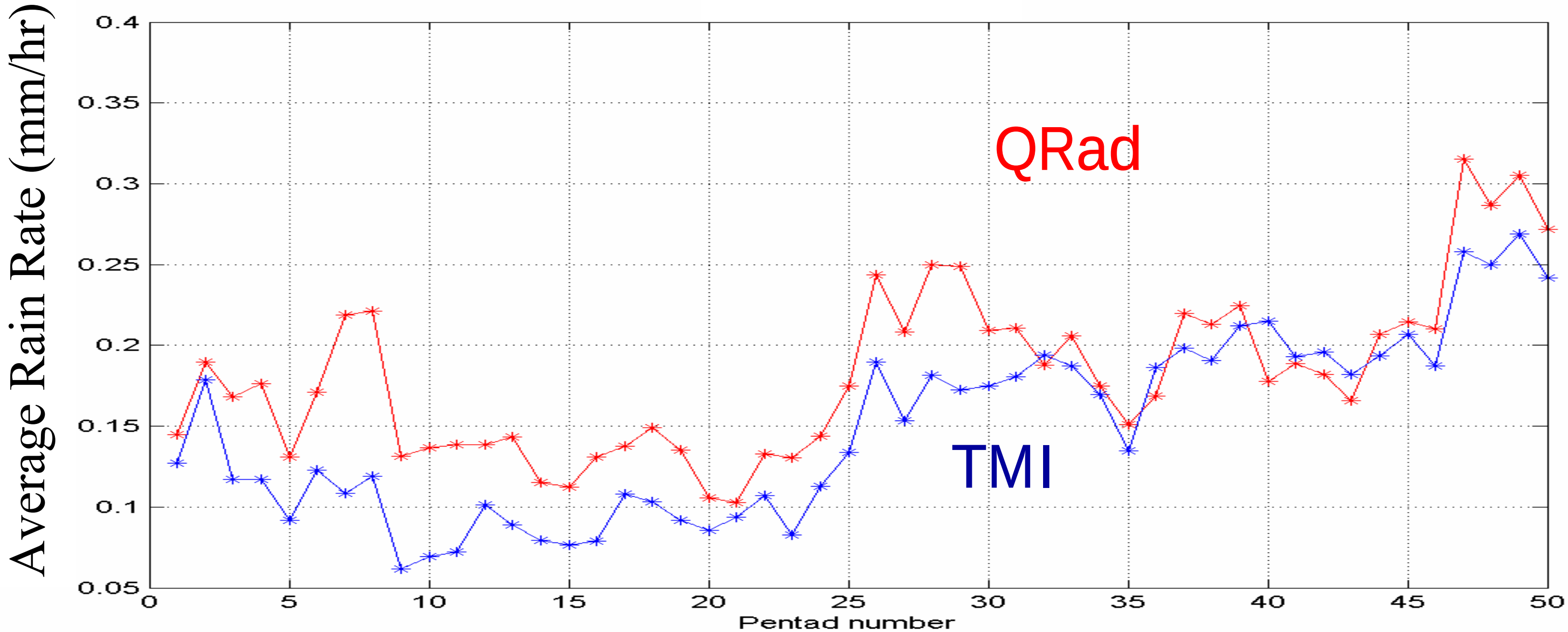
QRad / TMI Rain Pattern Classification



Zonal Average Rain Rate

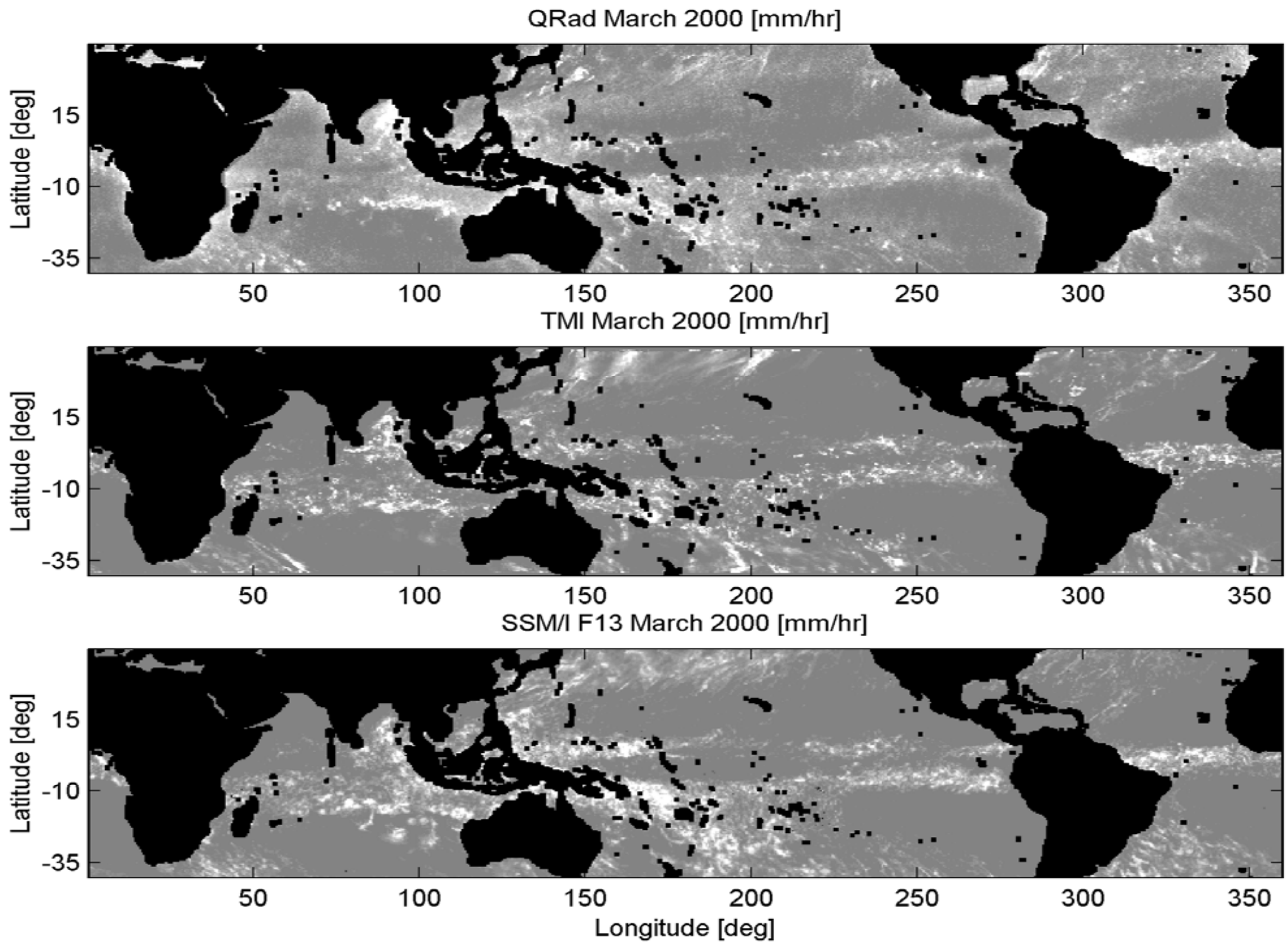


0° N to 20° N



Pentad number

Monthly Average Rain Rate



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SeaWinds Rain Algorithm

- Active Sigma-0 Model

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Rain Effects on SeaWinds σ^o

- In the presence of Rain, three major factors affect the measured ocean surface σ^o:
  - Two way path attenuation
    - Reduces received power
  - Volume backscatter
    - Enhances received power
  - Surface perturbation "Splash Effect"
    - Alters ocean surface roughness structure

$$\sigma^0_{meas}(r,u,\chi,p,\theta)=\alpha(r,p,\theta)\cdot\sigma^0_{wind}(u,\chi,p,\theta)+\sigma^0_{excess}(r,p,\theta)$$

σ^0_{meas} : Measured SeaWinds backscatter
σ^0_{wind} : Wind induced backscatter
$\sigma^0_{Ex\text{-}rain}$: Excess-backscatter due to rain
α : Two-way path attenuation

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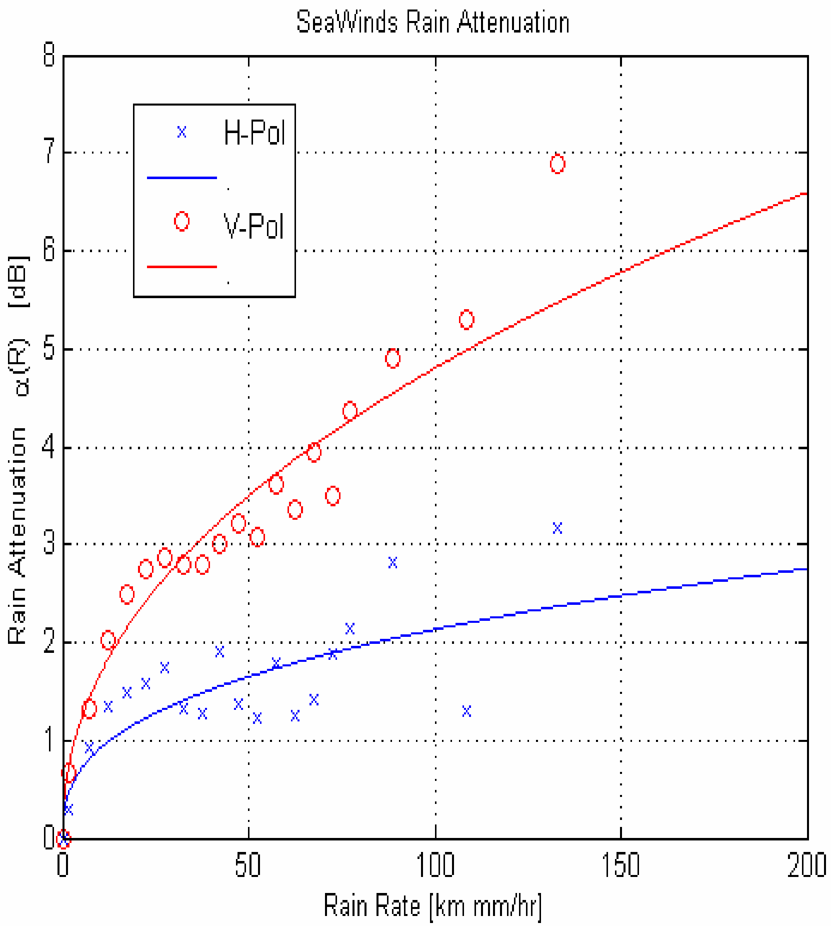
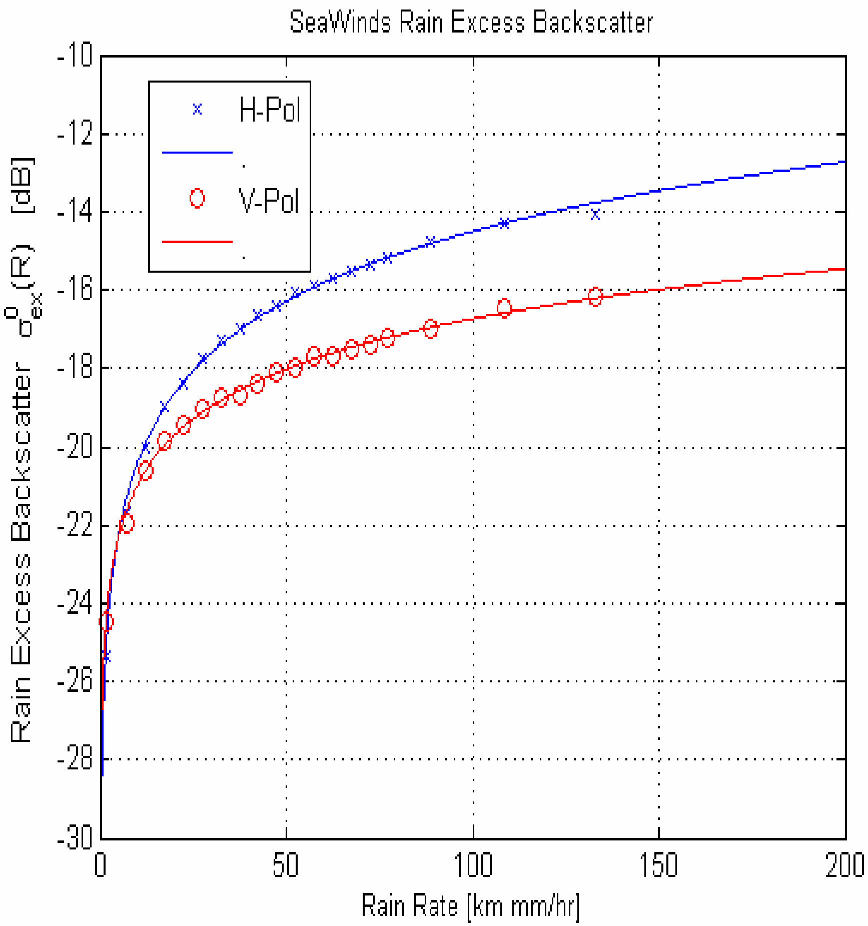
SeaWinds Rain Excess Backscatter and Attenuation Models





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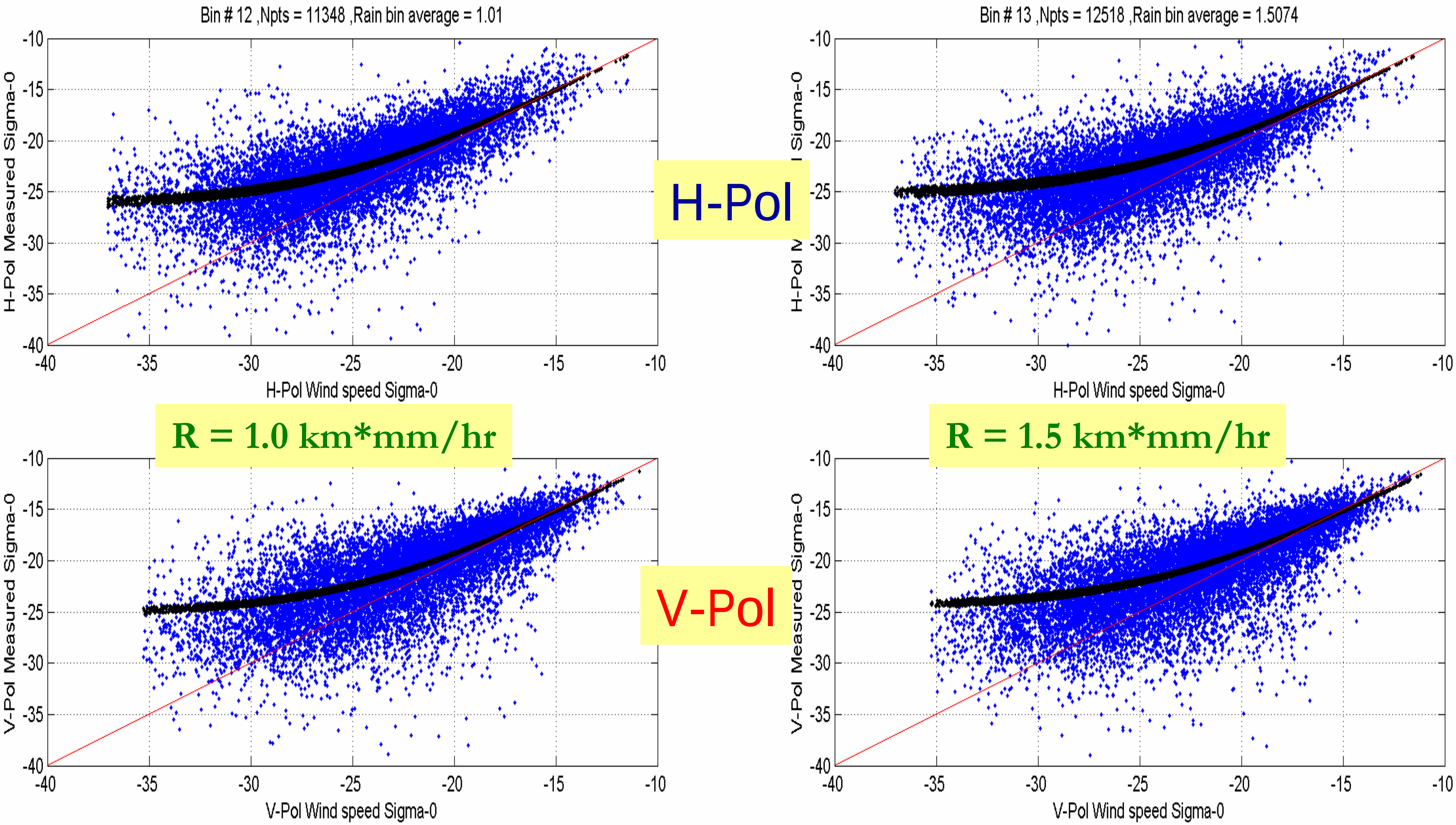
Sigma-0 Forward Model Validation (1)



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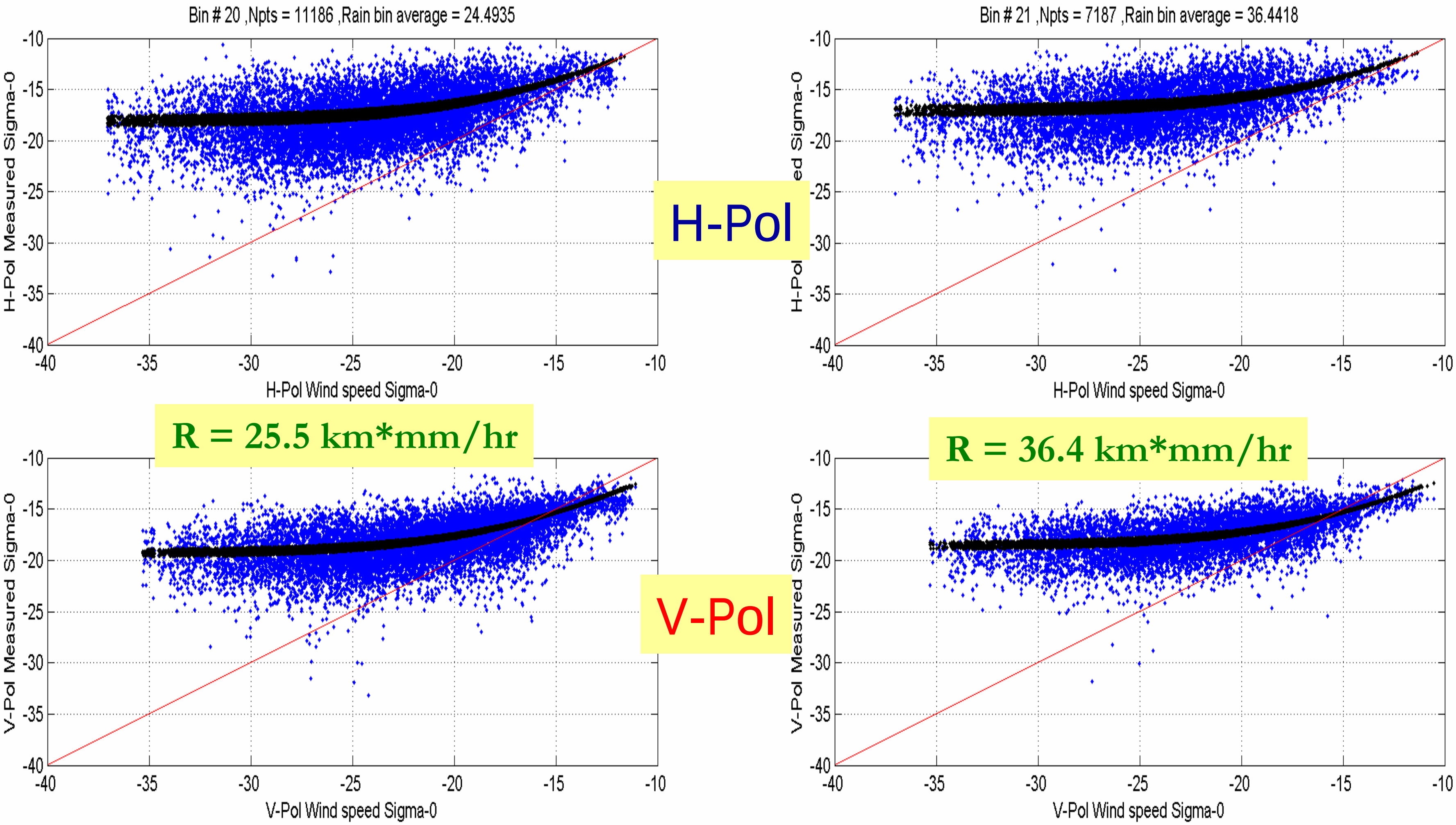
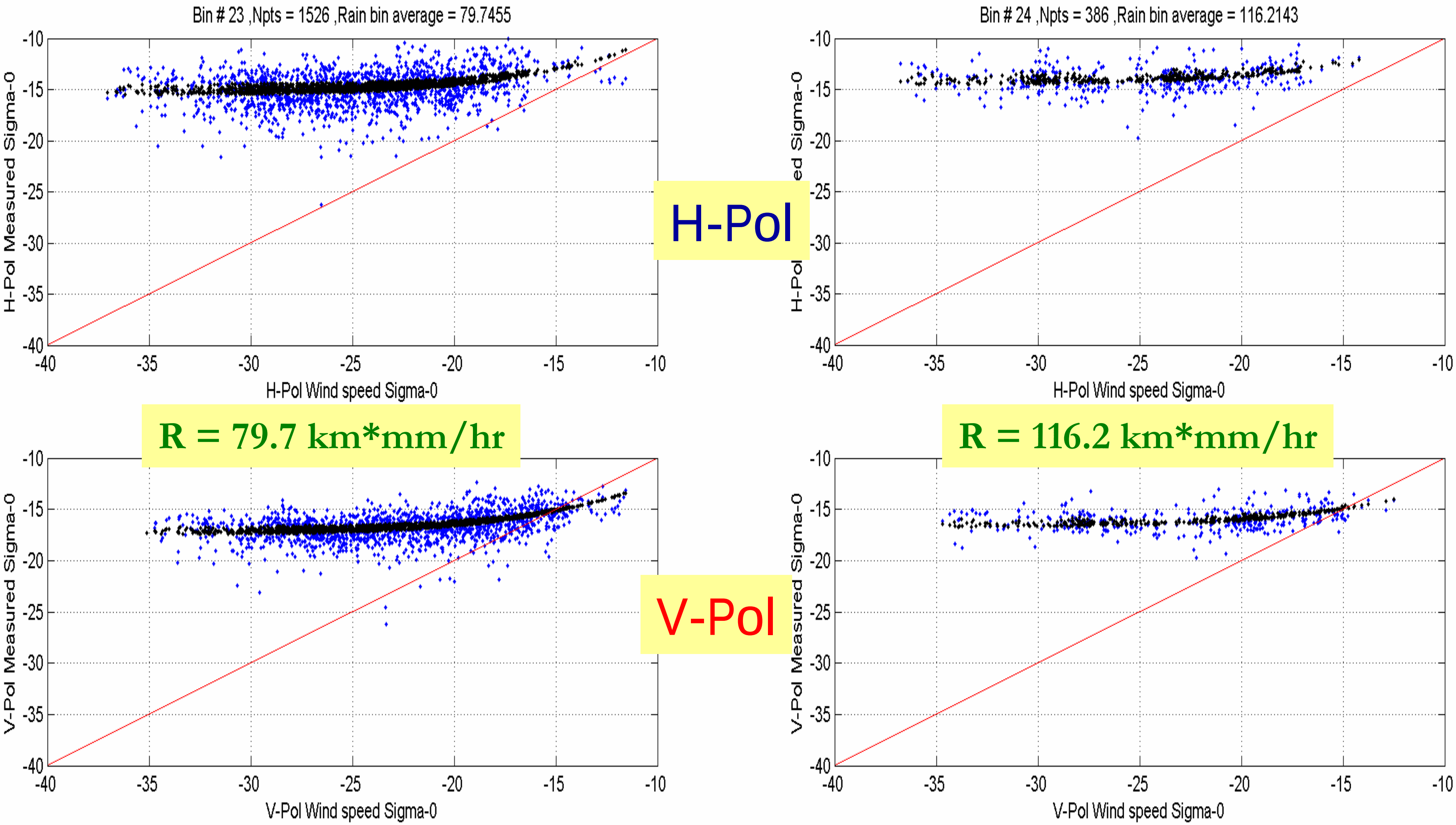
Sigma-0 Forward Model Validation (2)



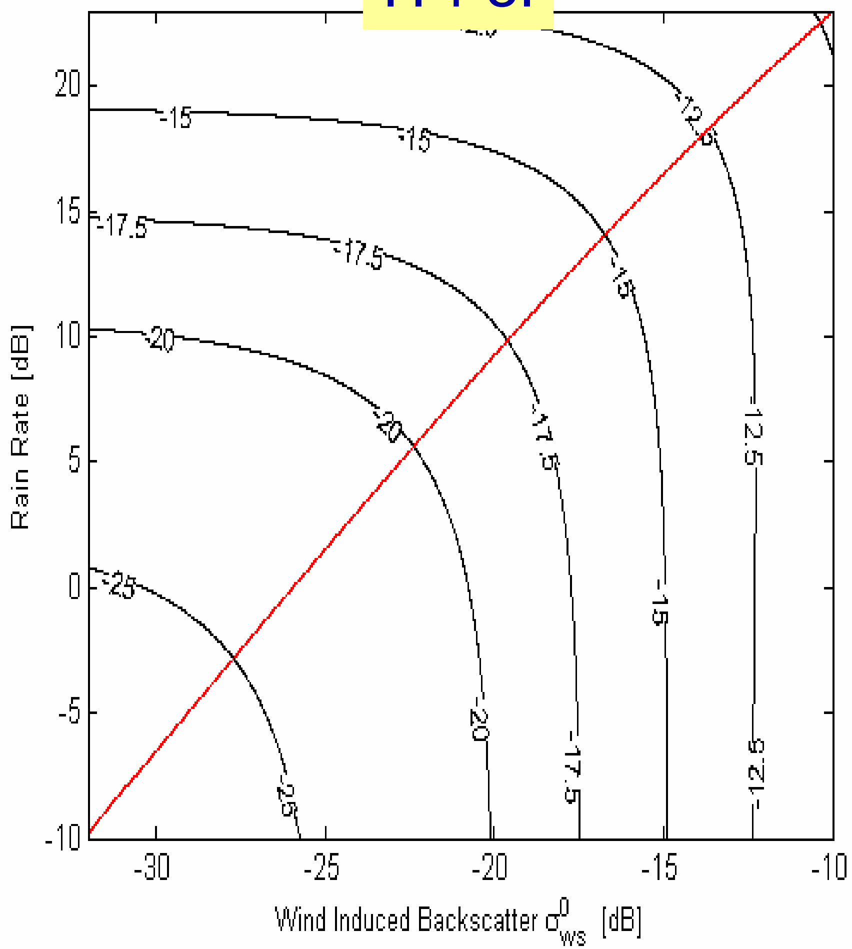
Sigma-0 Forward Model Validation (3)



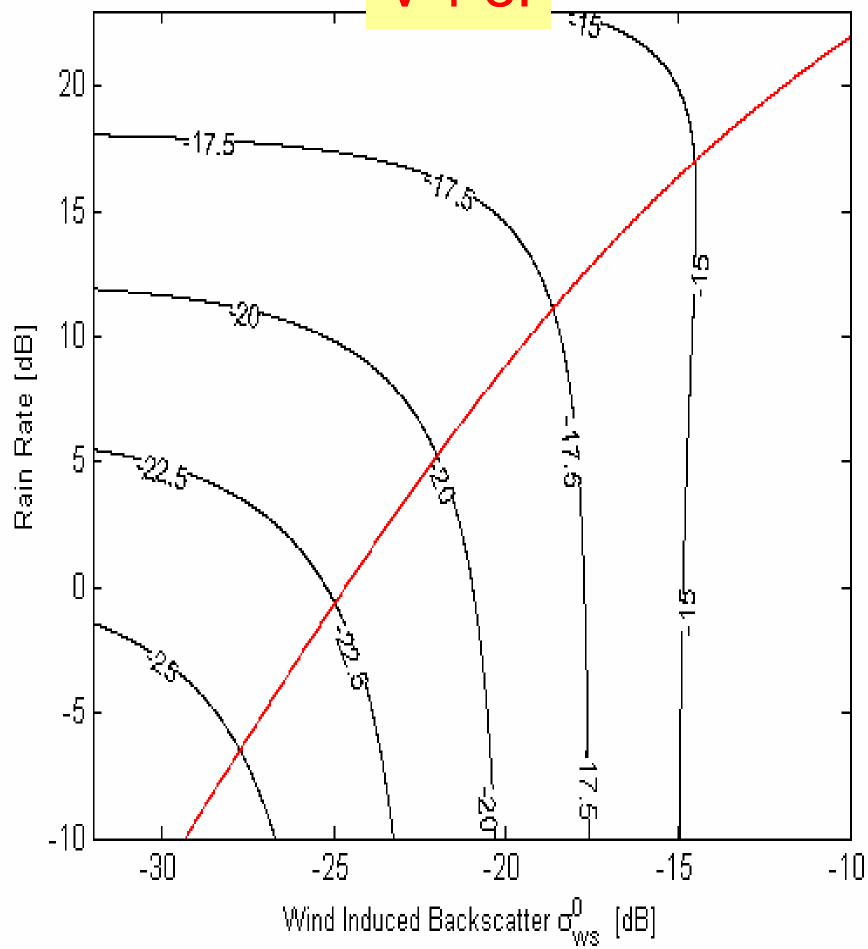
Scatterometer Response

$$\sigma^0_{meas}(r,u,\chi,p,\theta)=\alpha(r,p,\theta)\cdot\sigma^0_{wind}(u,\chi,p,\theta)+\sigma^0_{excess}(r,p,\theta)$$

H-Pol



V-Pol



SeaWinds Rain Algorithm

- Combined Passive / Active Retrievals

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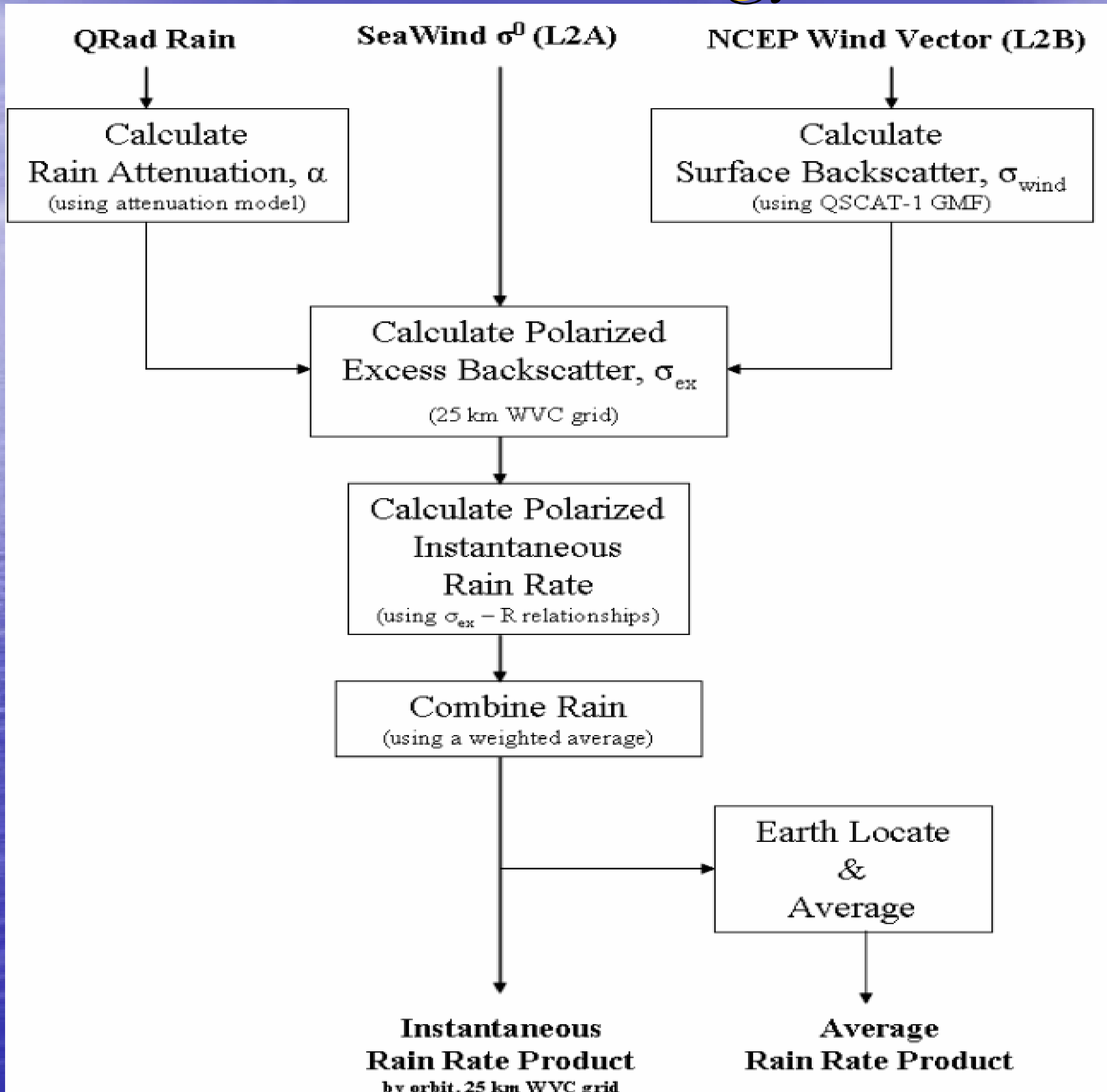
Methodology



SeaWinds Rain Calculations

Calculate Polarized Excess Backscatter:

$$\sigma^0_{ex}(r,p,\theta)=\sigma^0_m(r,u,\chi,p,\theta)-\alpha(r,p,\theta)\cdot\sigma^0_{ws}(u,\chi,p,\theta)$$

Minimize Objective Function:

$$J=\sum_{i=1}^{N}\frac{(\sigma^{meas}{}_{ex,i}-\sigma^{model}{}_{ex,i})^2}{\delta_i{}^2}$$

$\delta_i^2 = f(IRR_{QRad})$

Calculate Combined Rain Rates:

$$IRR_{SeaWinds}=\gamma_h\cdot IRR_h^{PA}+\gamma_v\cdot IRR_v^{PA}$$

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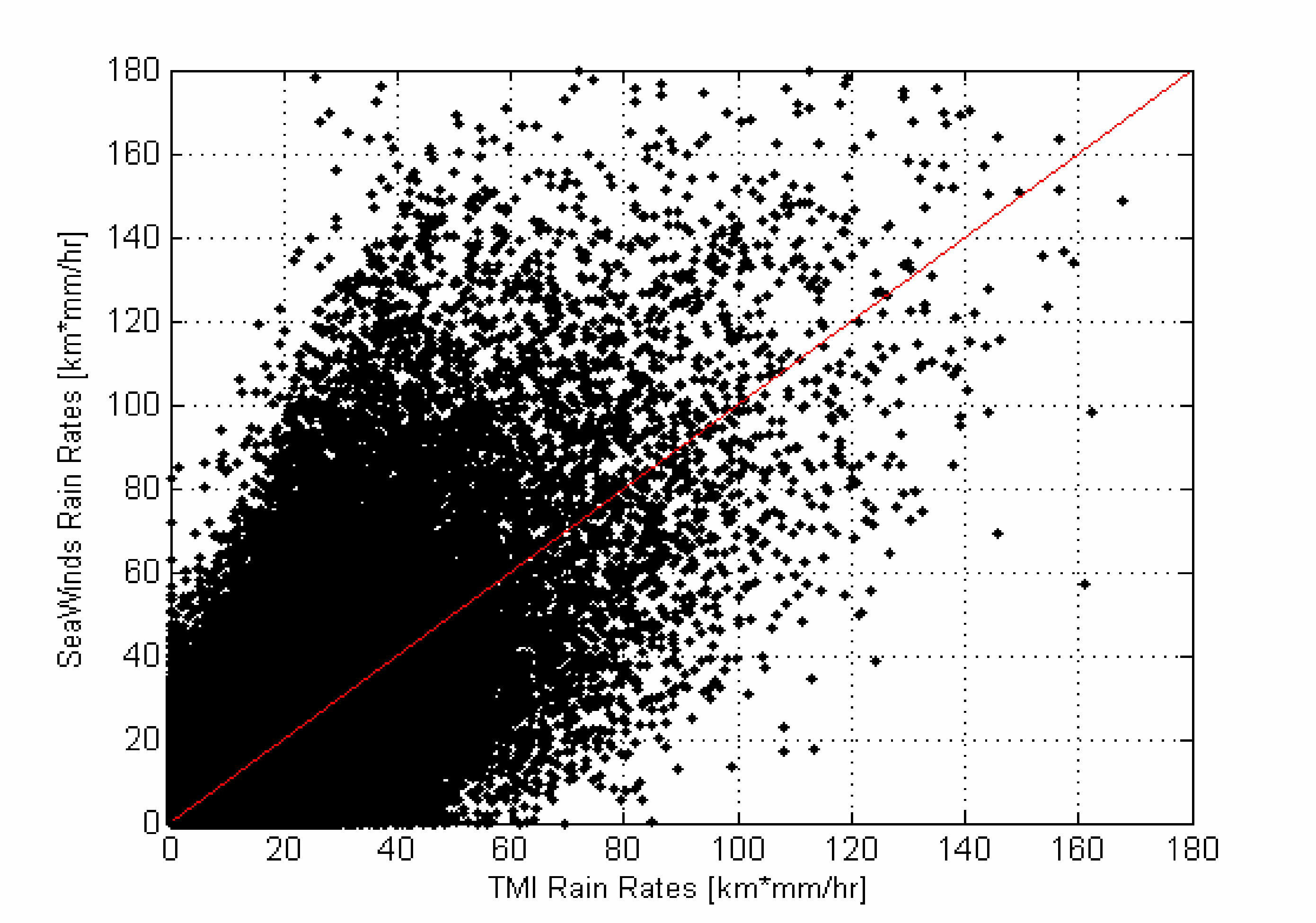
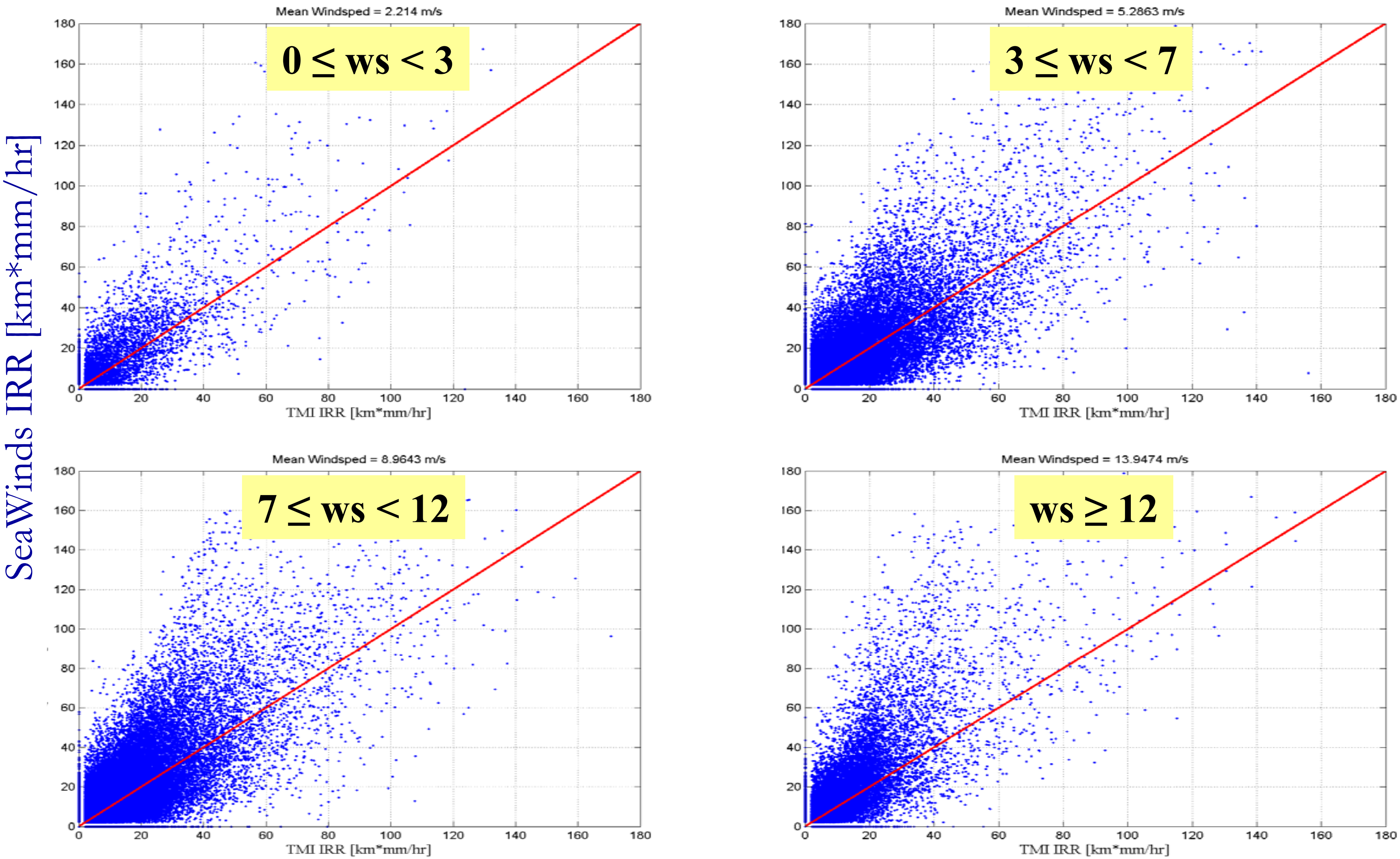
SeaWinds / TMI Rain Scatter

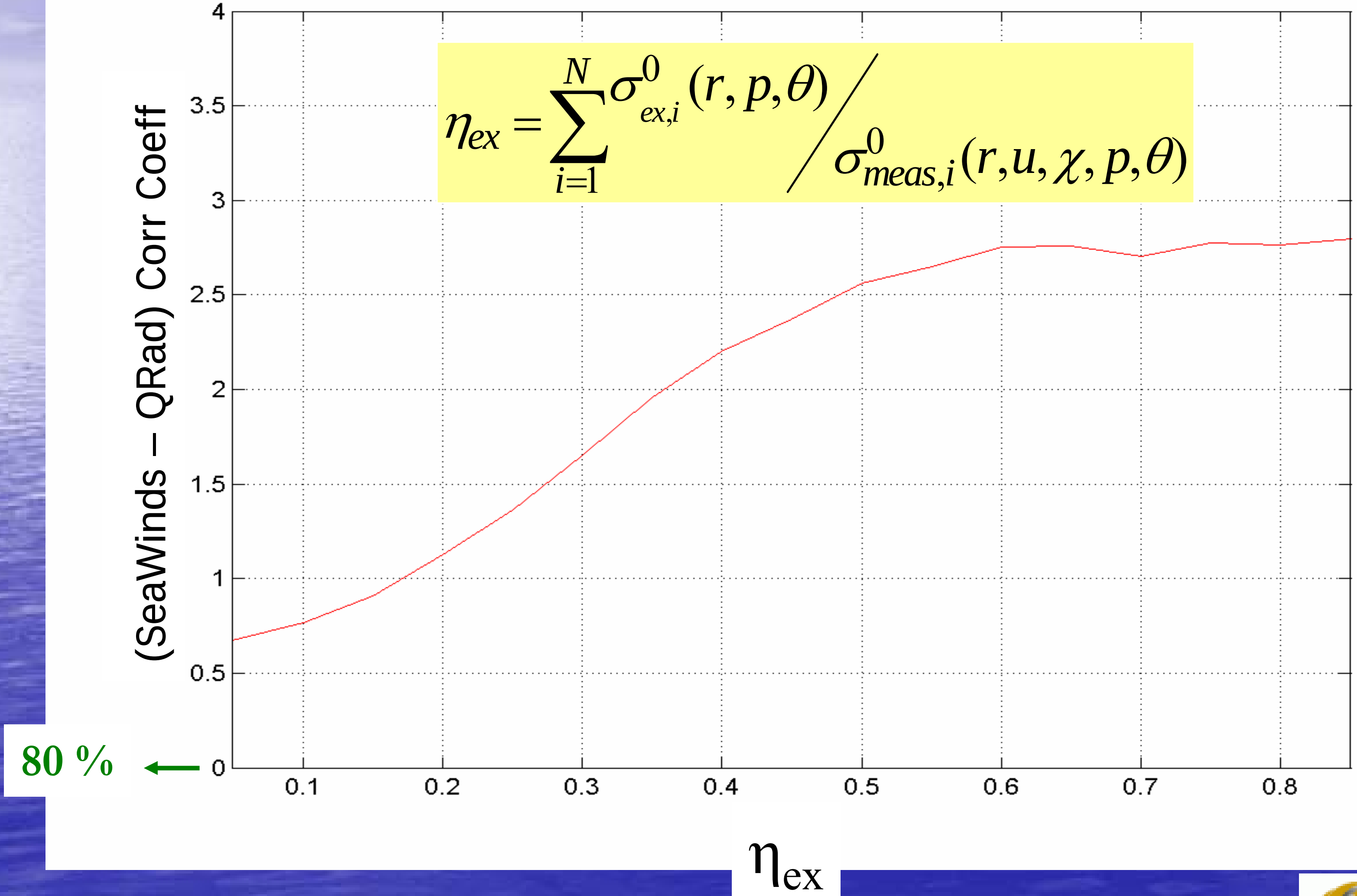


SeaWinds / TMI Rain Scatter



TMI IRR [km*mm/hr]

SeaWinds / QRad Comparison

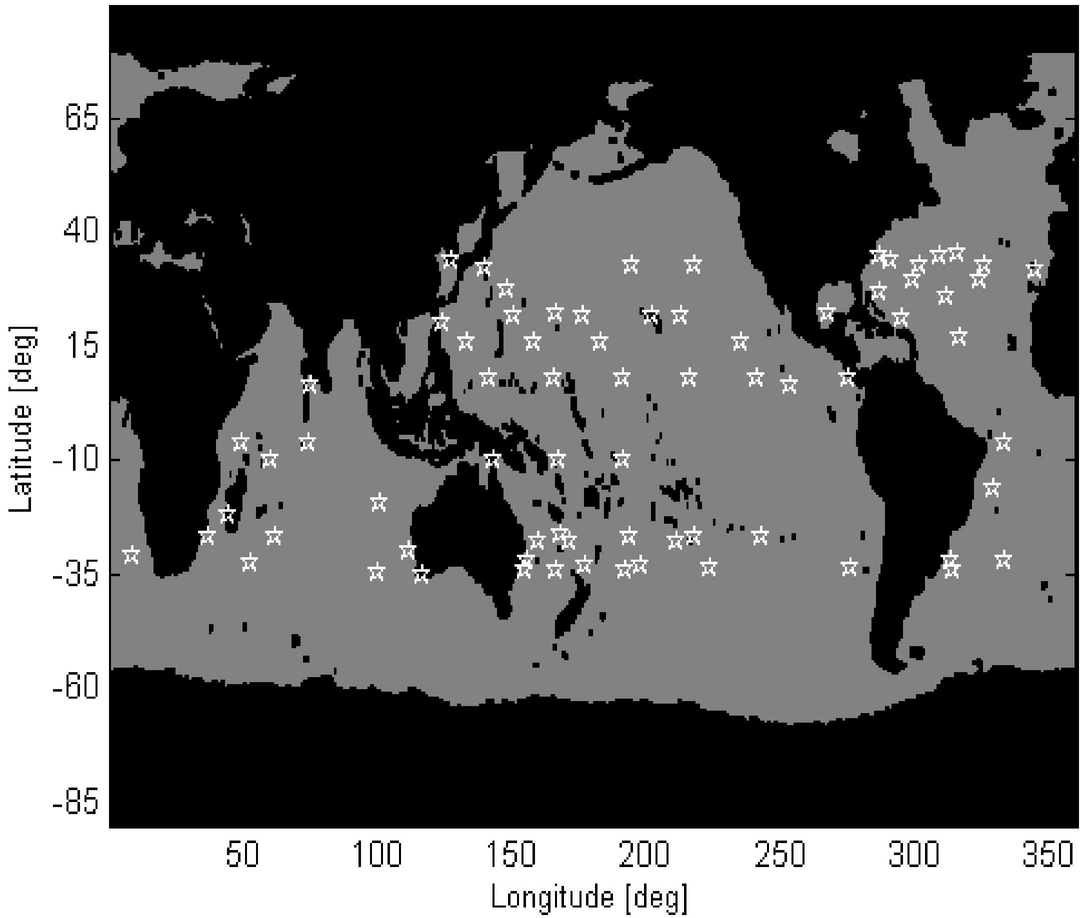


$$\eta_{ex} = \sum_{i=1}^{N} \sigma^{0}_{ex,i}(r,p,\theta) \Big/ \sigma^{0}_{meas,i}(r,u,\chi,p,\theta)$$

SeaWinds Rain Algorithm

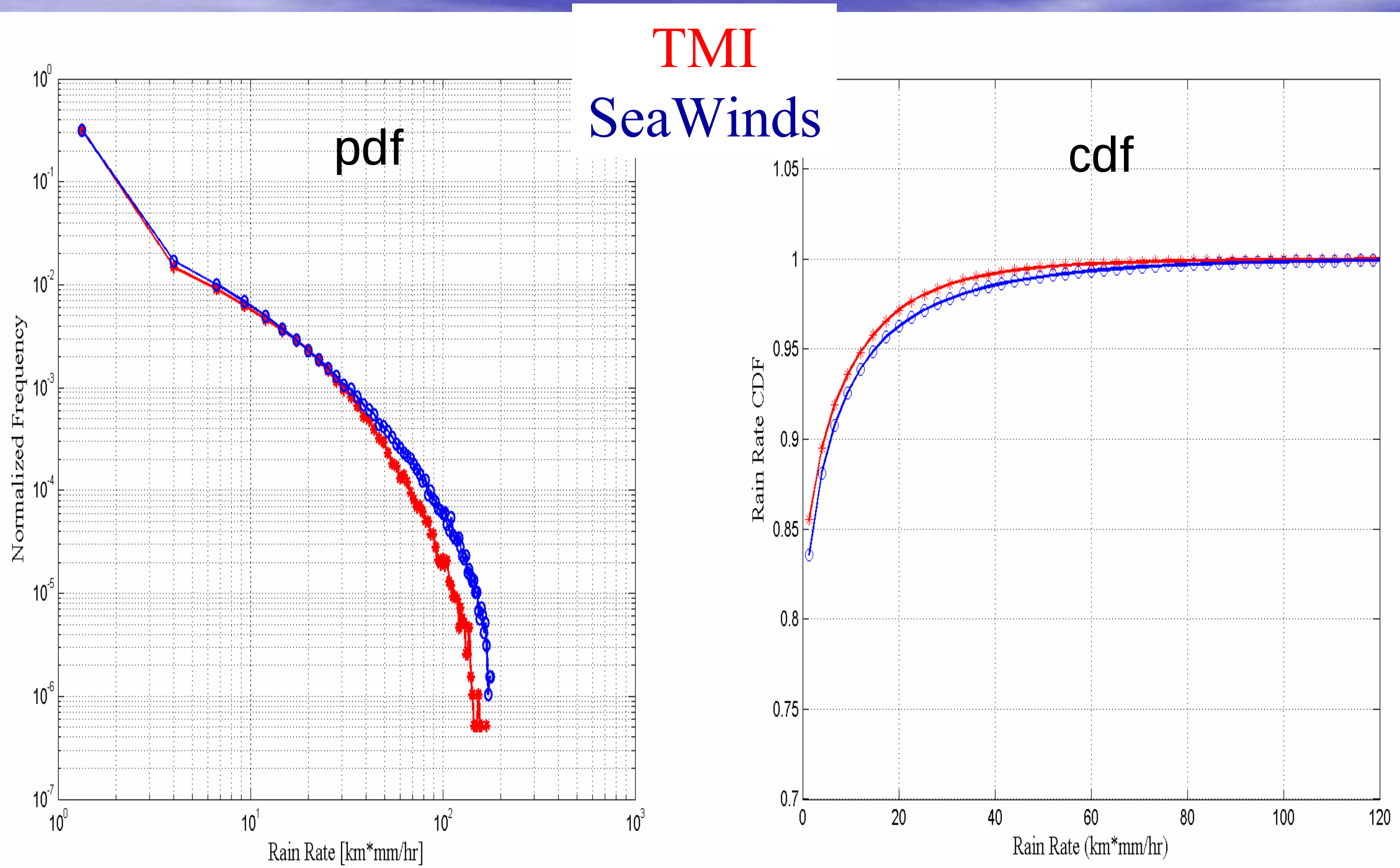
- Validation of SeaWinds Rain Retrievals

Validation Dataset



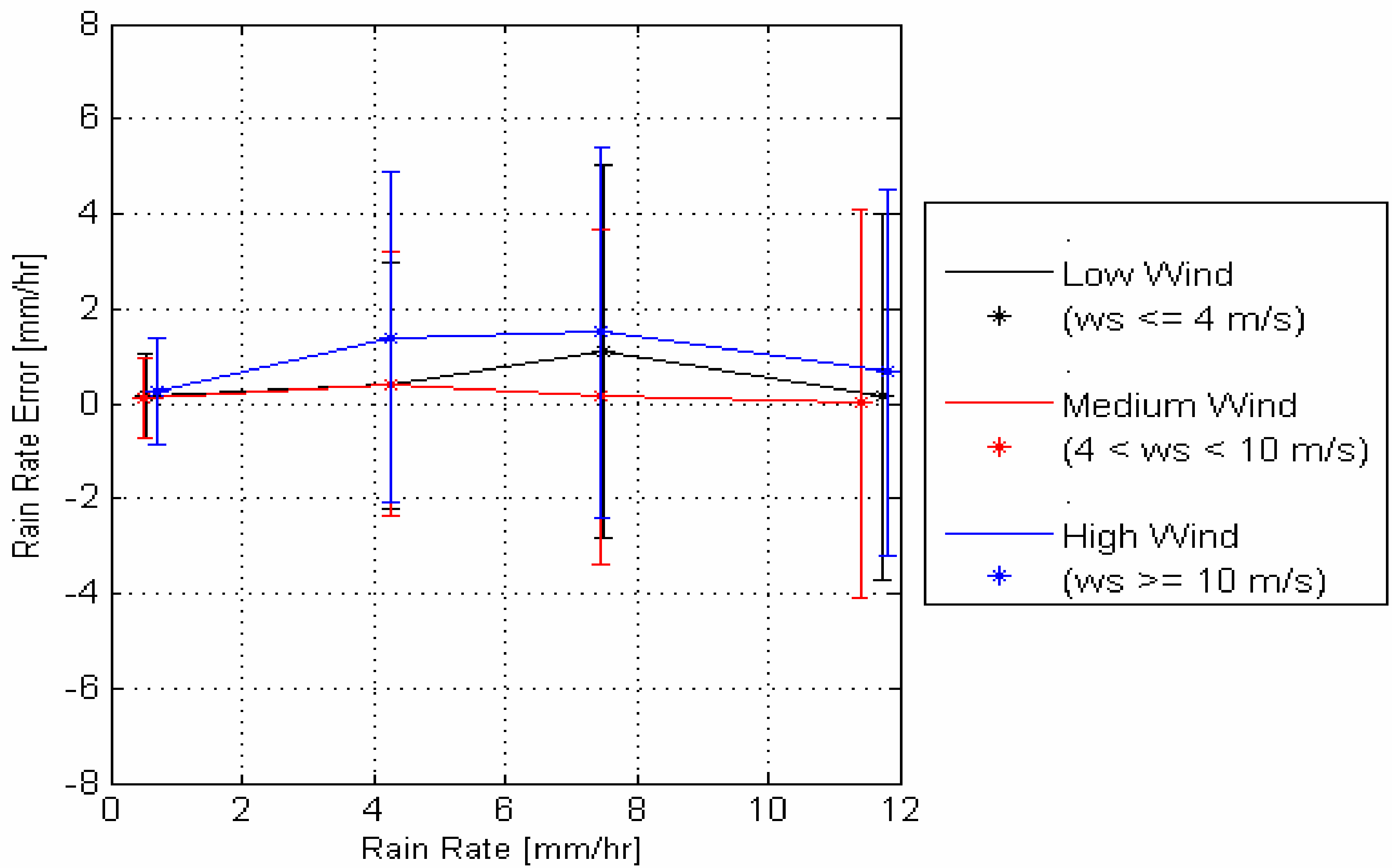
- 72 Collocated events
- Apr ~ Oct 2003
- ± 30 minutes

Rain Statistics

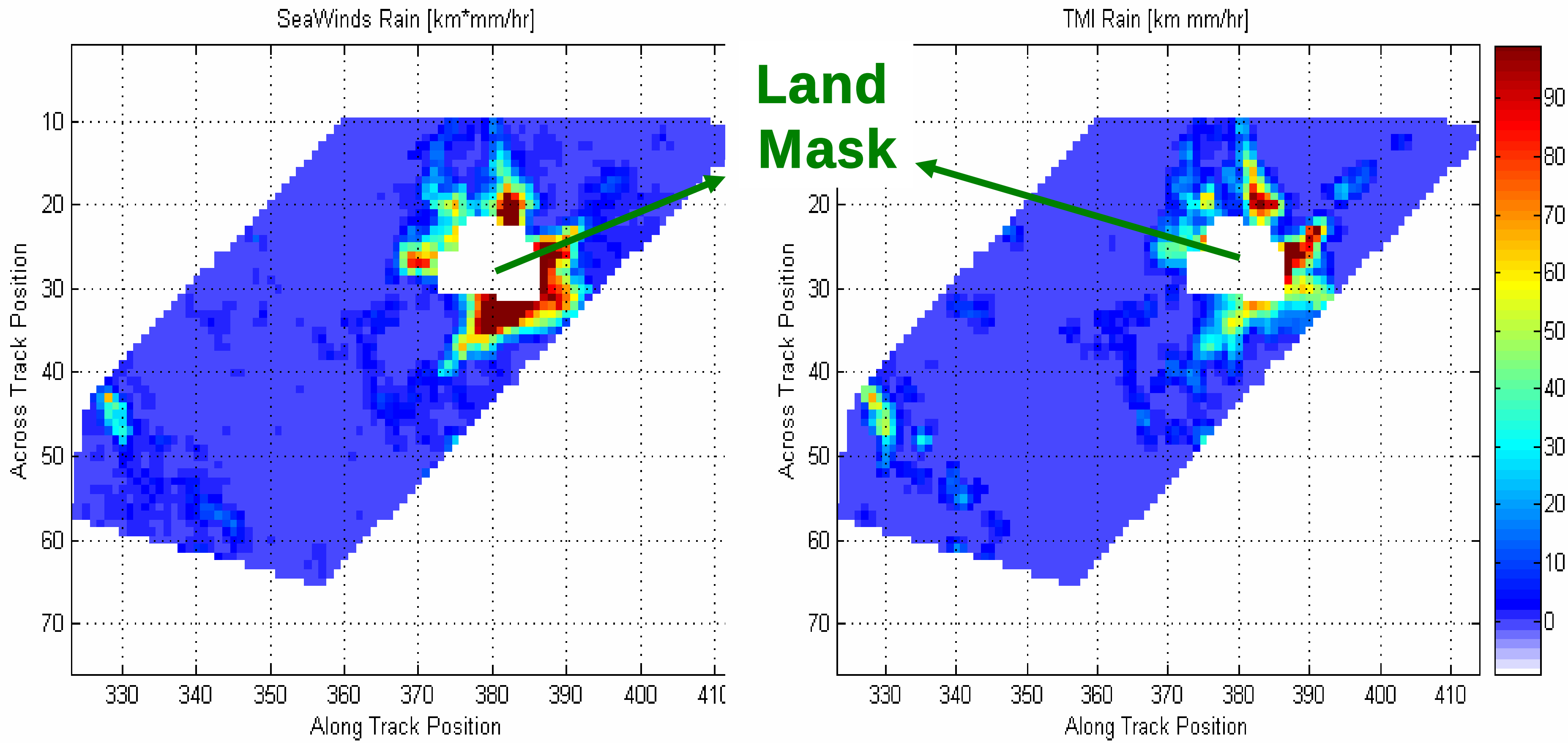


Rain Rate [km*mm/hr]

Rain Error Statistics



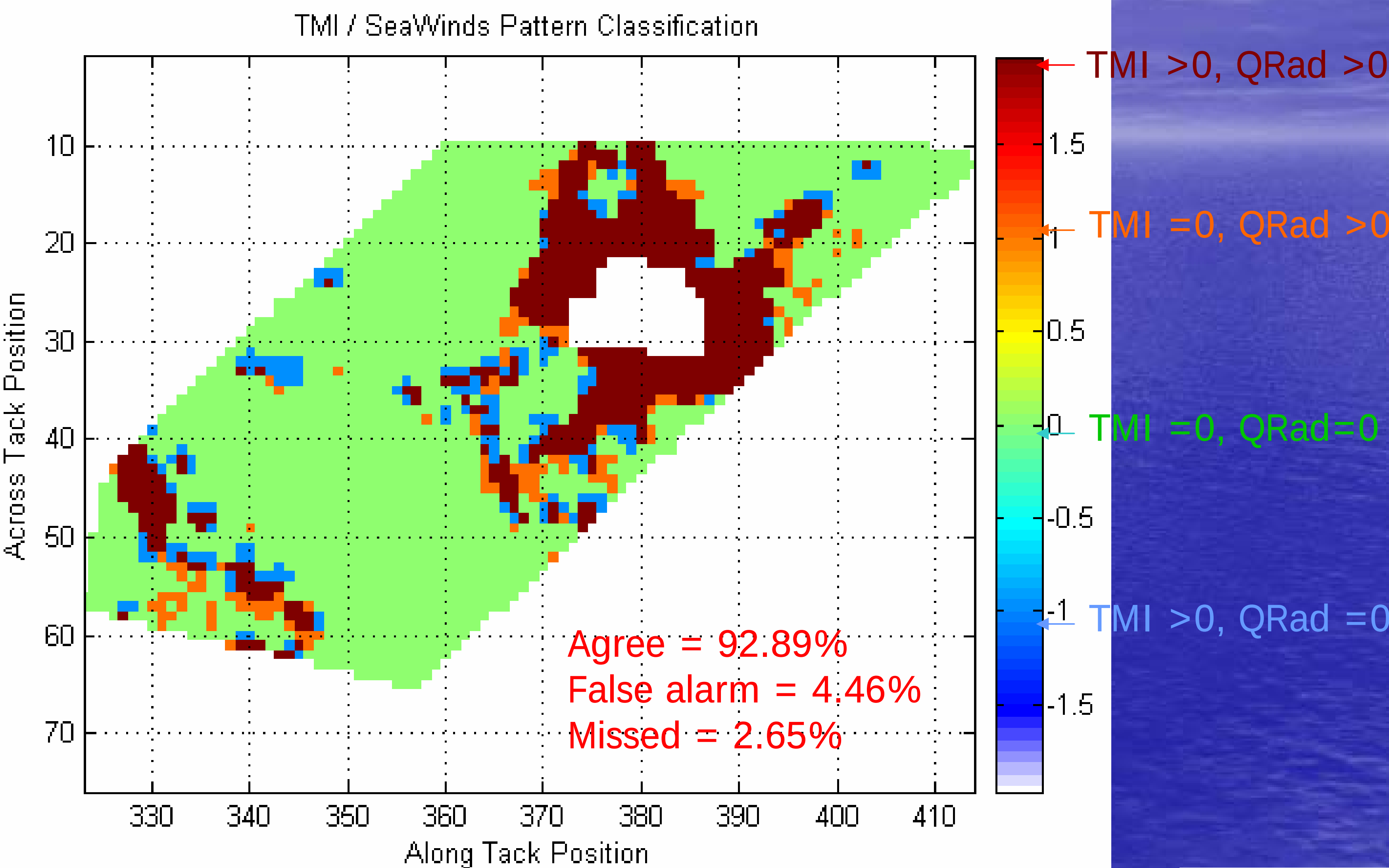
SeaWinds / TMI Rain Image Comparison



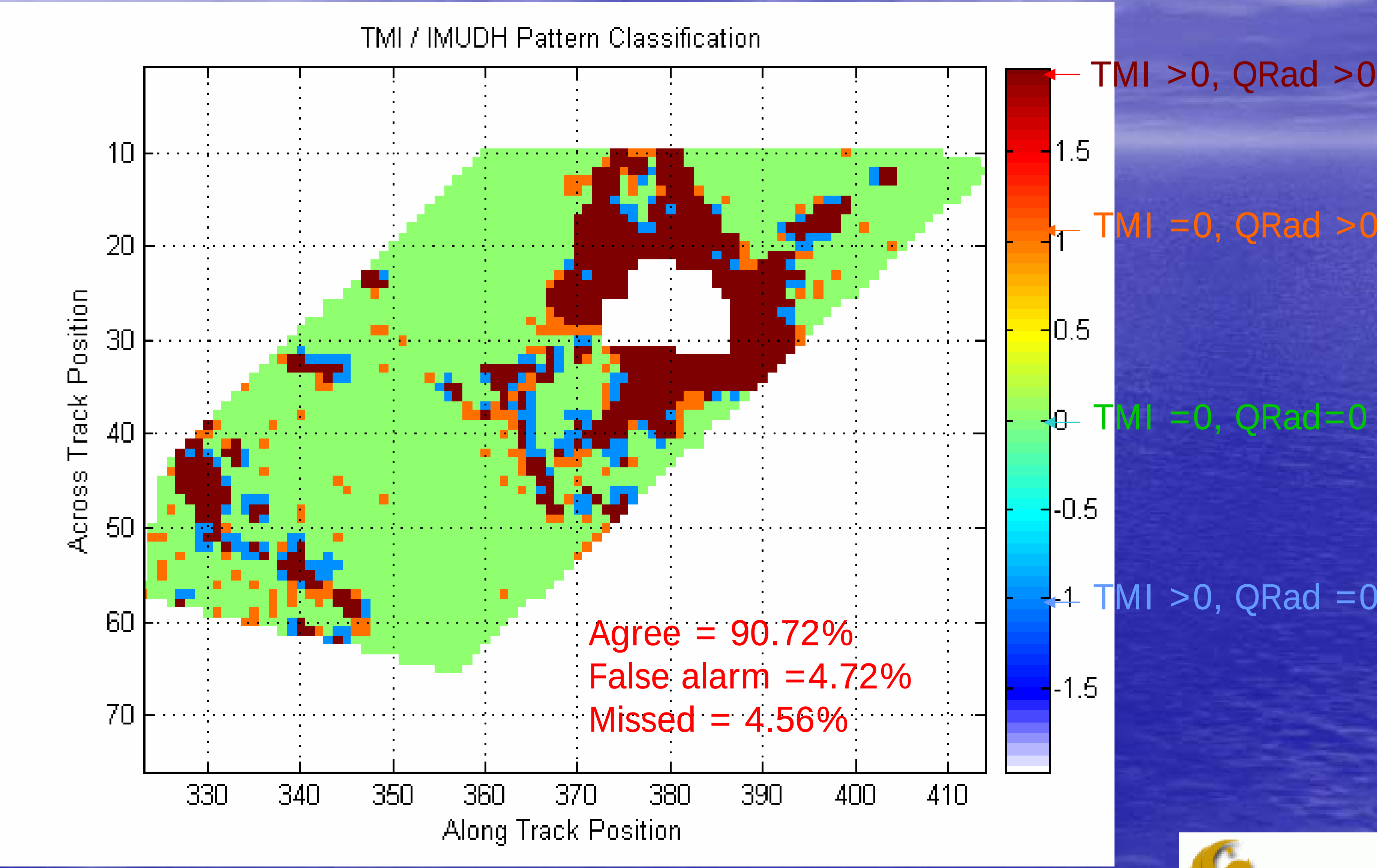
SeaWinds

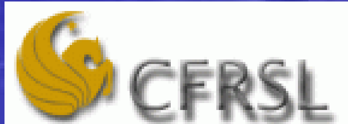
TMI

SeaWinds / TMI Rain Pattern Classification

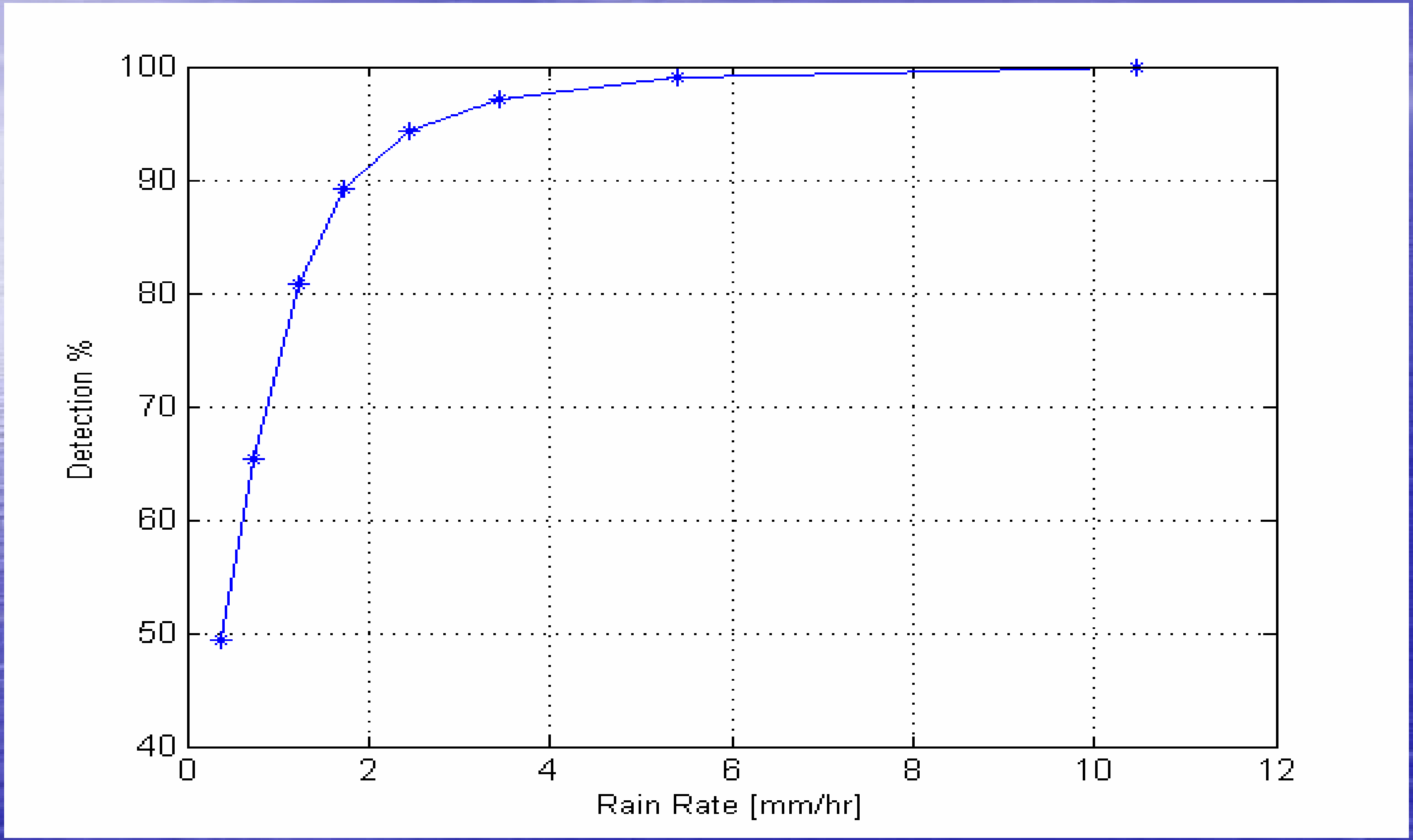


IMUDH / TMI Rain Pattern Classification





SeaWinds Rain Detection



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SeaWinds Rain Flag Statistics

Wind speed regime	Agreement %	Missed rain %	False Alarm %
$0 \leqslant ws < 3$	91.20	2.40	6.40
$3 \leqslant ws < 7$	90.38	3.46	6.15
$7 \leqslant ws < 12$	89.49	4.22	6.29
$ws \geqslant 12$	85.37	8.47	6.16
All Data	89.72	4.06	6.23

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Summary & Concluding Remarks

- The SeaWinds microwave sensor has the simultaneous capability to measure the active σ^o and the passive T_b from the Earth's surface and atmosphere
- SeaWinds measurements are sensitive to the presence of rain over the ocean
    - H-pol higher sensitivity (wider dynamic range)
- The passive T_b measurements are mainly rain dominant, while active σ^o measurements can be either wind /rain dominated

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Summary & Concluding Remarks

- Utilize measurement sensitivity to develop a passive-only and combined active / passive statistical rain retrieval algorithms for SeaWinds sensor
    - Excellent agreement with standard rain products
    - Nearly unbiased retrievals
    - Powerful "stand-alone" rain flag
- SeaWinds / QRad rain estimates can provide additional independent sampling of the oceanic rain and therefore, these rain retrievals have the potential for contributing to NASA's GPM Mission objectives of improving the global sampling of oceanic rain within 3 hour windows

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Summary & Concluding Remarks

- The passive-only QRad is implemented by NASA JPL as part of level 2B (L2B) science data product

Publications

Journal Papers:

- **Ahmad, K.A.**, Jones, W.L., Kasparis, T., Wiechecki Vergara, S., Adams, I.S., Park, J.-D., "Oceanic rain rate estimates from the QuikSCAT Radiometer, A Global Precipitation Mission path finder," *J. Geophys. Res.*, Vol 110, June 2005.

- Adams, I. S., Hennon, C. C., Jones, W. L., and **K. Ahmad**, "Evaluation of hurricane ocean vector winds from WindSat," IEEE Trans. Geosci. Rem. Sens. Vol, 44, March 2006.

- **K. A. Ahmad**, W. L. Jones, and T. Kasparis, "Estimation of Oceanic Rainfall Retrievals using passive and active measurements from SeaWinds Remote Sensor," IEEE Trans. Geosci. Rem. Sens. - *To be submited*

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Publications

❖ Conference proceedings:

- **K. A. Ahmad**, W. L. Jones, and T. Kasparis, "Oceanic Rainfall Retrievals using passive and active measurements from SeaWinds Remote Sensor," presented at IGARSS 07, Barcelona, Spain, 2007.

- **K. A. Ahmad**, W. L. Jones, and T. Kasparis, "QRad Level 2B Data product," presented at IGARSS 06, Denver, CO, 2006.

- Vasud Torsekar, Takis Kasparis, W. Linwood Jones , **Khalil A. Ahmad** and David G. Long," Oceanic Rain Identification using Multi-Fractal Analysis of QuikSCAT Sigma-0", Oceans 05, Sept. 18-23, 2005, Washington, D.C.

- Pet Laupattarakasem, W. Linwood Jones, **Khalil A. Ahmad** and Svetla Veleva "Calibration/Validation of the SeaWinds Radiometer Rain Rate Algorithm", Oceans 05, Sept. 18- 23, 2005, Washington, D.C.

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Conference proceedings:

- **Khalil A. Ahmad** , W. Linwood Jones and Takis Kasparis,"QuikSCAT Radiometer (QRad) Rain Rates for Wind Vector Quality Control", Oceans 05, Sept. 18-23, 2005, Washington, D.C.
- Adams, Ian s., Hennon, Christopher, Jones, W. Linwood and **Khalil A. Ahmad**, "Hurricane Wind Vector Measurements from WindSat Polarimetric Radiometer" , Proc. IEEE IGARSS 05, July 25-29, 2005, Seoul, Korea.
- **K. A. Ahmad**, W.L. Jones, J. Thomas-Stahle, and C. Kummerow, "Oceanic rain rates from the WindSat Radiometer," Proc. IEEE IGARSS 05, July 25-29, 2005. , Seoul, Korea.
- **Ahmad, K. A.**, Jones, W. L., and T. Kasparis, "Application of QuikSCAT Radiometer Rain Rates to Near-Real-Time Global Precipitation Estimates", Proc. IEEE IGARSS 04, Sept. 20-24, 2004, Anchorage, AK

Publications

Conference proceedings:

- **Khalil A. Ahmad** , W. Linwood Jones and Takis Kasparis,"QuikSCAT Radiometer (QRad) Rain Rates for Wind Vector Quality Control", Oceans 05, Sept. 18-23, 2005, Washington, D.C.
- **Ahmad, K. A.**, Jones, W. L. and T. Kasparis, "Precipitation Measurements using the QuikSCAT Radiometer", Proc. IEEE IGARSS 03, Jul 21-25, 2003, Toulouse, France
- Jones, W. L., **Ahmad, K. A.**, Park, J. D. and J. Zec, "Validation of QuikSCAT Radiometer Rain Rates using the TRMM Microwave Radiometer and the Special Sensor Microwave Imager", Proc. IEEE IGARSS 02, Jun 24-28, 2002, Toronto, Ontario, Canada