Advancing QuikSCAT Wind and Rain Retrieval

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Outline

- QuikSCAT Land/Ice Climate Record (*Poster*)
  - 10 years of Earth observations

- Rain effects on scatterometer measurements
- Retrieval methods: Simultaneous Wind/Rain (SWR), Rain-only (RO), Wind-only (WO)
  - Emphasis on scatterometer-only methods (for application with QuikSCAT)
- Bayes estimator selection & prior distributions
- Results
Surface Effects of Rain on Radar Measurements

- Splash products scatter the scatterometer signal (surface scattering from rain splash)
- Turbulence under the water attenuates the Bragg wave spectrum (Bragg scattering)
- Sea surface roughness also affected by the airflow associated with rain cell
- Atmospheric backscattering and attenuation (volume scattering from rain)

What is the “wind” do we want to measure?
Rain/Wind Backscatter Model

- Model for measured backscatter $\sigma_M^o$

\[
\sigma_M^o = (\sigma_W^o + \sigma_{sr}^o) \alpha_R + \sigma_R^o
\]

- Radar signal scattered by falling droplets $\sigma_R^o$

- Surface signal attenuated by atmospheric rain $\alpha_R$

- Surface wind-induced $\sigma_W^o$ backscatter perturbed by rain striking the water $\sigma_{sr}^o$

Simplified equivalent model:

\[
\sigma_M^o = \sigma_W^o \alpha_R + \sigma_S^o
\]
Attenuation Model

- Derived from collocated TRMM-PR or AMSR and QuikSCAT measurements
- Model as quadratic function of rain rate in dB
- Beam filling & 3-D effects
Effective Surface Scattering Model

- Derived from collocated TRMM-PR or AMSR and QuikSCAT measurements
- Model as quadratic function of rain rate in dB

- Assume conventional wind GMF
Wind Rain Backscatter Regimes

\[ \sigma_M^o(s, \chi, R, \ldots) = M(s, \chi, \ldots) \alpha_R(R) + \sigma_{\text{eff}}(R) \]

- **Regime 1**: rain dominates wind backscatter – poor quality wind estimates (10% of rain cases*)
- **Regime 2**: both wind and rain important – can retrieve wind and rain rate (34% of rain cases*)
- **Regime 3**: rain effects insignificant – wind estimates unaffected by rain (56% of rain cases*)

- Note: globally, about 4% of all QuikSCAT data affected by rain

* From collocated TRMM PR and QuikSCAT data in tropics
Simultaneous Wind/Rain Retrieval

- Scatterometer-only rain estimation is possible for QuikSCAT inner swath
  - Rain direction estimates have greater variability than wind-only retrieval (noisier wind when estimating rain)
  - SWR is an effective rain flag
- Beam-filling effects and mis-collocation of sigma-0 measurements increases variability


Wind and Rain Retrieval

**Noise model**

\[
p(\sigma^o_M | s, d, r) = \prod_k \frac{1}{\sqrt{2\pi\varsigma^2}} \exp\left\{-\frac{1}{2} \frac{(\sigma^o_M - \sigma^o_P)^2}{\varsigma^2}\right\}
\]

\[
\varsigma^2 = (1 + K_{pc}^2)(\alpha_R^2 \sigma^o_W (1 + (1 - 2\alpha_R + \alpha_R^2)K_{pa}^2)(1 + K_{pm}^2) + \sigma^2_E (1 + K_{pe}^2)) - \sigma^o_P^2
\]

\[
K_{pc}^2 = \sqrt{\alpha + \frac{\beta}{\sigma^o_P} + \frac{\gamma}{\sigma^o_P^2}}
\]

**SWR Maximum Likelihood Estimation**

\[
(\hat{S}, \hat{D}, \hat{R})_{MLE} = \arg\max(s, d, r | \sigma^o_M) \left\{-\frac{k}{2} \log(2\pi\varsigma^2) - \frac{1}{2} \sum_k \frac{(\sigma^o_M - \sigma^o_P)^2}{\varsigma^2}\right\}
\]
Estimator Limitations

- **Simultaneous wind/rain (SWR)** retrieval performance can be poor under unintended conditions, i.e. w/o both rain and wind
  - Wind-only (WO) retrieval better when no rain
  - Rain-only (RO) retrieval better when rain dominates backscatter

- Each estimator is best in a certain regime
  - How to decide which regime to use?
Problem

- Selecting best estimator to use

Possible mechanisms:
- Compare to true wind/rain
- Use scattering regime calculated by SWR
- Likelihood Ratio test
- M-ary Bayes decisions
Estimator Regimes

![Graphs showing different regimes of estimator performance based on wind speed and rain rate.](image)
Bayes Decision Overview

- Risk function
  \[ R(\vartheta, \phi(x)) = \sum_x L[\vartheta, \phi(x)] f_{x|\theta}(x | \vartheta) \]

- Bayes risk function
  \[ r(F_\theta, \phi) = \int_\vartheta R(\vartheta, \phi(x)) f_\theta(\vartheta) d\vartheta \]
  \[ r(F_\theta, \phi) = \int_\theta \sum_x L[\vartheta, \phi(x)] f_{x|\theta}(x | \vartheta) f_\theta(\vartheta) d\vartheta \]

- Bayes Decision
  \[ \phi_B = \arg\min_\phi r(F_\phi, \phi) \]

Variable Descriptions

- Parameter: \( \vartheta \)
- Observations: \( x \)
- Decision rule: \( \phi(x) \)
- Loss function: \( L[\vartheta, \phi(x)] \)
- Priors: \( f_\theta(\vartheta), f_{x|\theta}(x | \vartheta) \)
Loss Function

- **Definition**

\[ L[\vartheta, \phi_i(x_j)] = C(\vartheta, x_j)(\eta \delta_{ij} + \mu(1 - \delta_{ij})) \quad \delta_{ij} = 1 \text{ when } i = j \]

\[ C(\vartheta, x_j) = (\vartheta - x_j)^2 \]

- **Weight Error according to decision**

\[ (\eta \delta_{ij} + \mu(1 - \delta_{ij})) \]

- **Normalization matrix**

\[ (\vartheta - x_j)^2 = (\vartheta - x_j)^T N(\vartheta - x_j) \]
Bayes Estimator Selection

\[ r(F_\theta, \phi_i) = \int \sum_{\theta j=1,3} L[\varphi, \phi_i(x_j)]f_{X|\theta}(x_j \mid \varphi)f_\theta(\varphi)d\varphi \]

\[ r(F_\theta, \phi_i) = \int \sum_{\theta j=1,3} C(\varphi, x_j)[\eta \delta_{ij} + \mu(1 - \delta_{ij})]f_{X|\theta}(x_j \mid \varphi)f_\theta(\varphi)d\varphi \]

\[ r(F_\theta, \phi_i) = \int C(\varphi, x_i)[\mu + (\eta - \mu)f_{X|\theta}(x_i \mid \varphi)]f_\theta(\varphi)d\varphi \]

\[ r(F_\theta, \phi_i) = \int (\varphi - x_i)^2[\mu + (\eta - \mu)f_{X|\theta}(x_i \mid \varphi)]f_\theta(\varphi)d\varphi \]

\[ \phi = \arg \min_i r(F_\theta, \phi_i) \]
Application to Wind and Rain Estimation

- Choose normalization $N$
- Calculate wind-rain prior $f_{\theta}(\vartheta)$
- Estimate conditional prior $f_{X|\theta}(x_i | \vartheta)$
- Choose weights to meet performance criteria
Wind-Rain Prior Estimate Method

- NCEP winds
  - Numerically predicted
  - Low resolution, temporally and spatially
  - Known biases
    - Underestimate high wind speed compared to QuikSCAT

- TRMM PR rain rates
  - Measured rain

- Assume:
  - Uniform distributed wind direction
  - Weibull distributed wind speed

\[ 10 \log_{10} (f_\theta(v)) \]
Conditional Prior \( f_{X \mid \theta}(x_i \mid \vartheta) \)

- Probability of an estimator having minimum squared error given the wind conditions
  - Possible priors
    - Tabulate estimator performance
    - Use noise model to determine probability of a regime for each wind condition
- Noise model
  - Signal to interference ratio (SIR) of wind and rain
Conditional Prior

- Rain Fraction

- A threshold on rain fraction determines estimator boundaries

- Noise model gives conditional prior

\[ r(S, \chi, R) = \frac{M_{RO}(R)}{M_{WO}(S, \chi) \alpha(R)} \]

\[ X = \begin{cases} 
0: & r(S, \chi, R) < A \\
1: & A < r(S, \chi, R) < B \\
2: & r(S, \chi, R) > B 
\end{cases} \]

\[ f_{x|\theta}(x_0 \mid \psi) = P(r(S, \chi, R) < A) \]
\[ f_{x|\theta}(x_1 \mid \psi) = P(A < r(S, \chi, R) < B) \]
\[ f_{x|\theta}(x_2 \mid \psi) = P(r(S, \chi, R) > B) \]
Choose Weights

- Performance criteria can include
  - Rain false alarm rate or probability of detection (SWR only used when rain rate is above a threshold)
  - Speed accuracy in raining/non-raining conditions

\[(\eta \delta_{ij} + \mu (1 - \delta_{ij}))\]
Smoothing of Estimator Choice

- Estimator selection sensitive to noise
  - Slight noise changes result in selected estimator changes
- Spatial filtering with threshold
  - Correct for differences in the number of ambiguities
UHR Case Study

QuikSCAT Rain-only

TRMM PR Rain

QuikSCAT SWR Rain

QuikSCAT Wind-only

QuikSCAT SWR Wind

Rain

Wind
Bayes Estimator Results

Regimes
Bayes Estimator Selection
Bayes Estimator Selection (smoothed)

TRMM PR Rain
Bayes Wind
Bayes Rain
UHR Case Study

Rain-only

TRMM PR Rain

SWR Rain

Wind-only

Rain

Wind

SWR Wind
Bayes Estimator Results

Regimes

Bayes Estimator Selection

Bayes Estimator Selection (smoothed)

TRMM PR Rain

Bayes Wind

Bayes Rain
UHR Case Study

Rain-only

TRMM PR Rain

SWR Rain

Wind-only

Rain

Wind

SWR Wind
UHR Case Study

Rain-only

TRMM PR Rain

SWR Rain

Wind-only

= Rain Bands

Rain Wind
Bayes Estimator Results

Regimes
Bayes Estimator Selection
Bayes Estimator Selection (smoothed)
TRMM PR Rain
Bayes Wind
Bayes Rain
## Summary Wind Speed Statistics

**UHR**

### Sample set

<table>
<thead>
<tr>
<th>Condition</th>
<th>Bias</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>WO wind Rain &gt; 0</td>
<td>1.89</td>
<td>5.22</td>
</tr>
<tr>
<td>Bayes wind Rain &gt; 0</td>
<td>-0.096</td>
<td>4.98</td>
</tr>
<tr>
<td>SWR wind Rain = 0</td>
<td>-2.35</td>
<td>5.73</td>
</tr>
<tr>
<td>Bayes wind Rain = 0</td>
<td>-1.52</td>
<td>2.75</td>
</tr>
</tbody>
</table>
## Summary

### Benefits
- Computationally simple
  - Expected error can be pre-computed for all wind-rain vectors
- Estimates selected in correct operating regimes

### Limitations
- Determining priors
  - Model for wind-rain distribution
  - Model for regime given wind-rain vector
  - True wind data non-existent
- Wind-Rain error-scaling
  - Physical wind-rain relationship difficult to quantify
- Estimator computation
  - All estimators always fully computed
Conclusions

- Preliminary results promising
  - Reduced bias and MSE
  - Visually good rain estimates, improved wind estimates
  - Effective as a rain flag
- Prone to noise
  - Mitigated with spatial filtering
- Ongoing accuracy and refinement studies
Coincident SAR/Scatterometer Set

- C-band RADARSAT ScanSAR images 9/29/05 ~00 OTC
- NEXRAD
- QuikSCAT (within few mins)
- H*wind

19 Nov 2008 - DGL

Best track location of Katrina Eye

Eye

Rain cell

Rain band

SWA image A

SWA image B
Retrieved SAR Winds

- “Recalibrate” sigma to CMOD5 GMF using H*Winds
- Uncertainty/error in H*wind field direction
- Limitation of GMF at high winds, Rain effects

Rain Atmospheric Attenuation and Backscatter on SAR Measurements

- Atmospheric attenuation factor
- Path integrated attenuation (PIA) in dB
- Atmospheric attenuation
- Volume backscattering coefficient
- Observed volume backscattering cross-section
- Atmospheric backscatter

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Simultaneous Wind-Rain Retrieval

- Measurement model
  \[ \sigma^o = M_R(S, \chi, P, \omega, I, R) + \text{noise} \]
  \[ p(\sigma^o \mid S, \chi, R) = \prod_k \frac{1}{\sqrt{2\pi\zeta^2}} \exp \left\{ -\frac{1}{2} \frac{(\sigma^o - M_R(S, \chi, P, \omega, I, R))^2}{\zeta^2} \right\} \]

- MLE – log-likelihood function
  \[ (\hat{S}, \hat{\chi}, \hat{R})_{MLE} = \arg \max (S, \chi, R \mid \sigma^o) \left\{ -\frac{k}{2} \log(2\pi\zeta^2) - \frac{1}{2} \sum_k \frac{(\sigma^o - M_R(S, \chi, P, \omega, I, R))^2}{\zeta^2} \right\} \]

- UHR implementation
Rain cell at incidence angles between 22 and 23.6 degrees (C-band)

Attenuation
Significant at heavy rain

Atmospheric backscatter

Insignificant at low incidence angle

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Rain cell at incidence angles between 28 and 31.7 degrees (C-band)

SAR signature

Rain rate

Normal space

Log-Log
Rain cell at incidence angles between 44 and 45.7 degrees (C-band)

SAR signature of rain cell

Wind speed

Wind direction

19 Nov 2008 - DGL
Rain cell at incidence angles between 44 and 45.7 degrees (C-band)

SAR signature

Rain rate

Log-Log

Normal space
Problem Setup

**Variable Descriptions**
- Parameter: $\vartheta$
- Observations: $x$
- Decision rule: $\phi(x)$
- Loss function: $L[\vartheta, \phi(x)]$
- Prior: $f_\theta(\vartheta), f_{x|\theta}(x | \vartheta)$

**Estimator Selection**
- True Wind/Rain Vector
- Estimates: $x_j = \hat{\vartheta}_j : j \in \{0,1,2\}$
  \[ \phi_i(x_j) \Rightarrow \hat{\vartheta}_i \]
  \[ L[\vartheta, \phi_i(x_j)] \]
UHR SWR Rain Accuracy

- TRMM vs. QuikSCAT rain rates
- High variance –
- Regime 0 – biased high, wind backscatter mapped into rain space
- Regime 1 – unbiased wind & rain
- Regime 2 – biased low, rain backscatter mapped into wind space

19 Nov 2
UHR SWR Co-location Examples