Improved Modeling and Retrieval of Convective Precipitation from Spaceborne Passive Microwave Measurements

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Outline

• Radiative transfer validation using high-resolution aircraft measurements and a cloud resolving model
  – Simulation methodology
  – NAST-M aircraft sounder
  – Brightness temperature histograms

• Retrieval of rain rate using passive microwave observations
  – Simulation of ATMS and MIS measurements of precipitation
  – Neural network retrieval methodology
  – Retrieval performance assessment for preliminary, idealized cases

• Summary and future work
Background: Passive Microwave Sensing of Precipitation
Radiative Transfer Modeling and Validation

• Co-located brightness temperature observations and rain rates are needed to train precipitation retrieval algorithms
  – In situ rain rate measurements are sparse over most of the world (especially over ocean)
  – Numerical weather prediction (NWP) data and radiative transfer (RT) models can be used to produce training data

• Model validation is very important – comparison of NWP/RT simulations with NAST-M observations offers insight

• The NAST-M airborne sensor offers well-calibrated, high-resolution (2.5-km) measurements with channels in the 60, 118, 183, and 425-GHz bands

• Two radiative transfer models considered:
  – TBSCAT: Integration of trial functions using initial values
  – TBSOI: Combines “Successive Order of Scattering”, adding-doubling, and multiple streams (discrete ordinates)
Radiance Simulation Methodology

- **CRM** = MM5 1-km saved every 15 min
- **RTM** = multiple-stream radiative transfer solution (TBSCAT† or TBSOI*)
- Simulated NAST-M radiances
- Developed and adapted MIT software to LLGrid parallel computing facility


Radiative Transfer / NWP Interface Issues

Each level requires hydrometeor density per drop radius.

Marshall-Palmer

Sekhon-Srivastava

US Standard 1976

MM5

<table>
<thead>
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<th>Pressure [mb]</th>
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<td>850</td>
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<table>
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<th>Mass Density [g/m³]</th>
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Radius [mm]

- Rain water
- Snow
- Graupel

100 mb
NAST-Microwave (Airborne Sensor)

- Cruising altitude: ~17-20 km
- Cross-track scanning
- Scan angle: -65° to 65°
- 7.5° antenna beam width (FWHM)
- 2.5-km nadir footprint diameter
- Swath width of ~100 km
- Eight channels at 54 GHz
- Nine channels at 118 GHz
- Six channels at 183 GHz
- Seven channels at 425 GHz
- Nadir-viewing camera

AMSU-A’s diameter at nadir is ~50 km (3.3° IFOV)

Footprint diameter at nadir is ~2.6 km

AMSU-B ~15 km (1.1° IFOV)
Radiative Transfer Validation

* Black asterisks indicate NAST-M observations from ten flights, most during the 2002 CRYSTAL-FACE deployment (41,670 measurements)

* Red asterisks indicate simulated measurements (535,126) consisting of eight hours of MM5 simulation per day (15-min. increments) using a two-stream version of TBSCAT

* Blue asterisks indicate simulated measurements using a ten-stream version of TBSCAT

* Green asterisks indicate simulated measurements using a ten-stream version of TBSCAT; heaviest precipitation was replaced with a TBSOI simulation (for frequencies > 60 GHz)

Methodology based on:

Simulated versus Observed
Black = Observations, Red = Simulations

TBSCAT$_{10}$ + TBSOI$_4$ yields very good agreement, even at the higher precipitation rates (Low T$_b$)

Discrepancies at the warmest T$_b$’s are due primarily to misclassification of precipitating pixels

Very cold T$_b$’s observed near 183 GHz present the greatest challenge – more work is needed
ATMS Simulations vs. AMSU Observations Near 183-GHz

MM5 simulations performed by C. Surussavadee

Precipitation Retrieval Algorithm Methods

• Most current operational algorithms use variational approaches, Bayesian inversion
  – Advantage: Incorporates physics into algorithm
  – Disadvantages
    Computationally intensive
    Difficult to guarantee statistical optimality

• Alternative: Nonlinear regression
  – Neural networks
    Fast, simple, and approach statistical optimality
    Requires no a priori assumptions about statistics of data
  – Preprocessing can be used to transform data into a representation suitable for precipitation estimation
  – Algorithms based on neural networks can produce precipitation estimates in real time
Neural Network Retrieval Algorithm

• Input: all channels and secant of scan angle (Cross-track sensors)

• Target output: MM5 surface rain rate (mm/hr)

• Only pixels with rain rate > 1 mm/hr

• 25 storms over ocean divided among training (9), validation (8), and testing sets (8)

• Total of 10983 ATMS & 56300 MIS pixels

• Training:
  – Levenberg-Marquardt back propagation method, up to 100 epochs
  – Training stopped if RMS error over validation set does not decrease for each of six consecutive epochs
  – Nguyen-Widrow initialization method
  – 1 hidden layer with up to 10 nodes, 1 output node
  – 10 nets trained per topology
MM5 Output for Two Test Cases
(Pacific Ocean)
ATMS Rain-Rate Retrieval Images
Produced at 5.2° Resolution
MIS Rain-Rate Retrieval Images
Produced at 1.5° Resolution
Rain-Rate Retrieval Error Scatter Plots

ATMS Retrieval

MIS Retrieval

RMS Error: 0.83 mm/h
52% reduction of a priori

RMS Error: 1.42 mm/h
61% reduction of a priori
Next Steps

• Simulation infrastructure is in place that will allow generation and optimization of precipitation/radiance training data sets

• Retrieval results presented here are idealistic and preliminary. We need to improve:
  – Comprehensiveness of training data
  – Spatial processing in retrieval algorithm
  – Optimization of neural network topology

• Algorithm enhancements are underway to allow retrieval of precipitation over land

• Radiative transfer optimization/validation will continue to draw from high-resolution NAST-M data sets.
Summary

• Fundamental building blocks are in place for complete precipitation retrieval system:
  – NWP/RT models to produce training data
  – Model validation using NAST-M
  – Retrieval methodology based on neural networks

• Recent studies highlight the need for accurate radiative transfer modeling in regions of heavy precipitation

• AMSU experience and preliminary studies show ATMS can provide accurate, high-resolution, global precipitation products

• Future work will focus on NWP data generation, RT model validation and improvement using NAST-M, and retrieval algorithm optimization
Overview

• Experience with AMSU on POES/Aqua indicates that ATMS could provide accurate retrievals of precipitation parameters
  – Surface rain rate over ocean and land
  – Snowfall

• Delay of MIS deployment until 2016 leaves gap in NPOESS precipitation product availability

• In collaboration with MIT campus group (Prof. Dave Staelin), we are developing real-time, neural-network-based precipitation algorithms for ATMS and MIS (NPP/NPOESS)

• Components of current research:
  – Radiative transfer modeling and validation
  – Retrieval development
Microwave Radiance Simulation

- **MM5 Atmospheric Circulation Model**
  - Provides temperature profile, water vapor profile, hydrometeor profile, ...
  - Used Goddard hydrometeor model (Tao & Simpson, 1993)

- **Radiative Transfer**
  - MW: TBSCAT due to Rosenkranz (IEEE TGRS, 8/2002)
    - Multi-stream, initial-value
    - Improved hydrometeor modeling due to Surussavadee & Staelin (IEEE TGRS, 10/2006)
  - IR: SARTA

- **Filtering ("Satellite Geometry" toolbox for MATLAB)**
  - Accurately filtering $T_B$’s on MM5 grid to correct geolocation & resolution
  - Toolbox simplifies software development & minimizes approximation errors
ATMS:
Advanced Technology Microwave Sounder

• Heritage
  – AMSU-A/B (NOAA-15, NOAA-16, NOAA-17)
  – AMSU/HSB (Aqua)
  – AMSU-A/MHS (NOAA-18, METOP-A)

• Cross-track scanning, 2500-km swath

• Bands
  – Window channels: 23.8, 31.4, 89.0, 165.5 GHz
  – Channels in 60-GHz $O_2$ band
  – Channels in 183.31-GHz $H_2O$ band

• Improvements over AMSU
  – Improved spatial resolution in 60-GHz band (35km vs. 50km)
  – Improved spatial sampling in 60-GHz band (15km vs. 50km)
  – Identical spatial sampling across all channels
  – Improved spectral sampling in 183-GHz band (5 channels vs. 3 channels)
  – Swath width (~2500km vs ~2100km)
MIS: Microwave Imager/Sounder
(Conically Scanning)

• MIS specifications TBD
• Heritage: SSMIS, TMI, AMSR-E, WindSat
• For the simulations in this presentation, the following channel set was used:
  – 6.625 GHz (V/H)
  – 10.65 GHz (V/H)
  – 18.7 GHz (V/H)
  – 23.8 GHz (V/H)
  – 36.5 GHz (V/H)
  – 50.3 GHz (V)
  – 52.24 GHz (V)
  – 53.57 GHz (V)
  – 54.905 GHz (V)
  – 55.49 GHz (V)
  – 56.66 GHz (V)
  – 59.38 GHz (V)
  – 59.94 GHz (V)
  – 89.0 GHz (H,V)
  – 166 ± 0.7875 GHz (V)
  – 183.31 ± 0.7125 GHz (V)
  – 183.31 ± 3.10 GHz (V)
  – 183.31 ± 7.7 GHz (V)
Mesoscale and Cloud Models

• Why use mesoscale models?
  – Explicit forecasts of cloud and precipitation hydrometeors
    Clouds
    Convective storms
  – Detailed initial condition specification
    Terrain
    Land-use
    Meteorological observations

• Approach
  – Detailed storm simulations
  – Validate with surface radar observations
  – Apply satellite radiative transfer algorithms
Mesoscale Model v5 (MM5) Parameterizations

- 1 km horizontal resolution
- 32 vertical levels (surface to 100 mb)
- 15 minute resolution output

- Lower/lateral boundary conditions from Rapid Update Cycle (RUC)

- Explicit microphysics (Reisner2 - six phases)
- Boundary layer physics (MRF)
- Radiation scheme (IR SW+LW cloud interactions)

- Cold starts (~ 2-5 hours before target time)