Improved Calibration of Space-based Passive Microwave Cross-track Sounders

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Abstract

This poster outlines two calibration/validation efforts planned for current and future spaceborne microwave sounding instruments:

Below, a potential approach is presented for on-orbit angular field-of-view (FOV) calibration of the Advanced Technology Microwave Sounder (ATMS, to be launched in 2011). A variety of proposed spacecraft maneuvers that could facilitate the characterization of the radiometric boresight of all 22 ATMS channels is discussed. Radiative transfer simulations using a spherically stratified model of the Earth's atmosphere suggest that a combination of spacecraft pitch and roll maneuvers could identify and partially characterize antenna pattern anomalies.

On the right, the NPOESS Aircraft Sounder Testbed-Microwave (NAST-M) airborne sensor is used to directly validate the microwave radiometers (AMSU and MHS) on several operational satellites. NAST-M provides high spatial resolution as well as spatial and temporal coincidence with the satellite measurements. Comparison results for underflights of the Aqua, NOAA, and MetOp-A satellites are shown.

Angular Field-of-View Calibration of the Advanced Technology Microwave Sounder (ATMS)

Here we present a proposed approach for on-orbit FOV calibration of the ATMS satellite instrument using vicarious calibration sources with high spatial frequency content (the Earth's limb, for example).

ATMS Background and Status

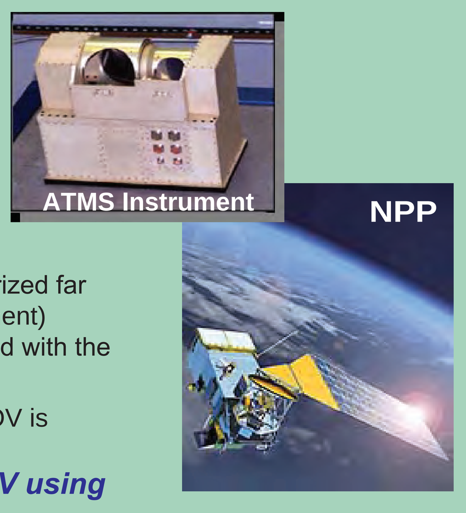
The ATMS flight unit for NPP (2011 launch) was delivered in 2005. Radiometrically, ATMS is well-characterized. Antenna pattern measurements indicated no major problems; however:

- ATMS antenna pattern measurements were (necessarily) sparse, only small number of cuts and beam positions were tested
- Some measurements may not have fully characterized far sidelobes for all channels (limitation of test equipment)
- Antenna pattern measurements were not measured with the sensor attached to spacecraft

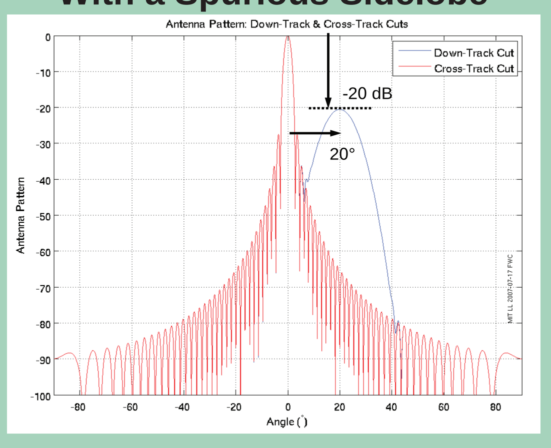
Additional pre-launch characterization of ATMS's FOV is problematic, prompting the question:

Is on-orbit characterization of ATMS's FOV using spacecraft maneuver(s) feasible?

The objective of this study is to quantitatively assess the benefits of various maneuvers, as well as the limitations of this type of on-orbit calibration approach.



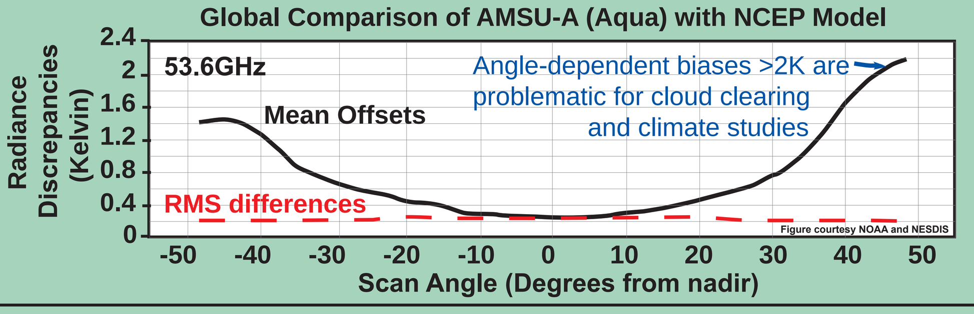
Example of Antenna Pattern With a Spurious Sidelobe



Possible vicarious calibration sources:

- Moon → Probably too weak / broad for pattern assessment
- Land / sea boundary → Good for verification of geolocation
- Earth's limb → ***Focus for this study***

Global Comparison of AMSU-A (Aqua) with NCEP Model

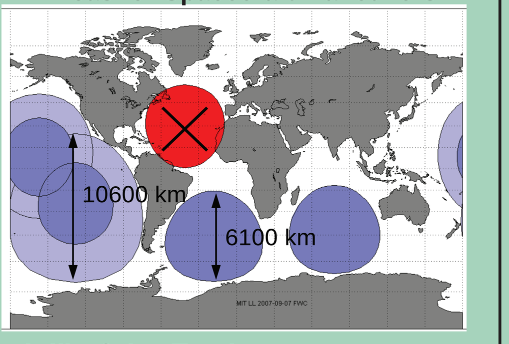


Methodology: Use the Earth's Limb for Vicarious Calibration

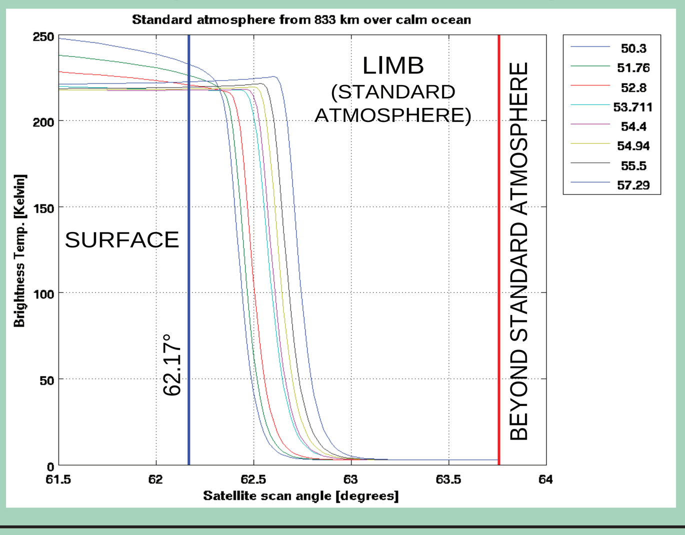
To characterize the radiometric boresight of each ATMS channel using the Earth's limb, an atmospheric characterization is required. With knowledge of the atmospheric state, the antenna pattern can be recovered with the following procedure:

1) The antenna beam is slowly swept across the target of interest
2) ATMS T_B measurements, as a function of pitch and roll, are captured
3) Then, the RMS error between measurements and simulations is minimized
   - A "first guess" pattern function is fit to the measurements
   - Free parameters include: Sidelobe location(s), width(s), and amplitude(s)
4) Re-test with sensor noise added to modeling

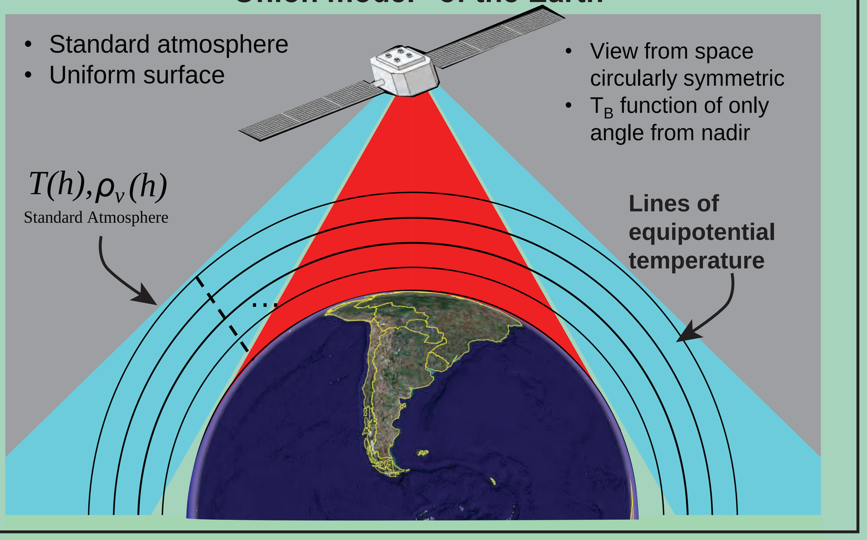
Areas for Spacecraft Maneuvers



Brightness Temperatures Across Earth / Space Transition



"Onion model" of the Earth



ATMS Image Restoration

The five FOV calibration exercises that have been analyzed for ATMS are on the right (Roll, Pitch, Cross, Star, 2-D array).

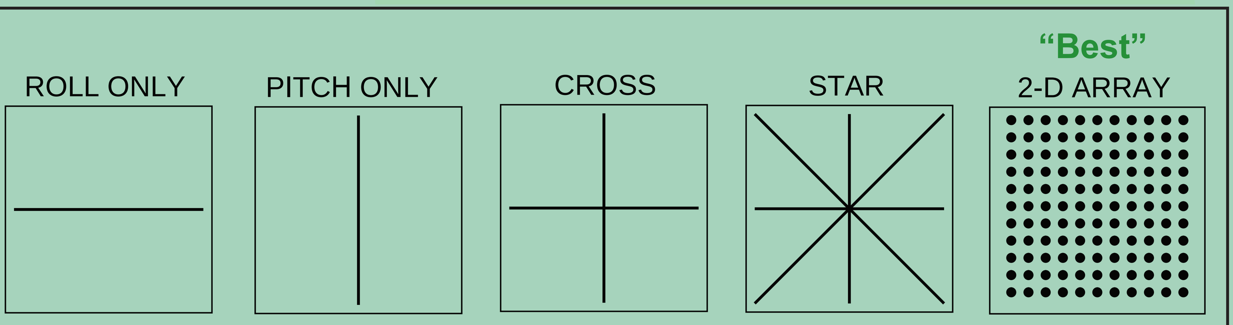
Sidelobe artifacts are a source of image distortion. ATMS images can be restored using a deconvolution technique (described below), but a two-dimensional sampling of the image space is needed for maximum benefit. The **deconvolution technique** is as follows.

Take: $\mathbf{m}(\theta, \Phi) = \mathbf{a}(\theta, \Phi) \otimes \mathbf{s}(\theta, \Phi) + \mathbf{n}$

where, $\mathbf{m}(\theta, \Phi)$ = ATMS measurements
$\mathbf{a}(\theta, \Phi)$ = ATMS antenna pattern
$\mathbf{s}(\theta, \Phi)$ = scene, ideally this would be a impulse function to allow recovery of $\mathbf{a}(\theta, \Phi)$
$\mathbf{n}$ = sensor noise

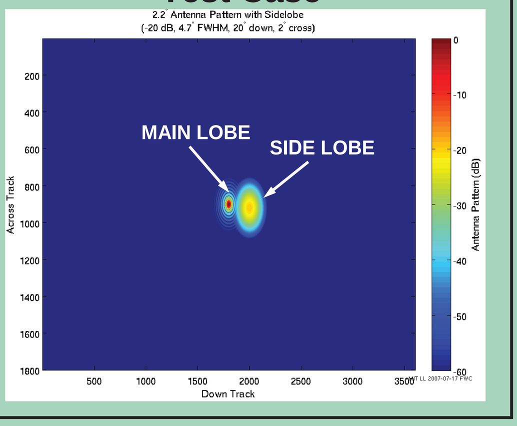
1) Approximate **s** with an un-ideal step funtion $\tilde{\mathbf{u}}$, the Earth's limb (see fig. in previous section): $\mathbf{s}(\theta, \Phi) = \tilde{\mathbf{u}}(\theta, \Phi)$

2) Estimate: $\mathbf{a}(\theta, \Phi)$ by $\frac{\delta(\mathbf{m}_u(\theta, \Phi))}{\delta_{\theta,\Phi}}$



In the simulation, a sidelobe was introduced into the ATMS FOV. Each ATMS pixel was simulated, and then the resulting image (right) was deconvolved to estimate the sidelobe.

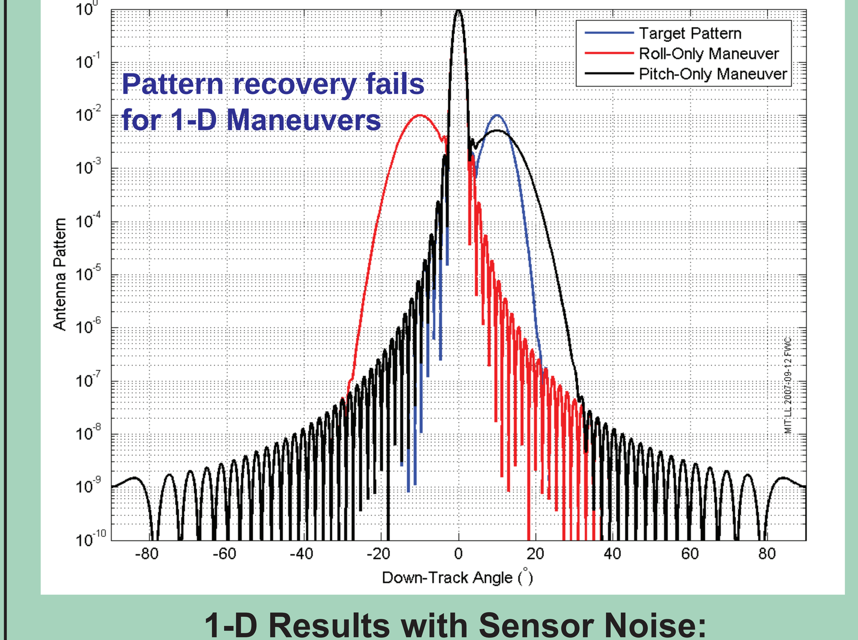
Test Case



ATMS Spacecraft Maneuver Simulation Results

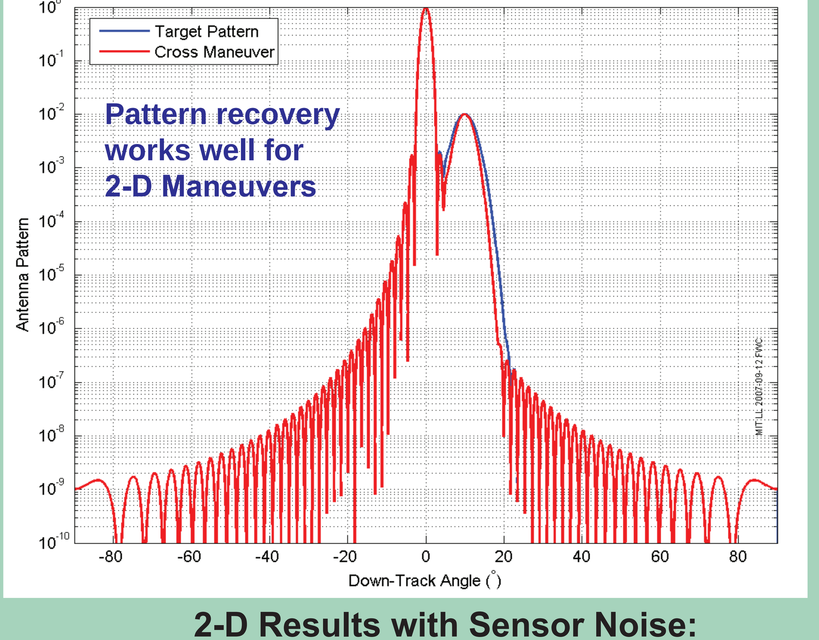
Radiative transfer simulations (described in the previous sections) were used to quantitatively assess the benefit of each satellite maneuver. Results for each satellite maneuver considered are shown below:

1-D Results



1-D Results with Sensor Noise:
- **Roll Only - FAILED**
- **Pitch Only - FAILED**

2-D Results



2-D Results with Sensor Noise:
- **Cross - SUCCESS**
- **Star - SUCCESS**
- **2-D Array - SUCCESS**

ATMS Spacecraft Maneuvers Summary

- **A preliminary study to assess and mitigate the potential impact of sidelobes on ATMS has been performed**
  - Calm ocean. Standard atmosphere, Single sidelobe model
- **Simulation components are in place to perform more sophisticated analysis, including the effects of global atmospheric variation**
- **Results suggest it is possible to accurately characterize antenna pattern sidelobes with on-orbit measurements *if 2-D maneuvers are used***
- **1-D maneuvers alone are likely to be inadequate**

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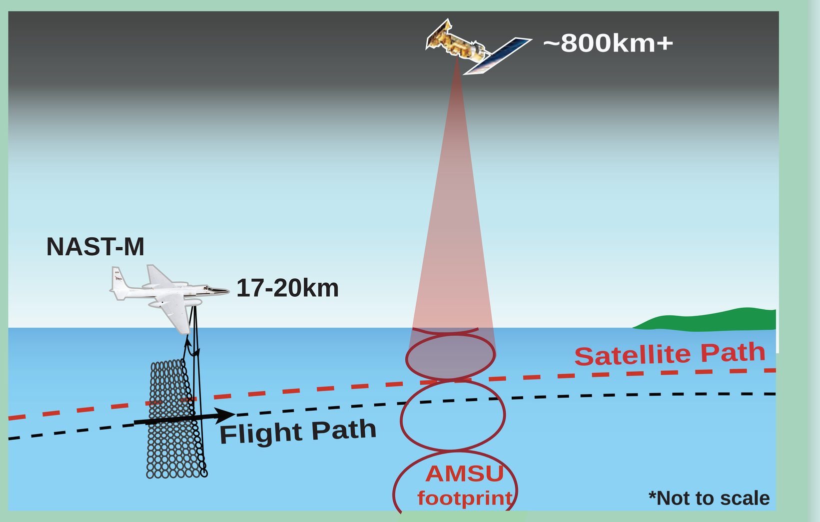
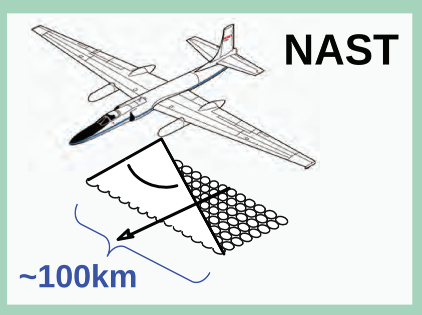
Satellite Radiometer Validation of the AMSU-A, AMSU-B, and MHS Instruments Using the NPOESS Aircraft Sounder Testbed - Microwave (NAST-M)

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

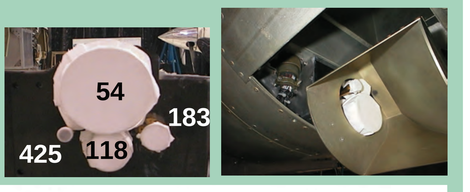
Why use aircraft measurements?
- Direct radiance comparisons
  → Mitigates modeling errors
- Mobile platform
  → High spatial and temporal coincidence achievable
- Spectral response matched to satellite
  → With additional radiometers for calibration
- Higher spatial resolution than satellite
- Additional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

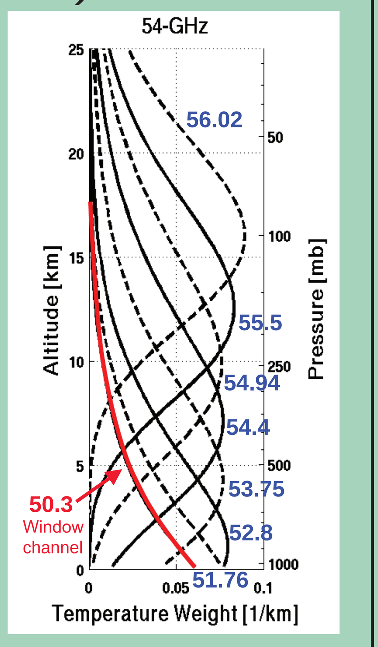


The Instrument: NPOESS Aircraft Sounder Testbed - Microwave (NAST-M)

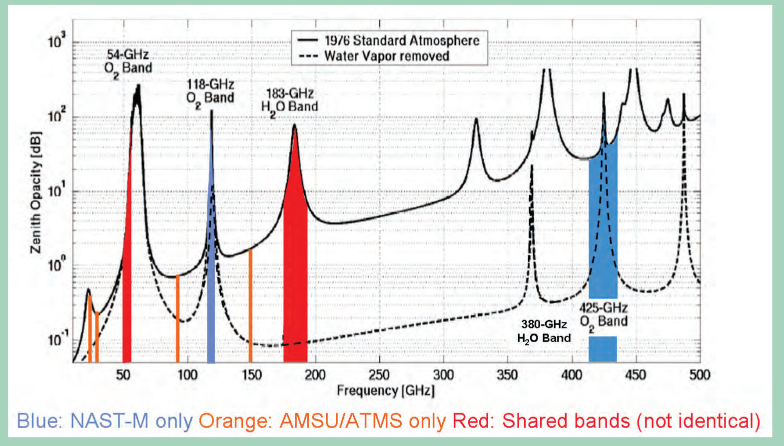


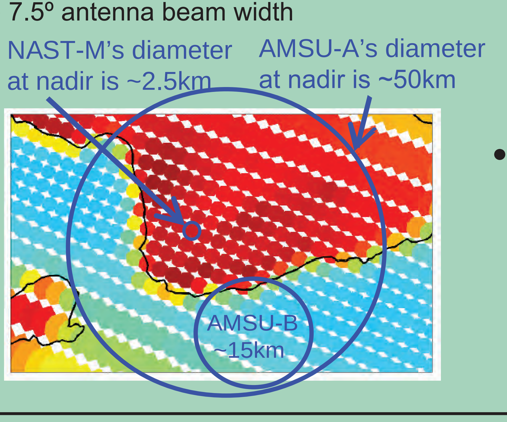
- Five spectrometers:
  23/31 GHz (to be added soon)
  54 GHz (8 O_2 channels)
  118 GHz (9 O_2 channels)
  183 GHz (6 H_2O channels)
  425 GHz (7 O_2 channels)





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



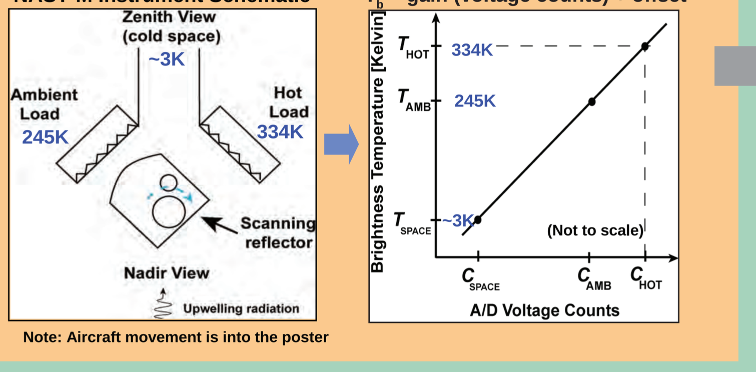


- Instrument suite flies aboard the ER-2, Proteus, and WB-57 aircraft

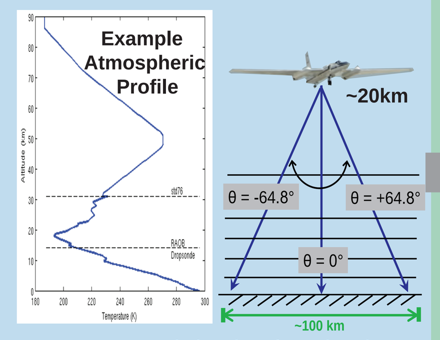
Methodology: NAST-M Calibration, Atmospheric Corrections, and Data Co-location

NAST-M Calibration

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



NAST-M Limb Correction

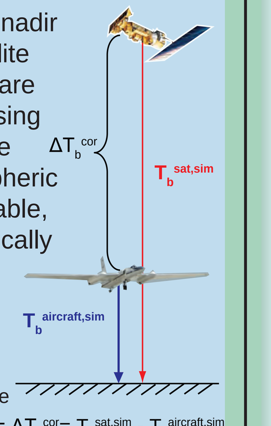


T_b across swath is simulated using RTM with the most accurate profile available, which gives $T_b^{sim}(\theta)$:

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

NAST-M Altitude Correction

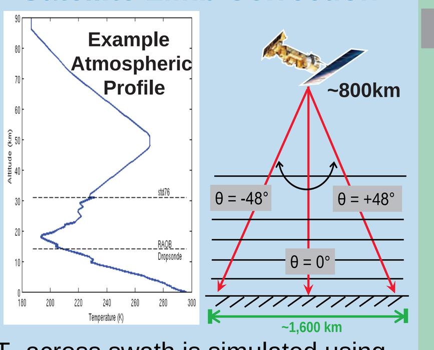
T_b values at nadir for the satellite and aircraft are simulated using RTM and the best atmospheric profile available, which is typically a hybrid of data from:
- Dropsondes
- Radiosondes
- US 1976 standard profile



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

Satellite T_b's

Satellite Limb Correction



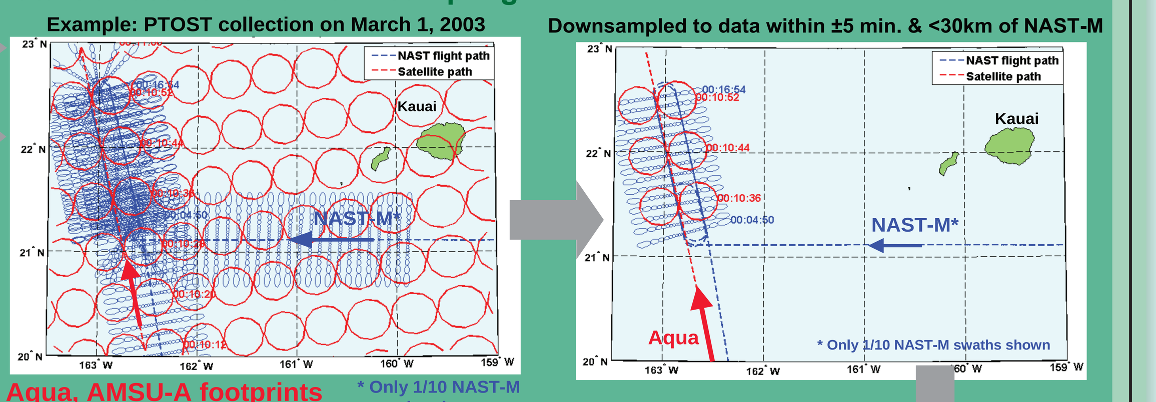
T_b across swath is simulated using RTM with the most accurate profile available, which gives $T_b^{sim}(\theta)$:

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



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.

Comparison: Averaged NAST-M T_b vs. Satellite T_b

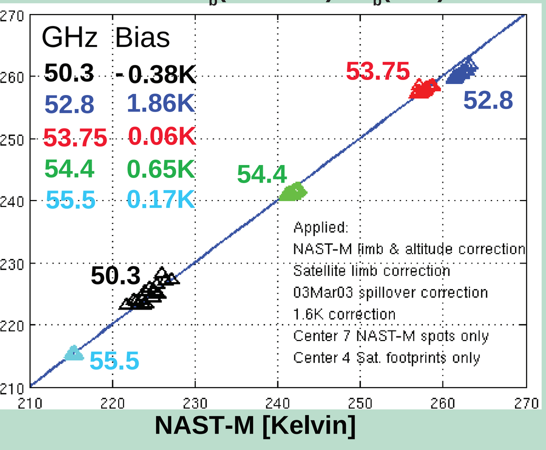
Campaigns and Results

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

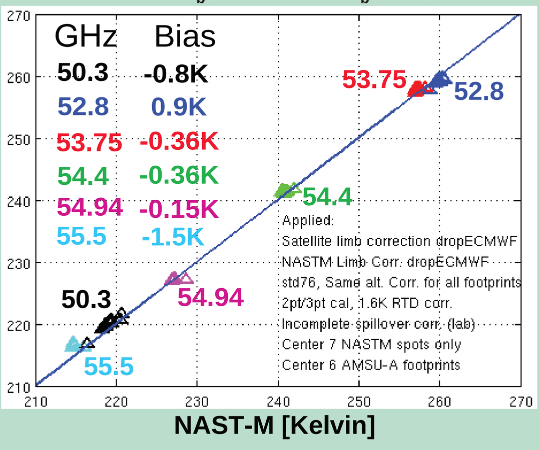
AMSU-B PTOST Bias Estimates

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

NAST-M 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

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References

- 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 Sensing, vol. 39, no. 11, pp. 2444-2453, Nov. 2001.
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