High-Resolution Passive Millimeter-wave Aircraft Measurements: Validation of Satellite Observations and Radiative Transfer Modeling

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Abstract

NPOESS Aircraft Sounder Testbed-Microwave (NAST-M) is a risk-reduction effort supported by the Integrated Program Office (IPO) for the upcoming National Polar-orbiting Operational Environmental Satellite System (NPOESS) and the NPOESS Preparatory Project (NPP). The motivation for this poster is to demostrate the capabilities of NAST-M for satellite radiance validation and its use as a powerful tool to validate and develop a simulation methodology for use in rain-rate retrieval techniques.

On the right, the NAST-M passive microwave spectrometer suite was used to help validate the radiometers (AMSU and MHS) on the MetOp-2/A satellite. Underflights of MetOp-2/A were made by the WB-57 high-altitude research aircraft during the Joint Airborne IASI Validation Experiment (JAIVEx – Apr. 2007). Microwave data from other satellites (Aqua, NOAA-16, and NOAA-17) is also presented.

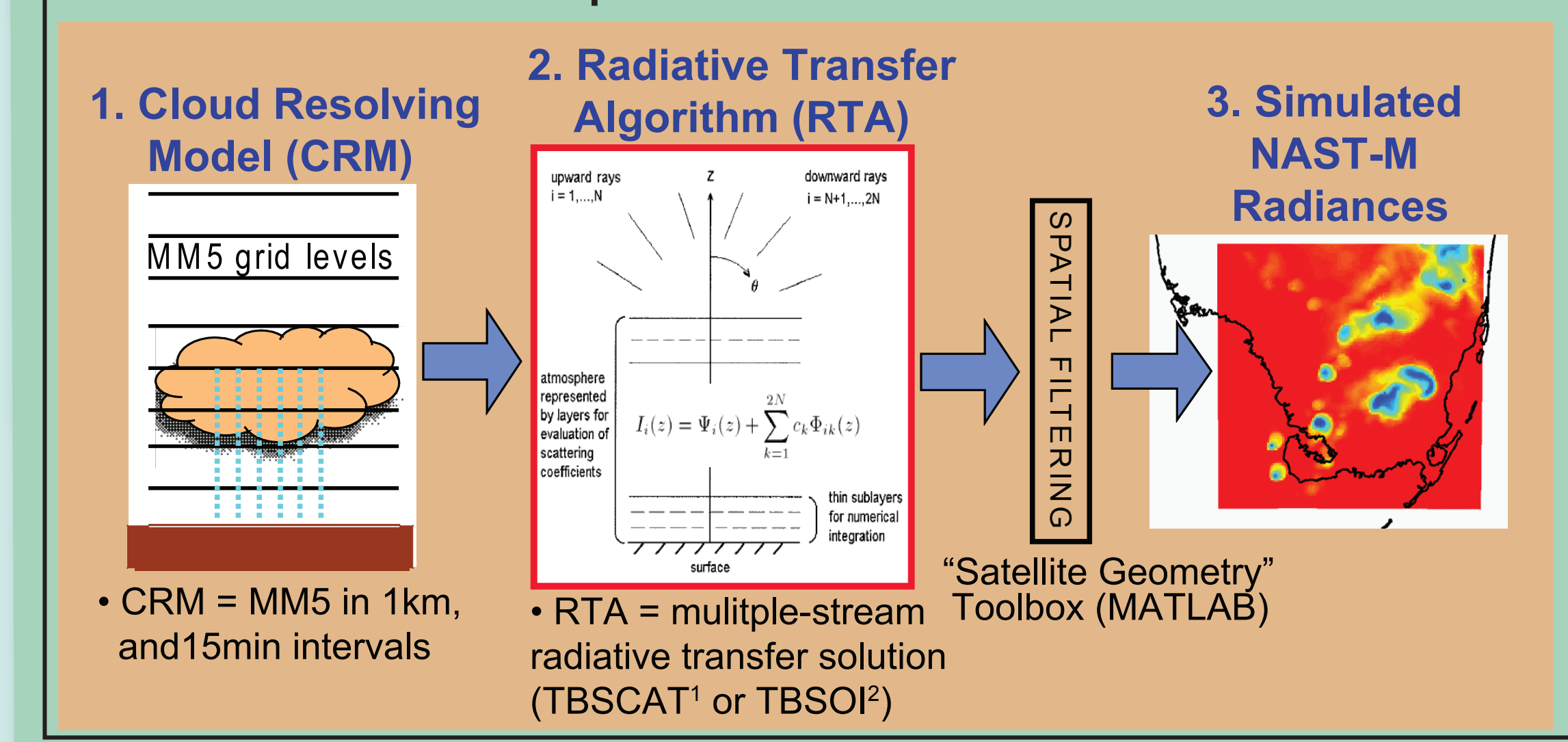
On the left, NAST-M data is used to validate the parameter values in a scattering Radiative Transfer Algorithm (RTA) coupled with a Cloud Resolving Model (CRM). The RTA parameter value selection utilizes the MM5 regional-scale circulation model to generate atmospheric thermodynamic quantities (e. g., hydrometeor profiles). These data are then input into the Rosenkranz multiple-stream initial-value RTA to simulate at-sensor millimeter-wave radiances. The simulated radiances are filtered and resampled to match the sensor resolution and orientation. While the parameters chosen in the CRM are important, the focus of the current work is the parameter selection in the RTA, and we aim to extend the work of Surussavadee and Staelin to higher spatial resolutions (from 15 km to 2 km) and frequencies (from 183 to 425 GHz). The RTA parameters are optimized by comparing histograms of observations from the NAST-M instrument and the simulated output from the RTA. The computations are performed using the MIT Lincoln Laboratory LLGrid High Performance Computing Facility. Over a dozen storms consisting of over 40,000 precipitation-impacted pixels have been studied.

Radiative Transfer Algorithm Validation using NAST-M

Radiative Transfer Modeling

The figure below illustrates the end-to-end simulation that must be performed to allow comparisons with NAST-M. This is a three step process:
1) The precipitating atmosphere is first simulated using a Cloud Resolving Model (CRM), e.g., MM5.
2) Then a numerical solution to the radiative transfer equation is used to transform the atmospheric state to a sensor-measured radiance, e.g., TBSCAT.
3) The CRM's native spatial resolution (~1 km) is convolved with NAST-M's FOV to produce simulated NAST-M radiances.

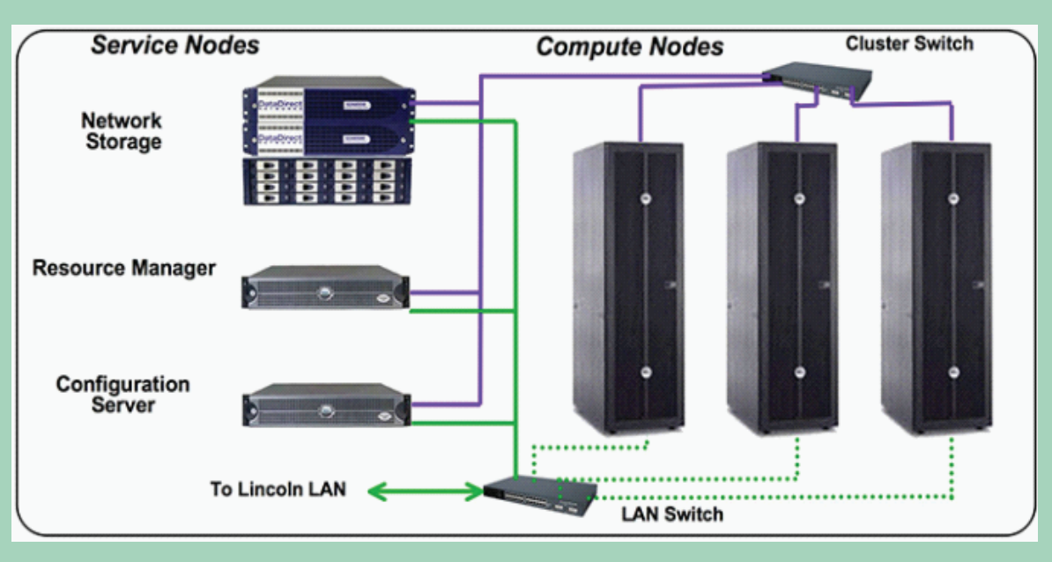
Precipitation Simulation



- CRM = MM5 in 1km, and15min intervals
- RTA = mulitple-stream radiative transfer solution (TBSCAT[1] or TBSOI[2])

"Satellite Geometry" Toolbox (MATLAB)

LLGrid system

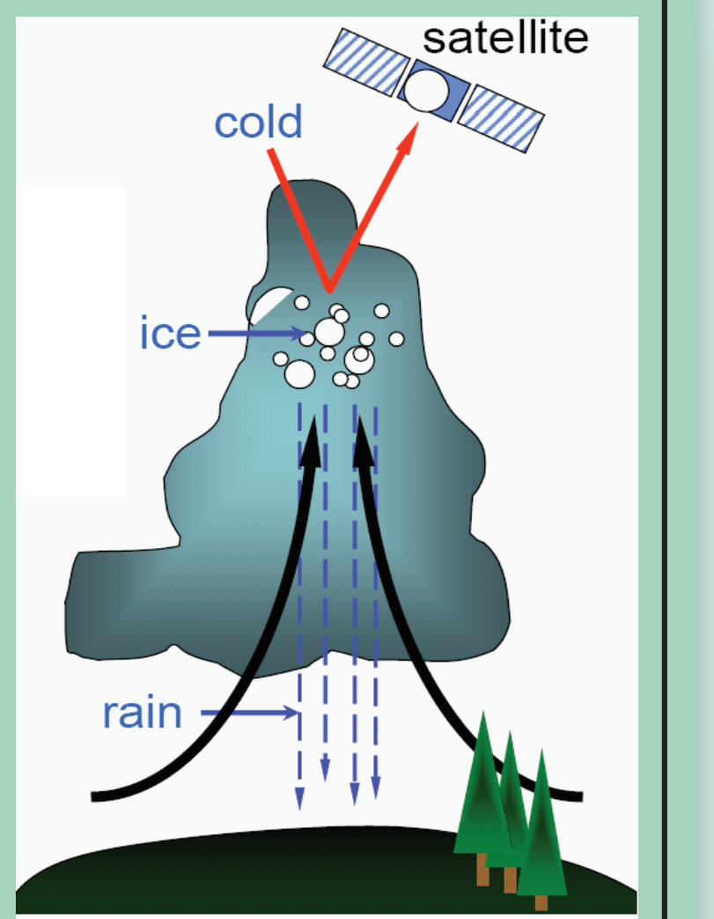


These simulation calculations are very time consuming, so the original MIT simulation software was adapted for use in the Lincoln Laboratory LLGrid High Performance Computing Facility, which consists of approximately 1000 Xeon processors.

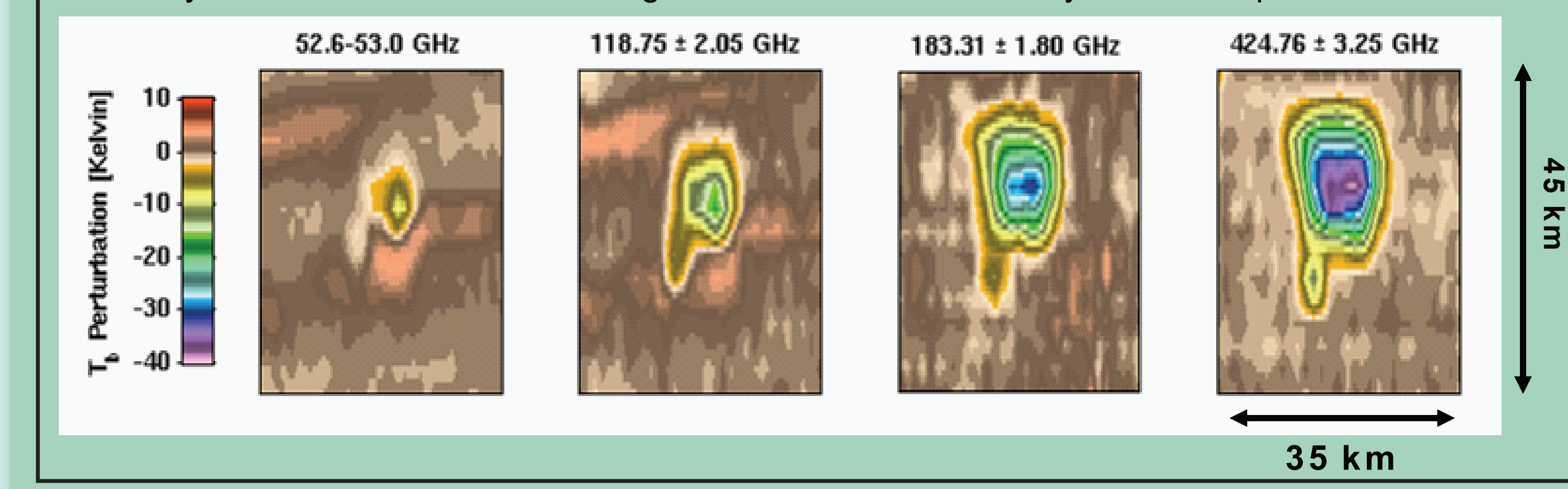
Passive Microwave Measurements of Precipitation using NAST-M

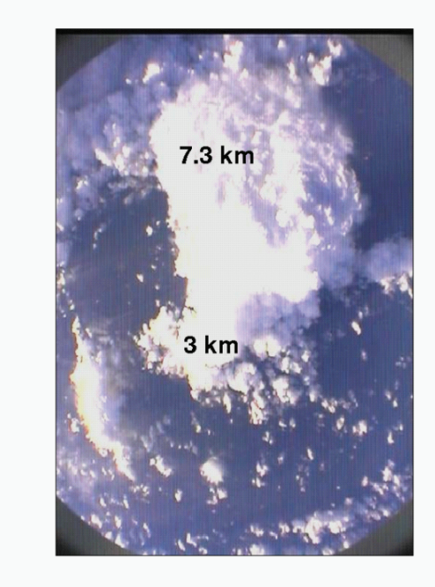
Passive microwave spectrometers measure the scattering of the cosmic background radiation off of hydrometeors. The NAST-M suite of radiometers span 50 to 425 GHz, which offers a unique range of frequencies that are sensitive to hydrometeors of varying diameter. The smallest wavelength is sensitive to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

Below 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) is sensitive to the smallest cloud particles (visible has a much smaller wavelength than millimeter or microwave). 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 can only view the top of the convective cell.



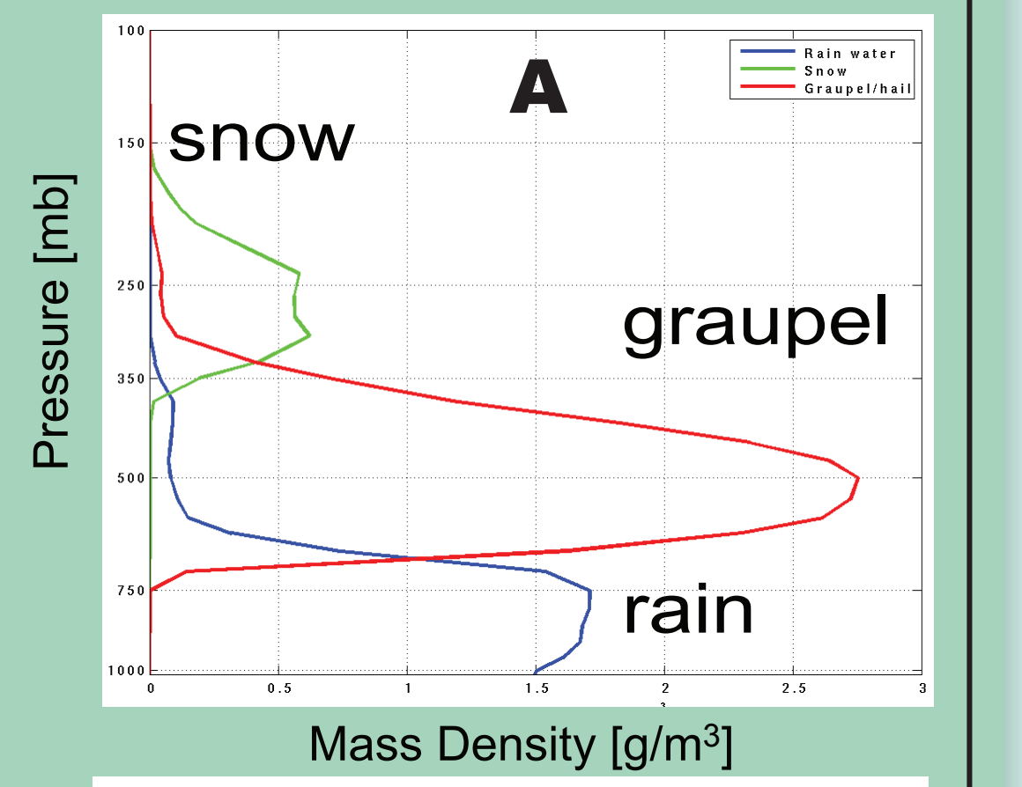
Idealized convective cell

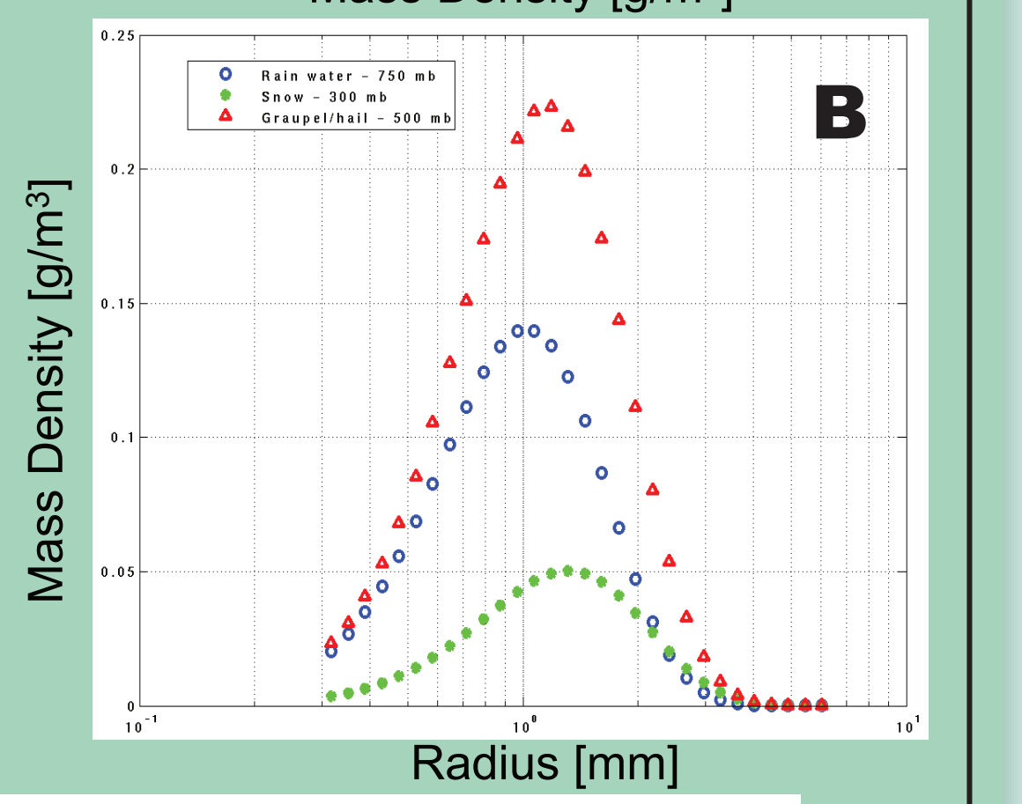




Radiative Transfer Algorithm Validation using NAST-M Data

Radiatve Transfer Algorithms (RTA) require a vertical profile for each hydrometeor type (i.e., rain, snow, and graupel). The Cloud Resolving Model (CRM) calculates the profile at each time step by simulating such processes as aggregation and riming. Figure A is a CRM example of a pixel (i.e., profile) in the middle of a convective cell. Each curve represents a different hydrometeor type in units of volumetric mass density. At each discrete level in the CRM, the hydrometeor density (g/m^3) is divided into radii bins. The bin's radius represents the amount of mass in perfect spheres. This bulk microphysics parameterization uses a Drop-Size Distribution (DSD), which typically follow an inverse expontial form (see Figure B). The explicit microphysics used in the MM5 simulations was the Reisner 2. Snow used the Sekhon Srivastava DSD, while the rain and graupel used the Marshall-Palmer DSD.





Progress

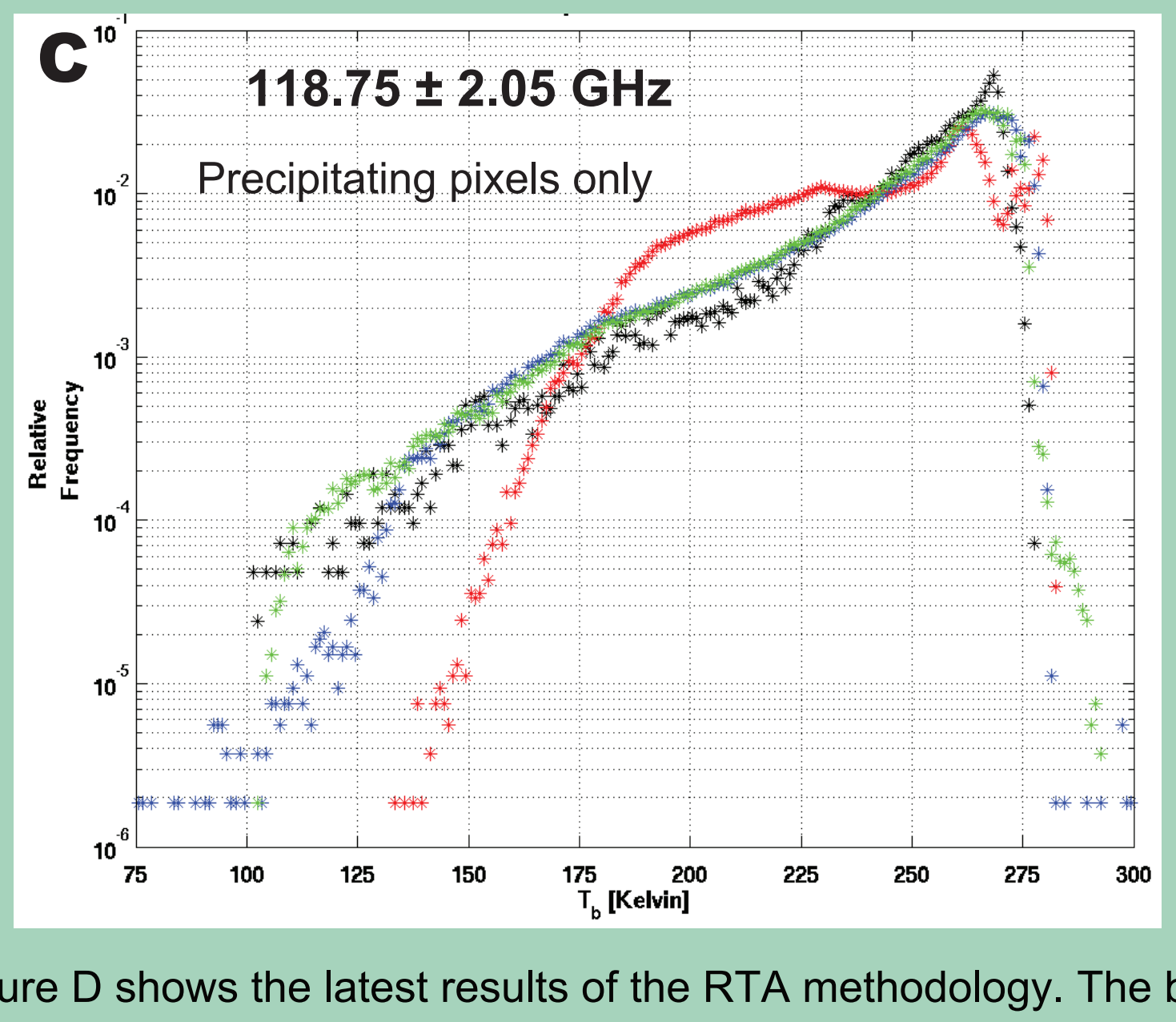
Figure C gives an example from one of NAST-M's channels, which represents the progress of the RTA parameter optimization. The histogram curves are normalized to give relative frequency. The pixels were tallied in one Kelvin bins.

* 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[3]

* 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



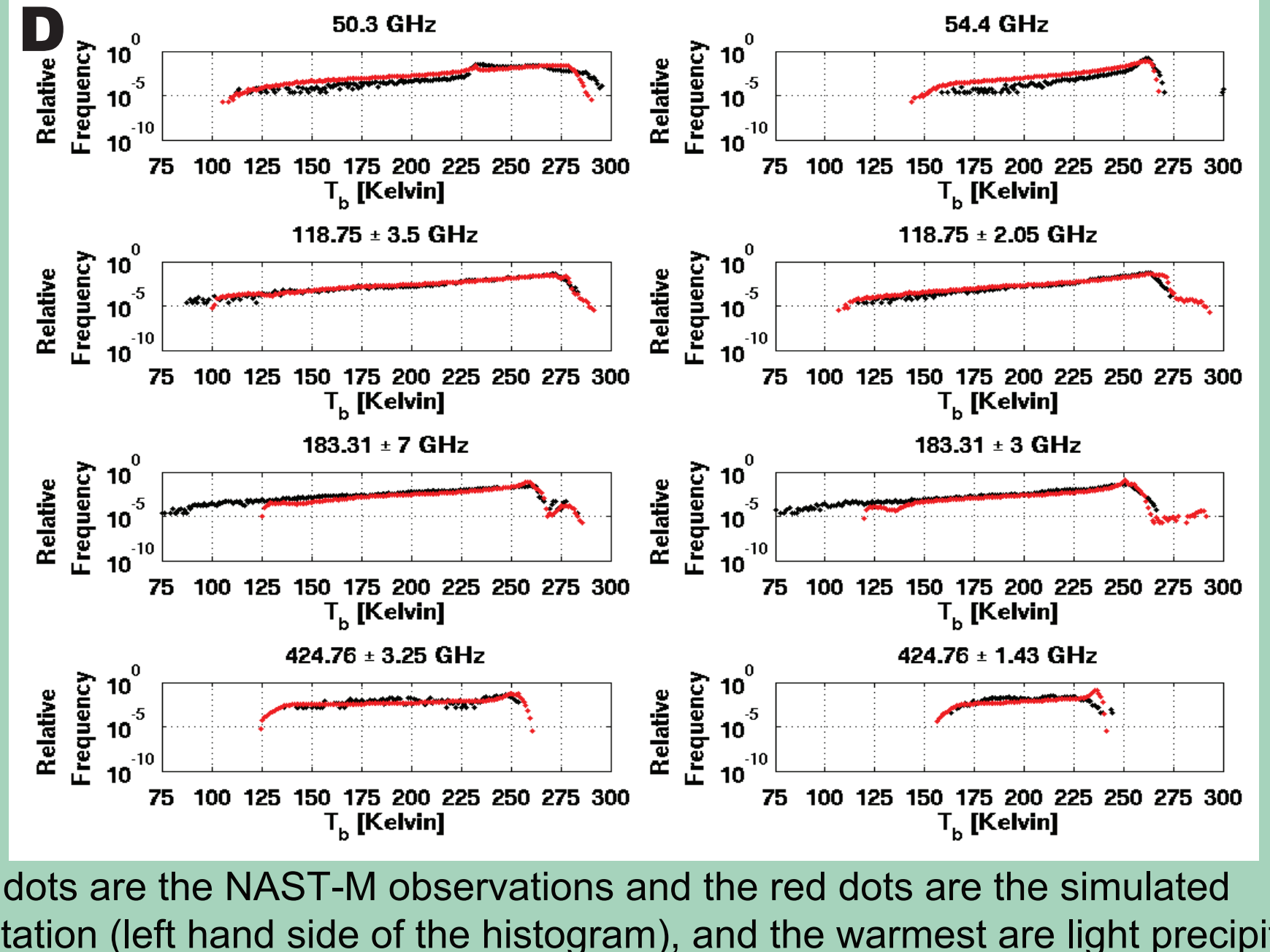


Figure D shows the latest results of the RTA methodology. The black dots are the NAST-M observations and the red dots are the simulated brightness temperatures (Tb). The coldest Tb are the heaviest precipitation (left hand side of the histogram), and the warmest are light precipitation. The discrepancies at the warmest Tb is attributed to the difficulty of identifying precipitating pixels from the NAST-M data and simulations that still have numerical instability (e.g., 183-GHz channels). Further work must be done on 183-GHz channels to provide stable and accurate Tb at the highest precipitation rates.

Radiative Transfer Algorithm Validation Summary

- **Fundamental simulation building blocks are in place**
  - **CRM/RTA produces retrieval algorithm training data**
  - **Validated with NAST-M data**
- **These studies highlight a need to further develop this RTA in regions of heavy precipitation**
- **Future work consists of tuning the microphysical parameters in both the CRM and RTA**

References

1. TBSCAT: Rosenkranz, P. W., "Radiative Transfer Solution Using Initial Values in a Scattering and Absorbing Atmosphere With Surface Reflection," *IEEE Trans. Geosci. Remote Sens.*, vol. 40, no. 8, pp. 1889-1892, Aug. 2002
2. SOI: Heidinger A. K., *et al.*, "The Successive-Order-of-Interaction Radiative Transfer Model. Part I: Model Development," *J. Appl. Meteor. Climatol.*, vol. 45, pp. 1388-1402, Oct. 2006
3. Surussavadee, C. & Staelin, D. H., "Comparison of AMSU Millimeter-Wave Satellite Observations, MM5/TBSCAT Predicted Radiances, and Electromagnetic Models for Hydrometeors," *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 10, pp. 2667-2678, Oct. 2006.

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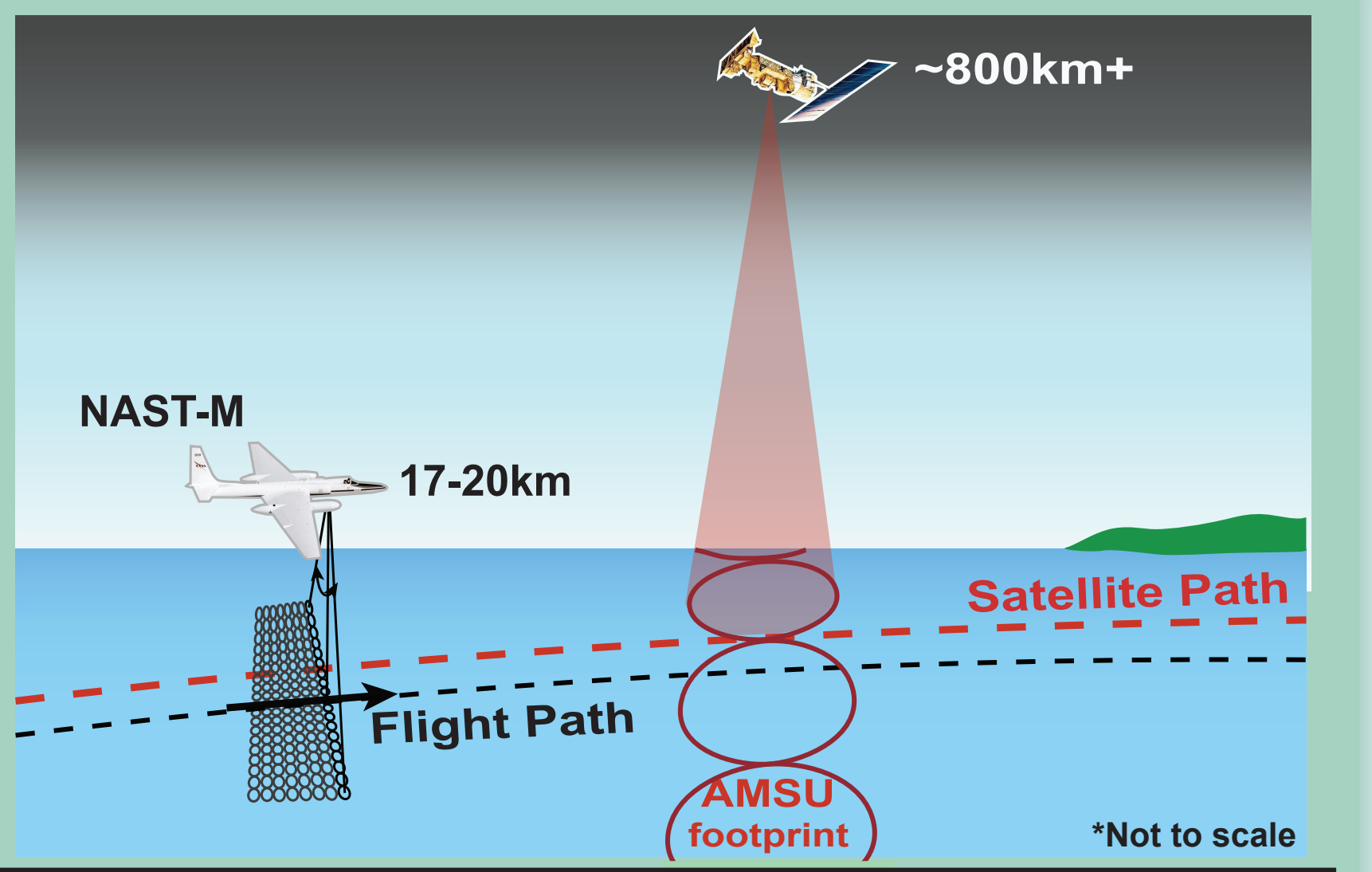
Satellite Radiometer Validation of the AMSU-A, AMSU-B, and MHS Instruments Using the NPOESS Aircraft Sounder Testbed - Microwave

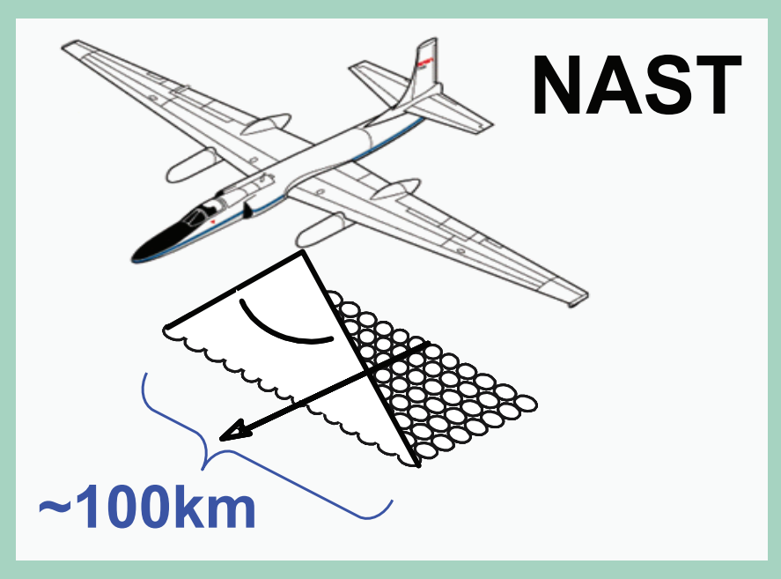
In this work, radiance observations from the NAST-M airborne sensor are used to directly validate the radiometric performance of spaceborne sensors.

Why use aircraft measurements?

- Direct radiance comparisons
  - → Mitigates modeling errors
- Mobile platform
  - → High spatial and temporal coincidence achievable
- Spectral response matched to satellite
  - → With additional radiometers for calibration
- Higher spatial resolution than satellite
- Additional instrumentation to support matchup and analysis process
  - → Coincident video data aid cloud analysis
  - → Dropsondes facilitate calibration of NAST-M

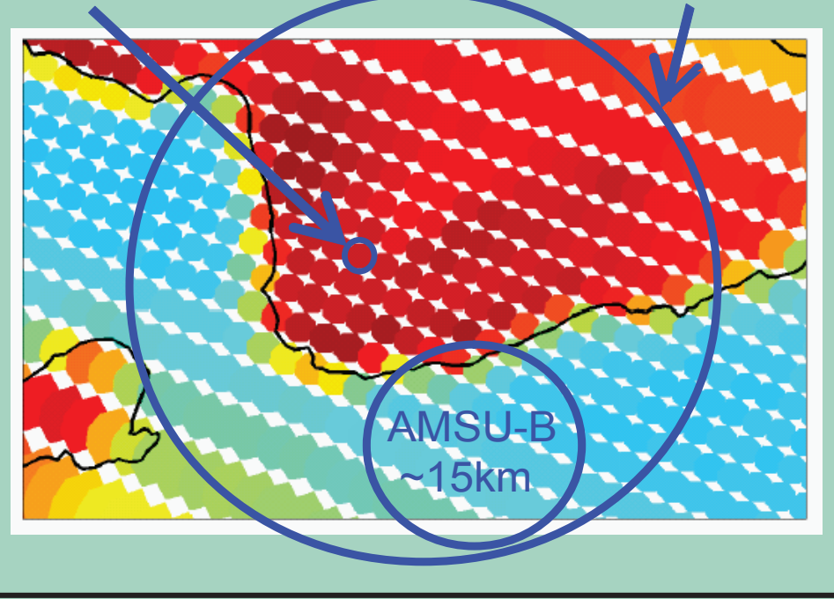


The Instrument: NPOESS Aircraft Sounder Testbed - Microwave (NAST-M)

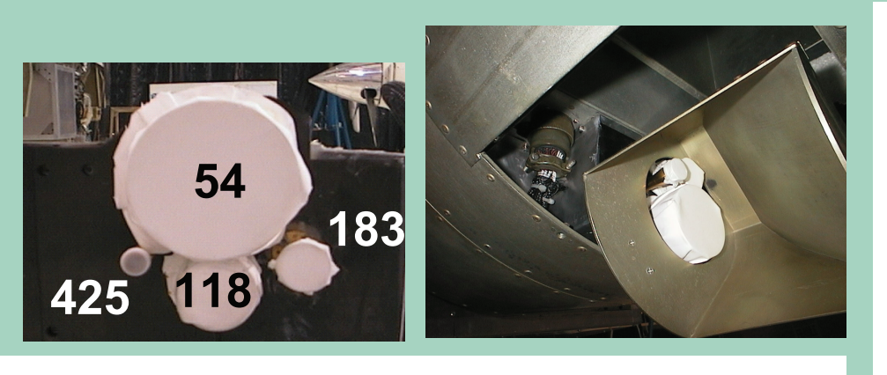


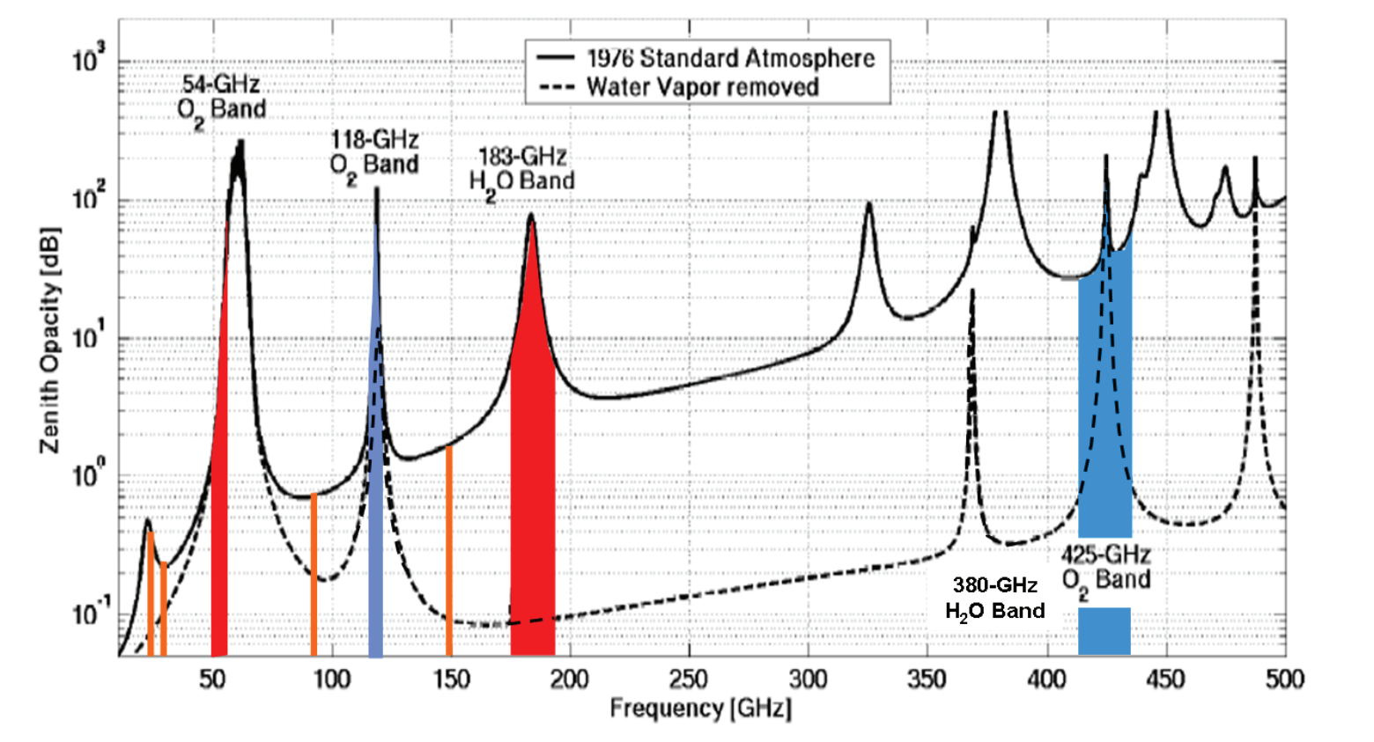
- Flies with sister sensor NAST-I (Infrared)
- Cruising altitude: ~17-20km
- Cross-track scanning: -65° to 65°
- 7.5° antenna beam width

NAST-M's diameter at nadir is ~2.5km
AMSU-A's diameter at nadir is ~50km

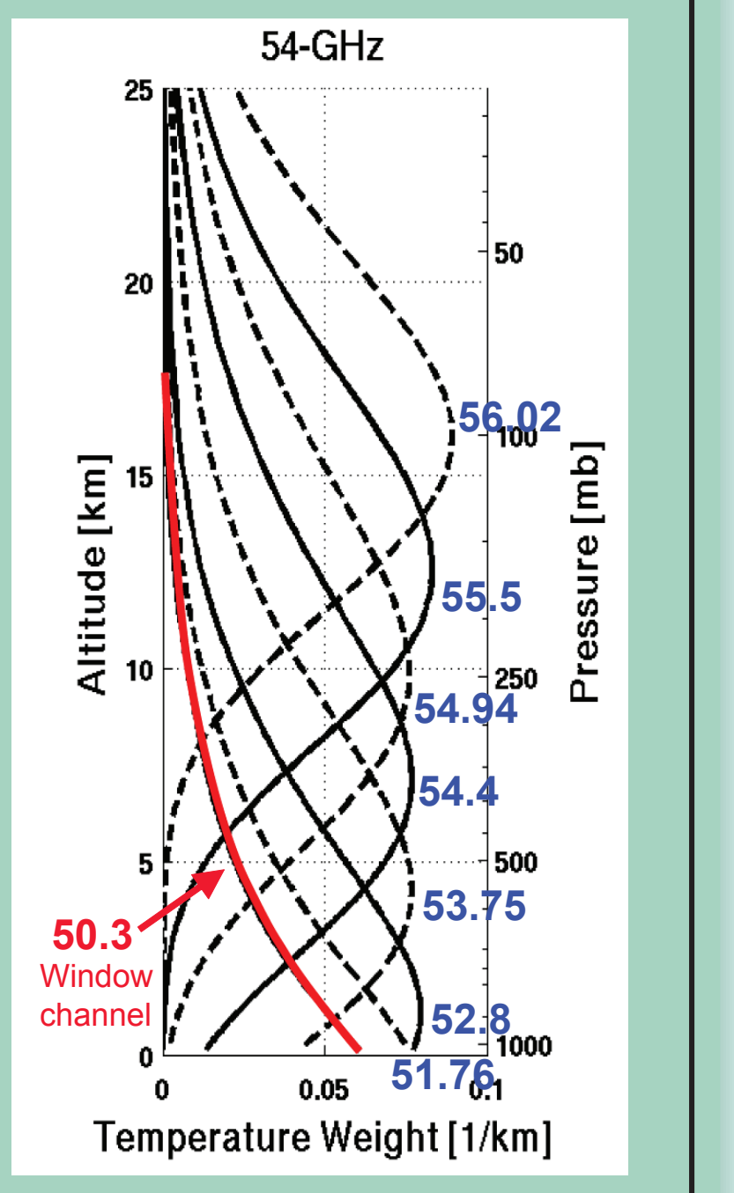


- Four spectrometers:
  - 54 GHz (8 O_2 channels)
  - 118 GHz (9 O_2 channels)
  - 183 GHz (6 H_2O channels)
  - 425 GHz (7 O_2 channels)





Blue: NAST-M only Orange: AMSU/ATMS only Red: Shared bands (not identical)

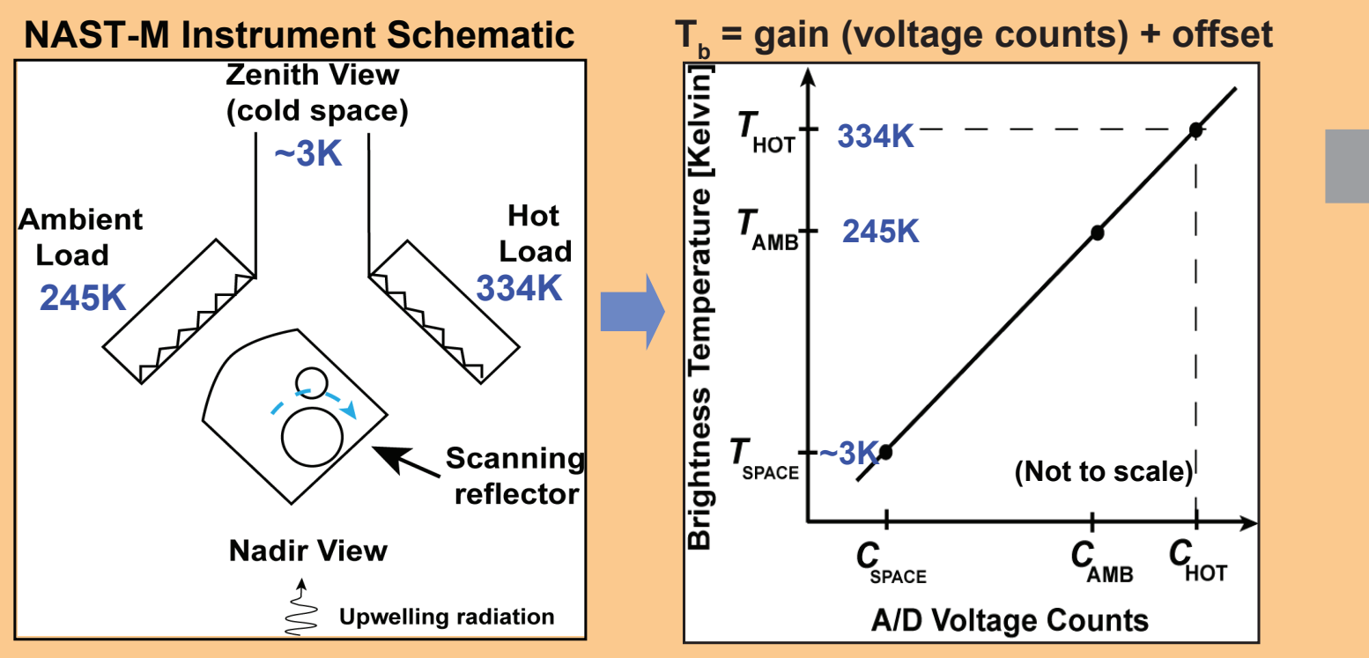


- Instrument suite flies aboard the ER-2, Proteus, and WB-57 aircraft

Methodology: NAST-M Calibration, Atmospheric Corrections, and Data Co-location

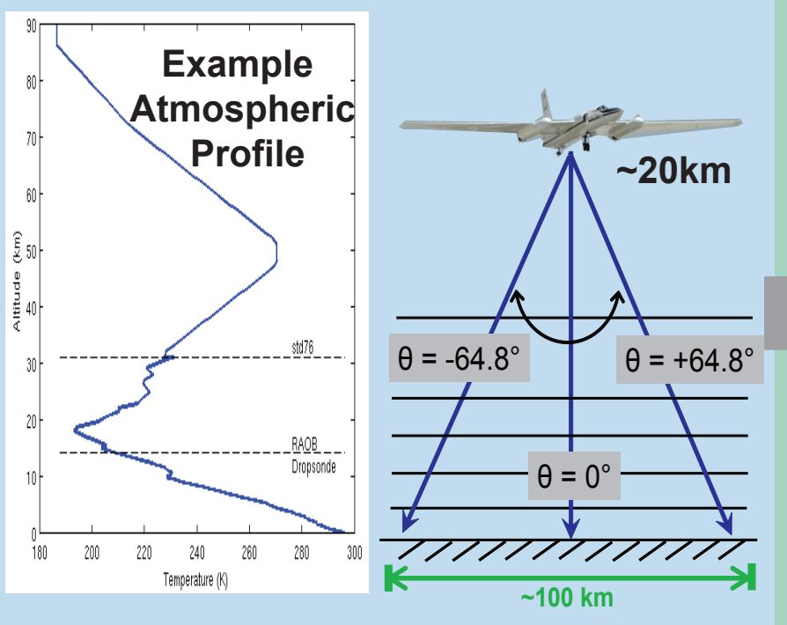
NAST-M Calibration

A three point calibration is used to convert NAST-M radiometer output voltage to radiances in brightness temperature units, T_b



Note: Aircraft movement is into the poster

NAST-M Limb Correction

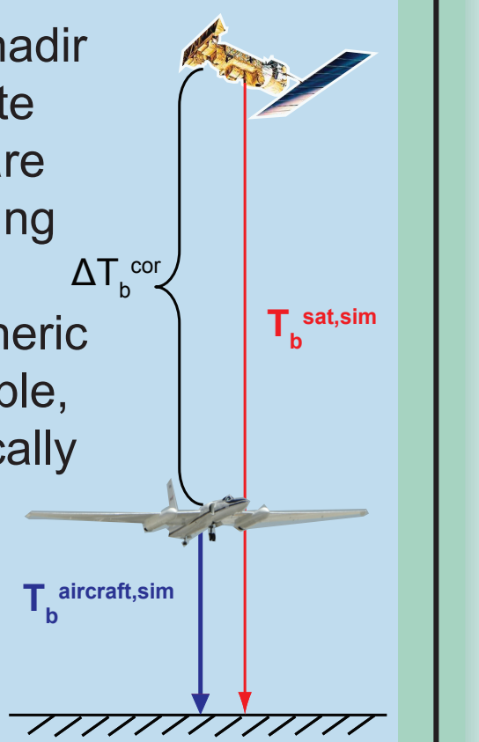


T_b across swath is simulated using RTM with the most accurate profile available, which gives $T_b^{sim}(\theta)$:

Correction factor = $\Delta T_b^{cor}(\theta) = T_b^{sim}(\theta) - T_b^{sim}(\theta=0)$

NAST-M Altitude Correction

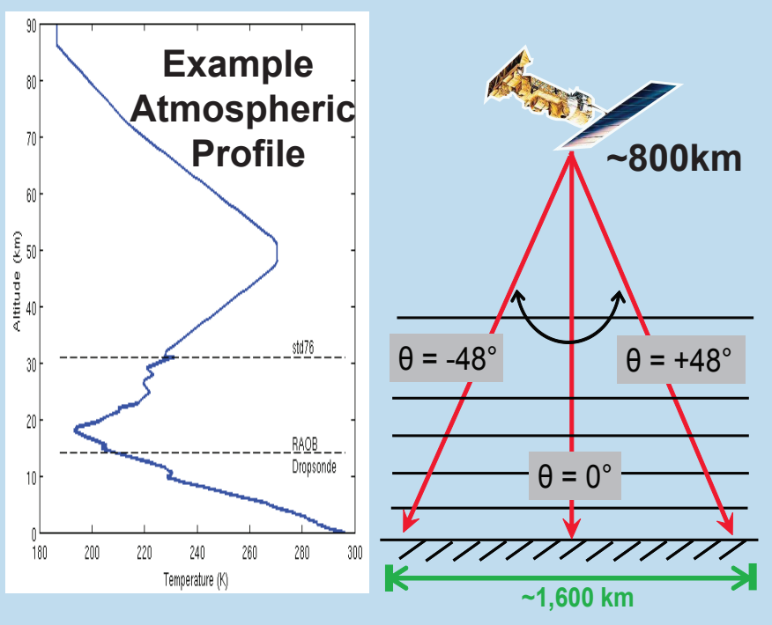
T_b values at nadir for the satellite and aircraft are simulated using RTM and the best atmospheric profile available, which is typically a hybrid of data from:
- Dropsondes
- Radiosondes
- US 1976 standard profile



Correction factor = $\Delta T_b^{cor} = T_b^{sat,sim} - T_b^{aircraft,sim}$

Satellite T_b's

Satellite Limb Correction



T_b across swath is simulated using RTM with the most accurate profile available, which gives $T_b^{sim}(\theta)$:

Correction factor = $\Delta T_b^{cor}(\theta) = T_b^{sim}(\theta) - T_b^{sim}(\theta=0)$

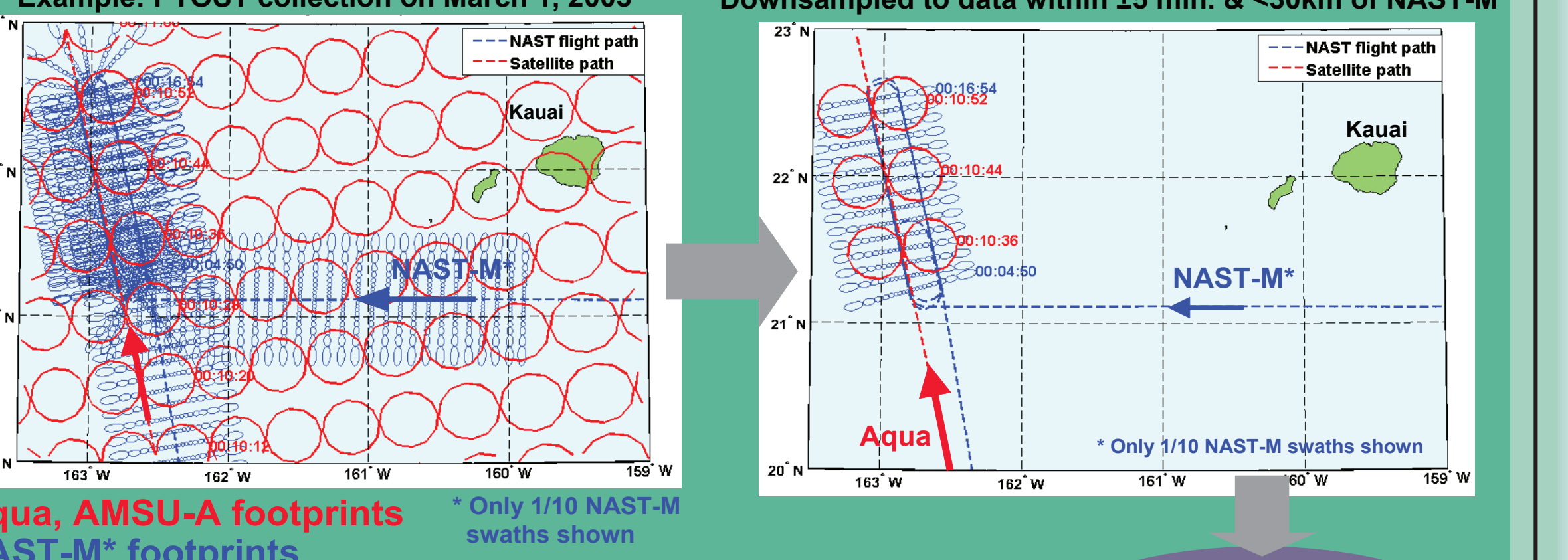
NAST-M T_b's

Sat. T_b's

Data Co-location and Downsampling

Example: PTOST collection on March 1, 2003

Downsampled to data within ±5 min. & <30km of NAST-M



Aqua, AMSU-A footprints
NAST-M* footprints
* Only 1/10 NAST-M swaths shown

Comparison: Averaged NAST-M T_b vs. Satellite T_b

The two datasets are co-located by projecting the satellite data onto the NAST-M collection. The overlapping data is then downsampled by applying temporal and spatial requirements. The NAST-M T_b's inside each footprint are averaged, and compared to the corresponding satellite T_b.

Recent Campaigns and Results

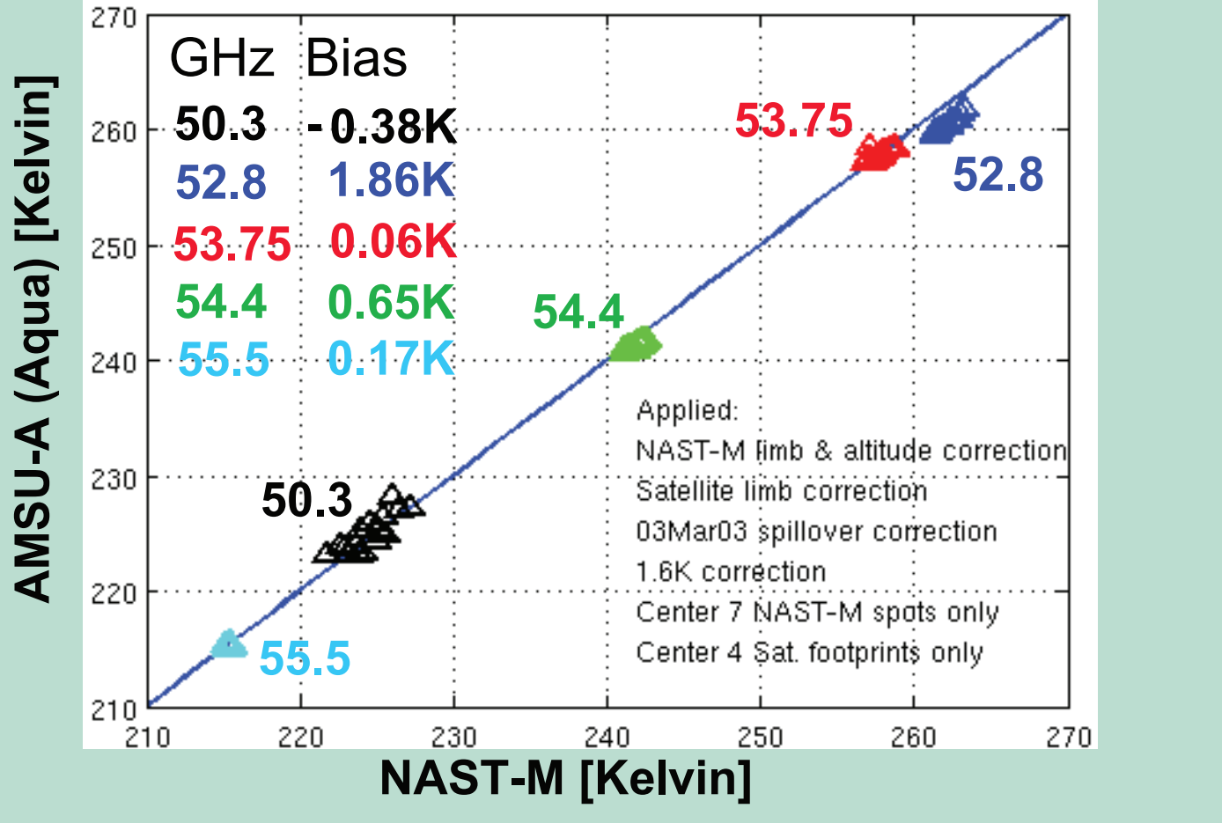
Results for two recent validation efforts are shown below:

1) **Pacific THORpex (THe Observing-system Research and predictability experiment) Observing System Test (PTOST)**
   - January-April 2003, Oahu, HI; Collections over the Pacific Ocean
   - Satellites presented: **Aqua, NOAA-16, NOAA-17**

2) **Joint Airborne IASI Validation Experiment (JAIVEx)**
   - April-May 2007, Houston, TX; Collections over the Gulf of Mexico
   - Satellites presented: **METOP-A**

PTOST Campaign: NAST-M Bias Estimates

Example: T_b Comparison AMSU-A, March 1, 2003
Bias = T_b(NAST-M) - T_b(Sat.)



AMSU-A PTOST Bias Estimates

GHz \ Satellite, Date	NOAA-16 3/11/03 μ	σ	NOAA-17 3/12/03 μ	σ	Aqua 3/1/03 μ	σ	Aqua 3/3/03 μ	σ
50.3	4K*	±7K	-1.7K	±1.1K	-0.38K	±0.9K	-0.45K	±1.3K
52.8	2.2K*	±1.3K	1.1K	±0.2K	1.86K	±0.1K	2K	±0.3K
53.75	-0.6K	±0.3K	-0.5K	±0.1K	0.06K	±0.4K	0.37K	±0.2K
54.4	0.64K	±0.2K	0.6K	±0.3K	0.65K	±0.3K	0.52K	±0.3K
54.94	0.4K	±0.2K	0.36K	±0.3K	N/A†		N/A†	
55.5	0.2K	±0.3K	-0.8K	±0.1K	0.17K	±0.2K	0.01K	±0.3K

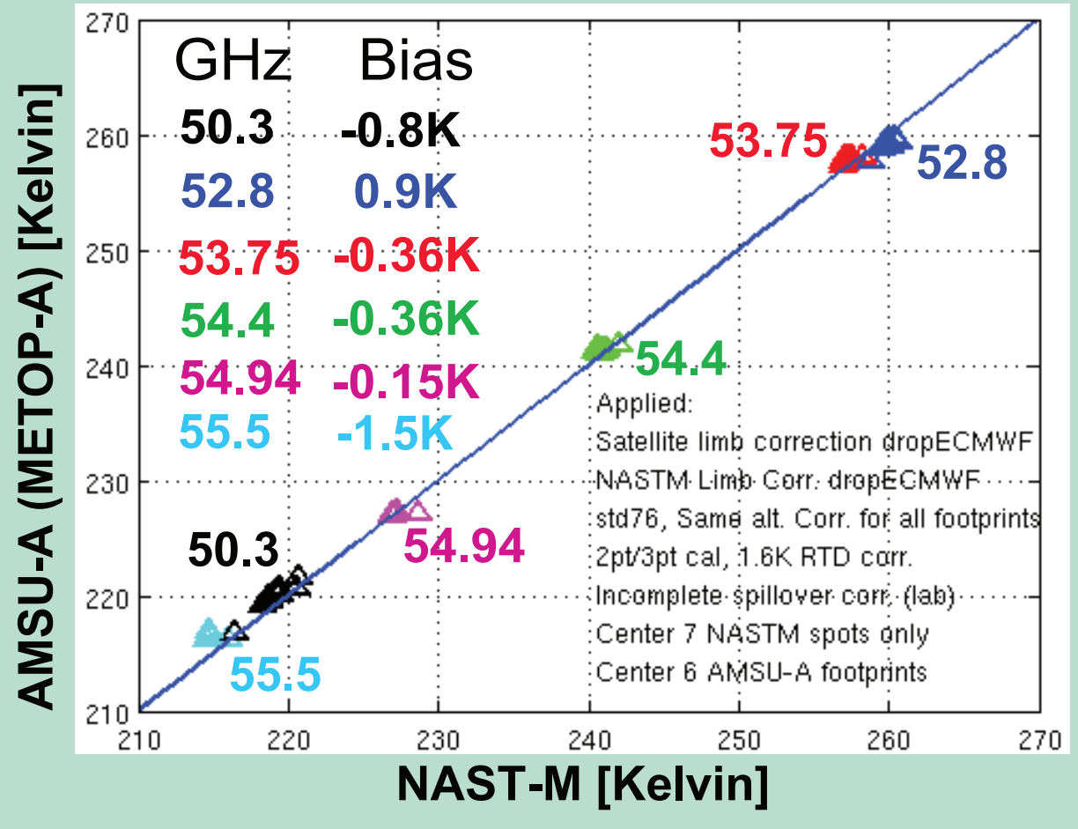
AMSU-B PTOST Bias Estimates

GHz \ Satellite, Date	NOAA-16 3/11/03 μ	σ	NOAA-17 3/12/03 μ	σ
183.3±1.0	4.2K*	±0.6K	-3K	±1.4K
183.3±3.0	1.2K*	±0.7K	-0.35K	±1.3K
183.3±7.0	2K*	±1.0K	-1K	±1.2K

PTOST NOTES:
Only best spatial and temporal alignment days are shown.
***This was a very cloudy day, which increases variation in window & humidity channels**
†Aqua channel 54.94GHz was disregarded due to excessive sensor noise corruption

JAIVEx Campaign: NAST-M Bias Estimates

Example: T_b Comparison AMSU-A, April 20, 2007
Bias = T_b(NAST-M) - T_b(Sat.)



AMSU-A JAIVEx Bias Estimates

GHz \ Satellite, Date	METOP-A 4/20/07 μ	σ
50.3	-0.8K	±0.4K
52.8	0.9K	±0.3K
53.75	-0.36K	±0.3K
54.4	-0.36K	±0.3K
54.94	-0.15K	±0.6K
55.5	-1.5K	±0.5K

MHS JAIVEx Bias Estimates

GHz \ Satellite, Date	METOP-A 4/20/07 μ	σ
183.3±1.0	1K	±0.7K
183.3±3.0	N/A§	
183.3+7.0	1.4K	±0.4K

§NAST-M channel not operational for this flight

Airborne Validation Summary

- **Observed biases between NAST-M and AMSU sensors are less than 1K for most channels**
  - **Comprehensive study included comparison with multiple satellites, atmospheric conditions, and geographic locations**
  - **Future studies will include additional data over a variety of surface types**
- **Improvement of NAST-M calibration is an ongoing effort**
- **NAST-M data are available online at http://rseg.mit/edu/nastm**

Acknowledgments *We would like to thank the NPOESS Integrated Program Office and the MIT Remote Sensing and Estimation Group*

References

1. Leslie, R.V. & Staelin, D.H., "NPOESS Aircraft Sounder Testbed-Microwave: Observations of clouds and precipitation at 54, 118, 183, and 425 GHz," *IEEE Trans. Geosci. Remote Sens.*, vol.42, no.10, p.2240-2247, Oct. 2004
2. W. J. Blackwell, J. W. Barrett, F. W. Chen, R. V. Leslie, P. W. Rosenkranz, M. J. Schwartz, and D. H. Staelin, "NPOESS Aircraft Sounder Testbed-Microwave (NAST-M): Instrument description and initial flight results," *IEEE Trans. Geosci. Remote Sens.*, vol. 39, no. 11, pp. 2444-2453, Nov. 2001.