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:

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

- Utilize the rain sensitivity of passive $T_B$ / active $\sigma^o$ 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
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.
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

SeaWinds daily coverage ~ 90%
Background
Microwave Scatterometry

- **Scatterometer**: A special purpose radar to measure $\sigma^o$

\[
P_r = \frac{P_t \lambda^2}{(4\pi)^3} \int \int_A \frac{G^2}{R^4} \sigma^o \, dA
\]

- $\sigma^o$: Normalized Radar Cross Section (NRCS) of the ocean surface

\[
\sigma^0 = \mathcal{M}(\nu, \chi, \theta, p, \ldots)
\]

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

\[
\chi = \alpha - \varphi
\]

Bragg scattering from short waves

\[
\frac{2L}{\lambda} \sin \theta = n, \quad n = 1, 2, 3, \ldots
\]
Microwave Scatterometry

Wind speed m/s

- 8 m s\(^{-1}\), Vertical polarization
- 12.8 m s\(^{-1}\)
- 5.5 m s\(^{-1}\)

Azimuth angle

Radar Backscatter \(\sigma^0\) (dB)

Frequency (GHz): 13.9

30°
40°
50°
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 (\( \Delta T \)):

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

- \( \tau \) is the integration time
Microwave Radiometry

\[ T_{AP} = T_{UP} + \left( \frac{1}{L_a} \right) (T_{BS} + T_{SC}) \]
SeaWinds Microwave Sensor

- SeaWinds is a Ku-band microwave scatterometer flown onboard two satellite missions:
  - QuikSCAT (June ‘99 ~ present)
  - ADEOS-II (Dec. ‘02 ~ Oct. ‘03)

- Instrument description:
  - Radar: 13.4 GHz / 110 W pulse / 189 Hz PRF
  - Mass / power: 200 kg / 220 W
  - Antenna: 1-meter-diameter parabolic dish

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<thead>
<tr>
<th>Parameter</th>
<th>Inner Beam</th>
<th>Outer Beam</th>
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<tr>
<td>Polarization</td>
<td>H</td>
<td>V</td>
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<td>Elevation Angle</td>
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<td>Surface Incidence Angle</td>
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<td>55°</td>
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<td>Slant Range</td>
<td>1100 km</td>
<td>1245 km</td>
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<td>3 dB Beam Dimensions (az × el)</td>
<td>1.8° × 1.6°</td>
<td>1.7° × 1.4°</td>
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<td>3 dB Footprint Dimensions (az × el)</td>
<td>34 × 44 km</td>
<td>37 × 52 km</td>
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<td>Peak Gain</td>
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<td>Rotation Rate</td>
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<td>Along Track Spacing</td>
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</tr>
<tr>
<td>Along Scan Spacing</td>
<td>15 km</td>
<td>19 km</td>
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</table>
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
SeaWinds Microwave Sensor

Outer beam
V-Pol
@ 54°

Inner beam
H-Pol
@ 46°

360° Azimuth Scan

900 km
700 km
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 $\sigma_{ex}^0$ vs. IRR relationship

- Trained using near-simultaneous collocations with TRMM Microwave Imager (TMI) oceanic rain rates
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.
SeaWinds sampling – 3 hr window
Daily average revisit time – 3 hr window

TMI & SSMI (3 satellites)

QRad, TMI & SSMI (3 satellites)
SeaWinds Rain Algorithm

- Passive-only (QRad)
Collocation Database

1st Quarter ~ 106
2nd Quarter ~ 121
3rd Quarter ~ 167
4th Quarter ~ 27
The polarized microwave “excess brightness” ($T_{ex_p}$) is proportional to the integrated rain rate

$$T_{ex_p} = T_{b\text{meas}} - T_{b\text{ocean}} - T_{b\text{w.speed}}$$

- $T_{b\text{ocean}}$ : Ocean background (includes atmospheric Emissions without rain)
  - based upon 7 year SSMI climatology
- $T_{b\text{w.speed}}$ : Wind speed brightness bias
Wind Speed Correction

- Calculate polarized wind speed correction:

\[
T_{ex} = T_{b \text{ meas}} - T_{b \text{ ocean}}
\]

- \(T_{b \text{ meas}}\): rain free brightness temperature measurements
- \(T_{b \text{ ocean}}\): ocean background (includes atmospheric Emissions without rain)
  - based upon 7 year SSMI climatology
H-Pol “Tex vs. IRR” Transfer Function
QRad Rain Calculations

- Calculate Polarized Rain Rates:

\[ IRR_p = \sum_{i=0}^{n} a_{i,p} \cdot (T_{EX,p})^i \quad (n = 3) \]

- Calculate Combined Rain Rates:

\[ IRR_{QRad} = c_0 + c_1 (\alpha \cdot IRR_h + \beta \cdot IRR_v) \]

- Calculate Coefficients:

\[
\min \sqrt{\frac{\sum_{i=1}^{N} (IRR_{TMI} - IRR_{QRad})^2}{N}}
\]
QRad Algorithm Block Diagram

QRad Tb (L2A) → Calc. Polarized Excess Brightness $T_{ex}$ @ 25 km → Ocean Tb background

NCEP wind Speed → Spatial Filtering 3x3 Window

→ Using ($T_{ex} - IRR$) Calc. Polarized Instantaneous Rain Rate

→ Combine using a weighted average

→ Apply threshold

Instantaneous Rain Rate Product
By orbit, 25 km resolution
Overall Rain Scatter

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

\[ T_{ex}_{total} = T_{ex}_{rain} + T_{ex}_{wind} \]

**H-Pol**

**V-Pol**

![Graphs showing relationship between wind speed and rain rate for H-Pol and V-Pol](image)

- **Rain rate (km * mm/hr)** vs. **Wind speed [m/s]**
- **Wind speed (m/s)**

Rain rate increases with wind speed for both H-Pol and V-Pol, indicating a radiometric response to wind and rain conditions.
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
QRad / TRMM 2A12 Instantaneous Rain Rate
Rain Image Comparison

QRad

TMI
Rain Scatter

![Graph showing scatter plot with axes labeled QRad IRR [km*mm/hr] and TMI IRR [km*mm/hr]]
QRad / TMI Rain Pattern Classification

Agree = 89.03%
False alarm = 5.07%
Missed = 5.90%
Zonal Average Rain Rate

0° N to 20° N

Average Rain Rate (mm/hr)

Pentad number

QRad

TMI
Monthly Average Rain Rate

QRad March 2000 [mm/hr]

TMI March 2000 [mm/hr]

SSM/I F13 March 2000 [mm/hr]
SeaWinds Rain Algorithm

* Active Sigma-0 Model
Rain Effects on SeaWinds $\sigma^o$

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

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

- $\sigma^0_{\text{meas}}$ : Measured SeaWinds backscatter
- $\sigma^0_{\text{wind}}$ : Wind induced backscatter
- $\sigma^0_{\text{Ex-rain}}$ : Excess-backscatter due to rain
- $\alpha$ : Two-way path attenuation
SeaWinds Rain Excess Backscatter and Attenuation Models

![Graph showing SeaWinds Rain Attenuation and Rain Excess Backscatter against Rain Rate.]
Sigma-0 Forward Model Validation (1)

Bin #12, Npts = 11348, Rain bin average = 1.01

Bin #13, Npts = 12518, Rain bin average = 1.5074

H-Pol

H-Pol Wind speed Sigma-0

V-Pol

V-Pol Wind speed Sigma-0

R = 1.0 km*mm/hr

R = 1.5 km*mm/hr
Sigma-0 Forward Model Validation (2)

Bin #20, Npts = 11186, Rain bin average = 24.4935

H-Pol

R = 25.5 km*mm/hr

V-Pol

Bin #21, Npts = 7187, Rain bin average = 36.4418

R = 36.4 km*mm/hr
Sigma-0 Forward Model Validation (3)

H-Pol

R = 79.7 km*mm/hr

V-Pol

R = 116.2 km*mm/hr
Scatterometer Response

\[ \sigma_{\text{meas}}^0 (r, u, \chi, p, \theta) = \alpha(r, p, \theta) \cdot \sigma_{\text{wind}}^0 (u, \chi, p, \theta) + \sigma_{\text{excess}}^0 (r, p, \theta) \]
SeaWinds Rain Algorithm

- Combined Passive / Active Retrievals
Methodology

QRad Rain

Calculate Rain Attenuation, $\alpha$
(using attenuation model)

SeaWind $\sigma^0$ (L2A)

Calculate Polarized Excess Backscatter, $\sigma_{ex}$
(25 km WVC grid)

NCEP Wind Vector (L2B)

Calculate Surface Backscatter, $\sigma_{wind}$
(using QSCAT-1 GMF)

Combine Rain
(using a weighted average)

Earth Locate & Average

Instantaneous Rain Rate Product
by orbit, 25 km WVC grid

Average Rain Rate Product
SeaWinds Rain Calculations

Calculate Polarized Excess Backscatter:

\[ \sigma_{ex}^0 (r, p, \theta) = \sigma_m^0 (r, u, \chi, p, \theta) - \alpha(r, p, \theta) \cdot \sigma_{ws}^0 (u, \chi, p, \theta) \]

Minimize Objective Function:

\[ J = \sum_{i=1}^{N} \left( \frac{\sigma_{meas}^{ex,i} - \sigma_{model}^{ex,i}}{\delta_i^2} \right)^2 \]

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

Calculate Combined Rain Rates:

\[ IRR_{SeaWinds} = \gamma_h \cdot IRR_{hPA} + \gamma_v \cdot IRR_{vPA} \]
SeaWinds / TMI Rain Scatter
SeaWinds / TMI Rain Scatter

Mean Windspeed = 2.214 m/s

0 ≤ ws < 3

Mean Windspeed = 5.2663 m/s

3 ≤ ws < 7

Mean Windspeed = 8.9643 m/s

7 ≤ ws < 12

Mean Windspeed = 13.6476 m/s

ws ≥ 12

SeaWinds IRR [km*mm/hr]

TMI IRR [km*mm/hr]
SeaWinds / QRad Comparison

\[
\eta_{ex} = \frac{\sum_{i=1}^{N} \sigma_{ex,i}^0 (r, p, \theta)}{\sigma_{meas,i}^0 (r, u, \chi, p, \theta)}
\]

80 %
SeaWinds Rain Algorithm

- Validation of SeaWinds Rain Retrievals
Validation Dataset

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

TMI

SeaWinds

Rain Rate [km*mm/hr]
Rain Error Statistics

![Graph showing rain error statistics for different wind speeds.](image)

- **Low Wind** (ws ≤ 4 m/s)
- **Medium Wind** (4 < ws < 10 m/s)
- **High Wind** (ws ≥ 10 m/s)
SeaWinds / TMI Rain Image Comparison

SeaWinds Rain [km$^2$mm/hr]

Land Mask

TMI Rain [km mm/hr]

SeaWinds

TMI
SeaWinds / TMI Rain Pattern Classification

Agree = 92.89%
False alarm = 4.46%
Missed = 2.65%
IMUDH / TMI Rain Pattern Classification

TMI >0, QRad >0
TMI =0, QRad >0
TMI >0, QRad =0
TMI =0, QRad=0
TMI >0, QRad =0

Agree = 90.72%
False alarm =4.72%
Missed = 4.56%
SeaWinds Rain Detection

[Graph showing the relationship between Rain Rate [mm/hr] and Detection %]
# SeaWinds Rain Flag Statistics

<table>
<thead>
<tr>
<th>Wind speed regime</th>
<th>Agreement %</th>
<th>Missed rain %</th>
<th>False Alarm %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 \leq ws &lt; 3$</td>
<td>91.20</td>
<td>2.40</td>
<td>6.40</td>
</tr>
<tr>
<td>$3 \leq ws &lt; 7$</td>
<td>90.38</td>
<td>3.46</td>
<td>6.15</td>
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<tr>
<td>$7 \leq ws &lt; 12$</td>
<td>89.49</td>
<td>4.22</td>
<td>6.29</td>
</tr>
<tr>
<td>$ws \geq 12$</td>
<td>85.37</td>
<td>8.47</td>
<td>6.16</td>
</tr>
<tr>
<td>All Data</td>
<td>89.72</td>
<td>4.06</td>
<td>6.23</td>
</tr>
</tbody>
</table>
Summary & Concluding Remarks

- The SeaWinds microwave sensor has the simultaneous capability to measure the active $\sigma^o$ 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 $\sigma^o$ measurements can be either wind /rain dominated.
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
The passive-only QRad is implemented by NASA JPL as part of level 2B (L2B) science data product.
Publications

**Journal Papers:**


Publications

Conference proceedings:


- 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.
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.


Publications

❖ Conference proceedings:

