Neural Network Retrieval of Precipitation Using NPOESS Microwave Sensors

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ABSTRACT

This poster describes the development and validation of passive microwave precipitation retrieval algorithms for the NPOESS (National Polar-Orbiting Operational Environmental Satellite System) satellite program in preparation for its initial launch in 2009. Efforts are currently focused on modeling passive microwave observations, and developing a statistics-based algorithm for estimating precipitation rate.

Successful development of precipitation retrieval algorithms requires good physical models that relate satellite-based observations to atmospheric state and topographic features. Such systems have been developed at the MIT Lincoln Laboratory for simulating data for both the cross-track ATMS (Advanced Technology Microwave Sounder) and the conically scanning MIS (Microwave Imager/Sounder). This system incorporates the MM5 cloud-scale numerical weather prediction model, the Rosenkranz radiative transfer model (IEEE TGRS, 40(8), 2002), the Surussavadee and Staelin hydrometeor electromagnetic modeling technique (IEEE TGRS, 44(10), 2006), and a satellite geometry toolbox for MATLAB developed at MIT Lincoln Laboratory for computing quantities relevant to satellite scans and geographical positions.

This simulation system predicts brightness temperatures with promising agreement with observations from the Advanced Microwave Sounding Unit instruments AMSU-A/B aboard the NOAA-16 satellite over Typhoon Pongsona in the western Pacific in Dec. 2002. This simulation system is also being validated with ~2-km resolution observations from the aircraft-based NPOESS Aircraft Sounder Testbed-Microwave (NAST-M) instrument. This simulation system is flexible and could be adapted for other current or future operational microwave or infrared instruments.

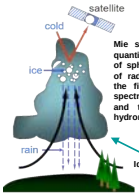
Precipitation algorithms are currently being developed for ATMS, MIS, and NAST-M. ATMS, like AMSU, will have channels in the opaque 54-GHz oxygen and 183-GHz water vapor resonance bands plus some window channels. It is an improvement over AMSU-A/B and similar NOAA and METOP satellite instruments. ATMS will have additional channels in the 183-GHz water vapor resonance band, Nyquist sampling in the 54-GHz oxygen resonance band, and ~33-km spatial resolution for channels in the 54-GHz band. The AMSU-A/B precipitation algorithm developed by Chen and Staelin (IEEE TGRS, 41(2), 2003) will be adapted for ATMS, and the 33-km resolution of ATMS and increased number of channels suggests that a superior precipitation retrieval algorithm can be developed. The new algorithm will be fast, statistics-based, and involve extensive signal processing and use of neural networks, in contrast to purely variational physics-based approaches which involve repeated radiative transfer computations. The signal processing methods will include regional Laplacian interpolation for cloud clearing, principal component analysis for temperature profile characterization, and image sharpening for enabling retrievals at the finest resolution possible. A major component of this study will involve understanding how various signal processing methods can be used or improved.

Detailed characteristics of the MIS system are currently being formulated. The flexibility of the simulation system facilitates selection of good channel sets, sampling rates, and resolutions. The MIS precipitation algorithm will leverage lessons learned from both AMSU and previously launched conical scanning spectrometers such as TMI, AMSR-E, and SSMIS.
Precipitation products on NPP and the NPOESS satellite series will maintain the important continuous observations provided by currently operational instruments. NPP will not only help provide continuity, but it will also facilitate the development of improved algorithms.

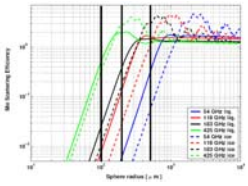
RADIATIVE TRANSFER MODELING

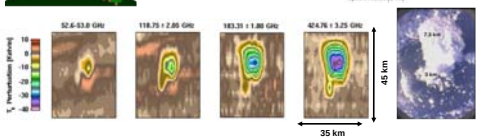
Passive Microwave Measurements and Precipitation

Passive microwave spectrometers measure the scattering of the cosmic background radiation off of hydrometeors. The NAST-M suite of radiometers span 50 to 425 GHz, which offers a unique range of frequencies that are sensitive to hydrometeors of varying diameter. The smallest wavelength is sensitive to the smallest particles, while the largest wavelengths only receives returns from the larger-diameter particles.



Mie scattering efficiency quantifies the reflectivity of spheres as a function of radius. Illustrated in the figure are the four spectrometer frequencies and the phase of the hydrometeor (i.e., sphere).





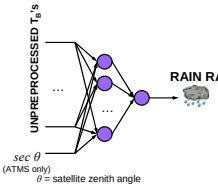
Here is a real convective cell measured during the PTOST campaign by NAST-M. The largest hydrometeors are in the center of the cell, and therefore the 54-GHz is only sensitive to that area. As the wavelength decreases, the higher frequency spectrometers are sensitive to a larger extent of the cell. The visible image (far right) shows the highest sensitivity to small cloud particles, as scattering for such particles in the visible region of the spectrum is much more significant than in the microwave/millimeterwave region. Microwave spectrometers produce data with more information on the inner dynamics of a convective cell then the images from the very short IR and visible wavelengths. IR and visible only view the top of the convective cell.

ALGORITHMS

Precipitation Retrieval Algorithm Methods

- Most current operational algorithms use variational approaches, Bayesian inversion
  - Advantage: Incorporates physics into algorithm
  - Disadvantages
    - Computationally intensive
    - Physical models can be imperfect
- 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



- Inputs
  - All channels
  - Secant of the satellite zenith angle (ATMS only)
- Target output: MM5 surface rain rate (mm/h)
- Only pixels with rain rate > 1 mm/h were included
- 25 storms over ocean divided among training (9), validation (8), and testing sets (8)
- Total of 10983 ATMS & 56300 MIS pixels
- Training:
  - Levenberg-Marquardt backpropagation 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

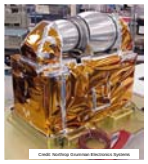
THE INSTRUMENTS

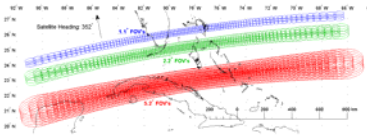
ATMS: Advanced Technology Microwave Sounder

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

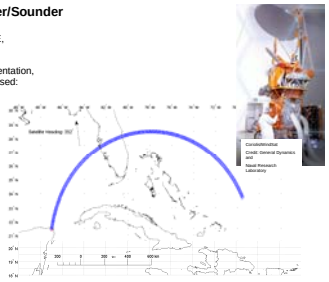

Credit: Northrop Grumman Electronics Systems



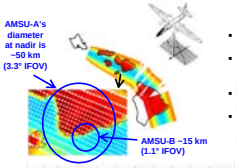
MIS: Microwave Imager/Sounder

Heritage
- SSMIS, TMI, AMSR-E, WindSat

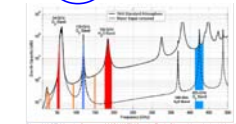
For the simulations in this presentation, the following channel set was used:
- 6.625 GHz (V/H)
- 10.65 GHz (V/H)
- 18.7 GHz (V/H)
- 23.8 GHz (V/H)
- 36.5 GHz (V/H)
- 50.3 GHz (V)
- 52.24 GHz (V)
- 53.57 GHz (V)
- 54.905 GHz (V)
- 55.49 GHz (V)
- 56.66 GHz (V)
- 59.38 GHz (V)
- 59.94 GHz (V)
- 89.0 GHz (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)

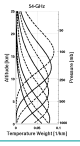


NAST-M: NPOESS Aircraft Sounder Testbed - Microwave



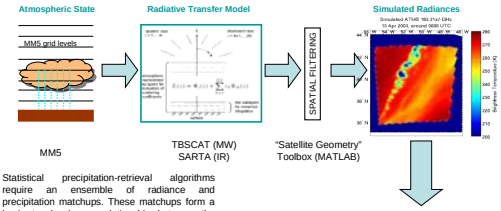
- Four Total-Power Spectrometers
- 24 Oxygen Channels around 50 GHz, 118 GHz, and 425 GHz
- 6 Water Vapor Channels around 183 GHz
- Flies aboard the ER-2, Proteus, and WB-57 aircraft



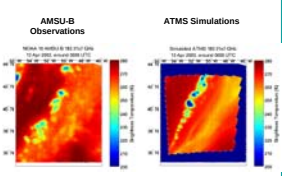


- Cruising altitude: ~17-20 km
- Cross-track scanning
- Scan angle: -65° to 65°
- 7.5° antenna beam width (FWHM)
- ~2.5 km nadir footprint diameter
- Swath width of ~100 km

Radiance Simulation Methodology



Statistical precipitation-retrieval algorithms require an ensemble of radiance and precipitation matchups. These matchups form a basis to develop a relationship between the radiance measured and the actual rain rate. Due to the paucity of real matchups, it is common to simulate the radiances. This requires a three-step simulation. First, the precipitating atmosphere must be simulated using a cloud resolving model (CRM), i.e., MM5. Second, a numerical solution to the radiative transfer equation must be used to transform the atmospheric state to an instrument's measured radiance (e.g., TBSCAT). The third step is convoluting the CRM's native spatial resolution (~1 km) to the satellite sensor's IFOV.



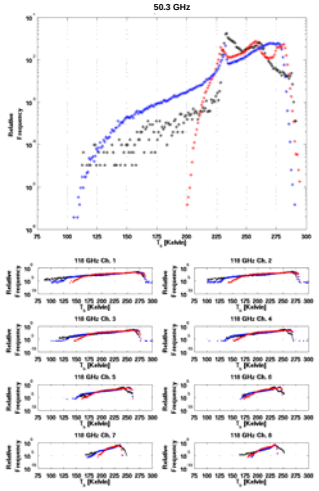
Radiative Transfer Model Validation using NAST-M

To validate the simulations, we compare coincidental aircraft measurements (NAST-M) with our simulated radiances. The cloud resolving models are not accurate enough spatially and temporally to allow a pixel to pixel comparison, so we compare the statistics of the two data sets with a histogram. The histogram above was normalized by the total number of pixels in each data set to allow a more even comparison. The histogram contains seven flights which totaled 30,501 precipitating pixels. The simulated data contained many more "scenes," to account for the potential temporal differences.

Black asterisks are NAST-M observations from eleven flights during the CRYSTAL-FACE deployment (41,670 measurements)

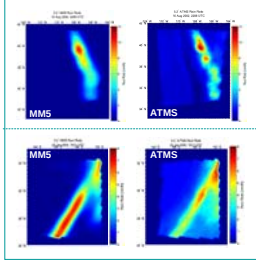
Red asterisks are simulated measurements (525,860) consisting of eight hours of MM5 simulation per day (15-min. increments) using a two-stream version of TBSCAT

Blue asterisks are also simulated measurements using a ten-stream, tuned version of TBSCAT



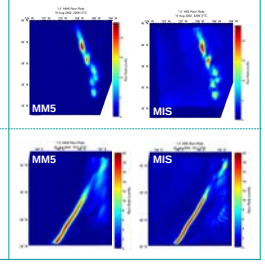
ATMS

Rain-Rate Retrieval Images Produced at 5.2º Resolution

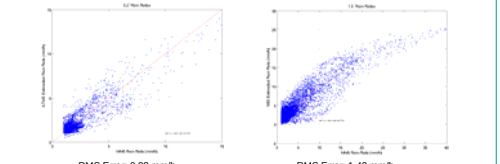


MIS

Rain-Rate Retrieval Images Produced at 1.5º Resolution



Rain-Rate Retrieval Error Scatter Plots



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

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

Summary

- AMSU experience and preliminary studies show ATMS can provide accurate, high-resolution, global precipitation products
- These products can help bridge the gap to MIS in 2016
- Fundamental building blocks are in place:
  - NWP/RT models for producing 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
- Future work will focus on NWP data generation, RT model validation and improvement using NAST-M, and retrieval algorithm optimization

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