Development and Predicted Performance of the Advanced Technology Microwave Sounder for the NPOESS Preparatory Project

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Outline

- NPP ATMS overview
- Pre-launch testing
- Post-launch cal/val
- Summary
NPOESS Preparatory Project

• Launch site: Vandenberg AFB
• Launch vehicle: Boeing Delta II
• Spacecraft: Ball Aerospace Commercial Platform 2000
• Instruments: VIIRS, CrIS, ATMS, OMPS, & CERES
• Orbits: 824 km (NPP); sun-synchronous with a 10:30 a.m. local-time descending node crossing

National Polar-orbiting Operational Environmental Satellite System → Joint Polar Satellite System
ATMS Development

• ATMS NPP unit (“PFM” – ProtoFlight Module) developed by NASA/Goddard
  – Sensor builder: Northrop Grumman Electronic Systems (formerly Aerojet)
  – ATMS NPP unit delivered in 2005
  – ATMS NPOESS C1 unit currently in development

• Principal challenges/advantages:
  – Reduced size/power relative to AMSU
    Scan drive mechanism
    MMIC technology
  – Improved spatial coverage (no gaps between swaths)
  – Nyquist spatial sampling of temperature bands (improved information content relative to AMSU-A)
• ATMS is a 22 channel passive microwave sounder
• Frequencies range from 23-183 GHz
• Total-power, two-point external calibration
• Continuous cross-track scanning, with torque & momentum compensation
• Thermal control by spacecraft cold plate
• Contractor: Northrop Grumman Electronics Systems (NGES)
ATMS Design Challenge

AMSU-A1

- 73x30x61 cm
- 67 W
- 54 kg
- 3-yr life

AMSU-A2

- 75x70x64 cm
- 24 W
- 50 kg
- 3-yr life

MHS

- 75x56x69 cm
- 61 W
- 50 kg
- 4-yr life

Reduce the volume by 3x

- 70x40x60 cm
- 110 W
- 85 kg
- 8 year life
## Spectral Differences: ATMS vs. AMSU-A

<table>
<thead>
<tr>
<th>Ch</th>
<th>Center Freq. [GHz]</th>
<th>Pol</th>
<th>Ch</th>
<th>Center Freq. [GHz]</th>
<th>Pol</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23.8</td>
<td>QV</td>
<td>1</td>
<td>23.8</td>
<td>QV</td>
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<td>2</td>
<td>31.399</td>
<td>QV</td>
<td>2</td>
<td>31.4</td>
<td>QV</td>
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<tr>
<td>3</td>
<td>50.299</td>
<td>QV</td>
<td>3</td>
<td>50.3</td>
<td>QH</td>
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<tr>
<td>4</td>
<td>51.76</td>
<td>QH</td>
<td>4</td>
<td>52.8</td>
<td>QV</td>
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<tr>
<td>5</td>
<td>53.595 ± 0.115</td>
<td>QH</td>
<td>6</td>
<td>53.596 ± 0.115</td>
<td>QH</td>
</tr>
<tr>
<td>6</td>
<td>54.4</td>
<td>QH</td>
<td>7</td>
<td>54.4</td>
<td>QH</td>
</tr>
<tr>
<td>7</td>
<td>54.94</td>
<td>QV</td>
<td>8</td>
<td>54.94</td>
<td>QH</td>
</tr>
<tr>
<td>8</td>
<td>55.5</td>
<td>QH</td>
<td>9</td>
<td>55.5</td>
<td>QH</td>
</tr>
<tr>
<td>9</td>
<td>fo = 57.29</td>
<td>QH</td>
<td>10</td>
<td>fo = 57.29</td>
<td>QH</td>
</tr>
<tr>
<td>10</td>
<td>fo ± 0.217</td>
<td>QH</td>
<td>11</td>
<td>fo ± 0.3222 ± 0.217</td>
<td>QH</td>
</tr>
<tr>
<td>11</td>
<td>fo ± 0.3222 ± 0.048</td>
<td>QH</td>
<td>12</td>
<td>fo ± 0.3222 ± 0.048</td>
<td>QH</td>
</tr>
<tr>
<td>12</td>
<td>fo ± 0.3222 ± 0.022</td>
<td>QH</td>
<td>13</td>
<td>fo ± 0.3222 ± 0.022</td>
<td>QH</td>
</tr>
<tr>
<td>13</td>
<td>fo ± 0.3222 ± 0.010</td>
<td>QH</td>
<td>14</td>
<td>fo ± 0.3222 ± 0.010</td>
<td>QH</td>
</tr>
<tr>
<td>14</td>
<td>fo ± 0.3222 ± 0.0045</td>
<td>QH</td>
<td>15</td>
<td>fo ± 0.3222 ± 0.0045</td>
<td>QH</td>
</tr>
<tr>
<td>15</td>
<td>89.0</td>
<td>QV</td>
<td>16</td>
<td>88.2</td>
<td>QV</td>
</tr>
</tbody>
</table>

**Notes:**
- **Green** indicates an exact match to AMSU-A.
- **Yellow** indicates only polarization is different.
- **Gray** indicates a unique passband.
- **Red** indicates a unique passband and different polarization from the closest AMSU channel.

**Legend:**
- AMSU-A
- ATMS
## Spectral Differences: ATMS vs. MHS

The table below compares the center frequencies and polarizations of the MHS and ATMS channels.

<table>
<thead>
<tr>
<th>Ch</th>
<th>Center Freq. [GHz]</th>
<th>Pol</th>
<th>Ch</th>
<th>Center Freq. [GHz]</th>
<th>Pol</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>89.0</td>
<td>QV</td>
<td>16</td>
<td>88.2</td>
<td>QV</td>
</tr>
<tr>
<td>17</td>
<td>157.0</td>
<td>QV</td>
<td>17</td>
<td>165.5</td>
<td>QH</td>
</tr>
<tr>
<td>18</td>
<td>183.31 ± 1</td>
<td>QH</td>
<td>18</td>
<td>183.31 ± 7</td>
<td>QH</td>
</tr>
<tr>
<td>19</td>
<td>183.31 ± 3</td>
<td>QH</td>
<td>19</td>
<td>183.31 ± 4.5</td>
<td>QH</td>
</tr>
<tr>
<td>20</td>
<td>191.31</td>
<td>QV</td>
<td>20</td>
<td>183.31 ± 3</td>
<td>QH</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td></td>
<td>21</td>
<td>183.31 ± 1.8</td>
<td>QH</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td>22</td>
<td>183.31 ± 1</td>
<td>QH</td>
</tr>
</tbody>
</table>

- **QV** = Quasi-vertical; polarization vector is parallel to the scan plane at nadir
- **QH** = Quasi-horizontal; polarization vector is perpendicular to the scan plane at nadir

- **Exact match to MHS**
- **Only Polarization different**
- **Unique Passband**
- **Unique Passband, and Pol. different from closest MHS channels**
<table>
<thead>
<tr>
<th>Beamwidth (degrees)</th>
<th>ATMS</th>
<th>AMSU/MHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>23/31 GHz</td>
<td>5.2</td>
<td>3.3</td>
</tr>
<tr>
<td>50-60 GHz</td>
<td>2.2</td>
<td>3.3</td>
</tr>
<tr>
<td>89-GHz</td>
<td>2.2</td>
<td>1.1</td>
</tr>
<tr>
<td>160-183 GHz</td>
<td>1.1</td>
<td>1.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spatial sampling</th>
<th>ATMS</th>
<th>AMSU/MHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>23/31 GHz</td>
<td>1.11</td>
<td>3.33</td>
</tr>
<tr>
<td>50-60 GHz</td>
<td>1.11</td>
<td>3.33</td>
</tr>
<tr>
<td>89-GHz</td>
<td>1.11</td>
<td>1.11</td>
</tr>
<tr>
<td>160-183 GHz</td>
<td>1.11</td>
<td>1.11</td>
</tr>
<tr>
<td>Swath (km)</td>
<td>~2600</td>
<td>~2200</td>
</tr>
</tbody>
</table>

ATMS scan period: 8/3 sec; AMSU-A scan period: 8 sec
## ATMS Data Products

<table>
<thead>
<tr>
<th>Data Product</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDR (Raw Data Record)</td>
<td>FOV(^1) antenna temperature (counts)</td>
</tr>
<tr>
<td>TDR (Temperature Data Record)</td>
<td>FOV(^1) antenna temperature (K)</td>
</tr>
<tr>
<td>SDR (Sensor Data Record)</td>
<td>FOR(^1) brightness temperature (K)</td>
</tr>
<tr>
<td>EDR (Environmental Data Record)</td>
<td>P/T/WV profile</td>
</tr>
<tr>
<td>CDR (Climate Data Record)</td>
<td>“Climate-optimized” product</td>
</tr>
<tr>
<td>IP (Intermediate Product)</td>
<td>Used to generate EDR/CDR</td>
</tr>
</tbody>
</table>

\(^1\)FOV = ATMS “Field of View”; FOR = CrIMSS “Field of Regard”
• Goals:
  – Error *characterization* of radiances and derived products that is:
    Extensive (global, seasonal, all channels, etc.)
    Comprehensive (wide assortment of meteorological conditions, ground truth, etc.)
  – Error *attribution* to atmospheric, sensor, or algorithm mechanisms

• Necessary Ingredients:
  – Prelaunch sensor testing and calibration
  – Prelaunch algorithm evaluation
  – Error models and budgets (including ground truth)
  – Post-launch radiance/product characterization
  – Refinement of error models/budgets based on observations

• Detailed validation plans for SDRs and EDRs
Major Components of ATMS Post-Launch Calibration/Validation

• ATMS/CrIMSS system error model/budget
  – RDR → TDR → SDR → EDR+IP
  – Derived and evaluated with four data sources:
    Thermal Vac; Simulated data; Proxy data; Observed data

• Development of Cal/Val “machinery”
  – Teams: close-knit, multi-agency, multi-national
  – Plans: clear, actionable, prioritized, coordinated
  – Resources: ground truth, other data/sensors, tools, etc.

• Planned spacecraft maneuvers offer unique opportunity for detailed characterization of ATMS antenna pattern

• NAST-M aircraft comparisons

• Improved pre-launch characterization of future sensors
ATMS Pre-Launch Testing

• Essential for two objectives:
  – Ensure sensor meets performance specifications
  – Ensure calibration parameters that are needed for SDR processing are adequately and accurately defined

• PFM testing revealed several issues that will require calibration corrections in the SDR:
  – Non-linearity (temperature-dependent for 31.4-GHz channel)
  – Cross-polarization (sometimes 10X higher than AMSU)
  – Antenna beam spillover from secondary parabolic reflector approaching 2% for some channels

• EDR specifications may still be met (evaluation in progress) if pre-launch corrections are “valid” on-orbit

• On-orbit spacecraft maneuvers for NPP could provide improved calibration parameters to correct any scan bias
• Pre-launch SDR/EDR testing is in progress

• “Proxy” ATMS data is needed to test operational software
  – Observed data from on-orbit microwave sensors AMSU-A and MHS are transformed spatially/spectrally to resemble ATMS data
  – Captures real-world atmospheric variations better than simulations based on imperfect/incomplete surface, atmospheric, and radiative transfer models
  – Caveats: Radiometric characteristics of original sensor are embedded in proxy data

• Lincoln’s roles:
  – Generate ATMS proxy data and provide it to “NPOESS community”
  – Coordinate with other proxy data providers to ensure consistency
  – Solicit feedback from community to improve/extend data set
Example of ATMS proxy data

ATMS Channel 4, ocean, mid-latitude, January 5th, 2008 (12hrs)

Note: The most extreme scan angles are not plotted here

Due to bad scan in contributing channel
Utility of Aircraft Underflights

What do aircraft measurements provide that we cannot get anywhere else?

- Why not just compare to radiosondes or NWP?

- Direct radiance comparisons
  - Removes modeling errors

- Mobile platform
  - High spatial & temporal coincidence achievable

- Spectral response matched to satellite
  - With additional radiometers for calibration

- Higher spatial resolution than satellite

- Additional instrumentation deployed
  - Coincident video data
  - Dropsondes

Example video image

- Solar glint
- Ocean
- Clouds
MetOp Satellite Validation

JAIVEx

April 20th, 2007 collection

Gulf of Mexico

<20min

AMSU-A (MetOp) [Kelvin] vs NAST-M [Kelvin]

GHz    Bias
50.3  -0.25K
52.8   1.4K
53.75  -0.2K
54.4  -0.2K
54.94  -0.9K

Applied:
17.5km NAST-M altitude correction
1.6K RTD corr.
Lab Spillover corr.
Center 3 NAST-M spots only
Center 6 Sat; footprints only
• Spacecraft maneuvers (constant pitch up or roll, for example) could be used to sweep antenna beam across vicarious calibration sources
  – Moon (probably too weak/broad for pattern assessment)
  – Earth’s limb (requires atmospheric characterization)
    Focus of today’s presentation
  – Land/sea boundary (good for verification of geolocation)

• With knowledge of the atmospheric state, the antenna pattern can be recovered with deconvolution techniques

• Objectives of this study - quantitatively assess:
  – The benefits of various maneuvers
    How accurately can the pattern be recovered?
  – The limitations of this approach
    How much roll/pitch is needed for an adequate measurement?
    The error sources and their impact
Summary

• ATMS will continue and improve the data record provided by MSU and AMSU
  – ATMS for NPP delivered in 2005
  – NPP has a tentative launch in Oct. 2011
  – NPOESS C1 unit scheduled for testing in 2010 and delivery in ~2011

• Prelaunch testing has revealed excellent ATMS performance

• Planned post-launch validation activities will confirm performance and offer opportunities for improvement
  – Community involvement is critical
  – Conflation of different user perspectives enhances the process
Backup Slides
OBJECTIVES

- Satellite calibration/validation
- Simulate spaceborne instruments (i.e. CrIS, ATMS, IASI)
  - Preview high resolution products
  - Evaluate key EDR algorithms

INSTRUMENTS: NAST-I & NAST-M

NAST-I: IR Interferometer Sounder
NAST-M: Microwave Sounder
- 4 Bands: 54, 118, 183, 425 GHz

Cruising altitude: ~17-20 km
Cross-track scanning: -65° to 65°
Summary of ATMS Prelaunch Testing

• All key radiometric requirements were satisfied
• Radiometric accuracy exceeds 1K
• Radiometric sensitivity exceeds requirements
  – Similar to AMSU for similar effective footprint sizes
• Linearity performance generally exceeds AMSU
  – Slight temperature-dependent nonlinearity for non-nominally high instrument temperatures
• Antenna pattern testing indicates good performance
  – Some G-band data are of questionable quality
  – Schedule/budget constraints prevented exhaustive testing
  – Opportunity for spacecraft maneuvers allows improved characterization of ATMS spatial response function
Observation impact: 3dVar DAS & Forecasts

Accumulated forecast error reduction due to various observing instruments for the 24-forecasts for February 2007 - 1/2degree system.
ATMS Storm Mapping: Improvements Relative to AMSU

Black and red circles highlight “before” and “after” differences between AMSU and ATMS, and between ATMS and ATMS-sharpened, for six simulated storms validated with AMSU. Note the better definition of strong convective cells with ATMS due to its 33-km resolution and Nyquist sampling, and the better recovery of the warm rain with sharpening.

Source: Surussavadee and Staelin, NASA PMM Presentation, July 2008
Example of ATMS proxy data

ATMS Channel 4, ocean, mid-latitude, January 5th, 2008 (12hrs)

Brightness Temperature ($T_B$) [Kelvin]

Note: The most extreme scan angles are not plotted

- coast
- USGS landmask (used to identify ocean pixels)
Overview of Proxy Methodology

- Generation of ATMS proxy data is non-trivial due to spectral and spatial differences between AMSU/MHS and ATMS.

- A linear relationship (regression) is derived between ATMS and AMSU channels that are not common to both sensors.

- Simulated data are used to derive the regressions.

- The simulated data are calculated using global AIRS Level2 profile data (Dec 2004 – Jan 2006), fastem 2.0 ocean surface model, and Phil Rosenkranz’s radiative transfer package.

- The relationships between ATMS and AMSU can vary as a function of lat/lon, surface topography, and sensor scan angle. Data stratification is used to improve the fit quality.
Scanning Characteristics

### Footprints (km)

<table>
<thead>
<tr>
<th>Chan</th>
<th>Δx</th>
<th>Beam width</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2</td>
<td>74.8</td>
<td>5.2°</td>
</tr>
<tr>
<td>3-16</td>
<td>31.6</td>
<td>2.2°</td>
</tr>
<tr>
<td>17-22</td>
<td>15.8</td>
<td>1.1°</td>
</tr>
</tbody>
</table>

- Cross-track (for CrIS coincidence)
- Contiguous 1.1° cells
- Contiguous coverage at equator

### Footprints (km)

<table>
<thead>
<tr>
<th>Chan</th>
<th>Δx</th>
<th>Δy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2</td>
<td>323.1</td>
<td>141.8</td>
</tr>
<tr>
<td>3-16</td>
<td>136.7</td>
<td>60.0</td>
</tr>
<tr>
<td>17-22</td>
<td>68.4</td>
<td>30.0</td>
</tr>
</tbody>
</table>

Subsatellite track

- Swath = 2503 km
- Scan spacing
- Sample interval
- 17.6 km
- 16.0 km

(824 Km orbit, NPP)
“Onion” Model of Earth

- Standard atmosphere
- Uniform surface
- View from space circularly symmetric
- $T_B$ function of only angle from nadir

$T(h), \rho_v(h)$
Standard Atmosphere
TB’s Across Earth/Space Transition

Standard atmosphere from 833 km over calm ocean

LIMB (STANDARD ATMOSPHERE)

SURFACE

Brightness Temp. [Kelvin]

62.17°

Satellite scan angle [degrees]

BEYOND STANDARD ATMOSPHERE

50.3
51.76
52.8
53.711
54.4
54.94
55.5
57.29
Results (with sensor noise)

- **ROLL ONLY**
  - Result in same $T_B$’s

- **PITCH ONLY**
  - Noise causes problems with width estimation

- **CROSS**
  - Single dimension inadequate

- **STAR**
- **2-D ARRAY**
Proxy Methodology Details

Three step procedure:

1. Compile AIRS L2 profile ensembles for each stratification (~10,000)
   Stratifications planned:
   - Scan angle (16 angles total, from nadir out to 51.15°)
   - Ocean/Land
   - Latitude (North, Tropical and mid-latitude, South)
   - Surface pressure for Land (8 strats)
   - Total: 432 transformation matrices

2. Simulate ATMS, AMSU/MHS radiances with Rosenkranz radiative transfer model (RTM) software
   - Account for beamwidth and polarization per channel
   - Surface emissivity models:
     - For ocean, use fastem2*
     - For land, uniform distribution from [0.9 – 1]†

3. Generate 22x20 transformation matrix (“C”) via linear regression for each stratification
Compact Antenna Range Testing

- **Compact Antenna Test Range**
  - RF source illuminates the Antenna Under Test (AUT), i.e., ATMS antenna subsystem
  - Uses a parabolic reflector to collimate the electromagnetic radiation to illuminate the AUT in the far-field region
  - AUT is attached to a positioner to rotate the AUT into the proper orientation

- Test measures the power received by the AUT compared to a standard antenna with a known antenna gain pattern

- **Specifications verified:**
  - Beam pointing accuracy
  - Beamwidth
  - Beam efficiency
  - Earth intercept
Areas for Spacecraft Maneuvers with Ocean View

- Ocean has less surface emissivity variation than land
- Earth visible to 62.17° from nadir (dark blue), or 6100 km diameter
- Complete ocean view possible over Indian, S. Atlantic, Pacific
- Wide range of possibilities over Pacific (light blue)
### Summary of Key Sensor Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PFM Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Envelope dimensions</td>
<td>70x60x40 cm</td>
</tr>
<tr>
<td>Mass</td>
<td>75 kg</td>
</tr>
<tr>
<td>Operational average power</td>
<td>100 W</td>
</tr>
<tr>
<td>Operational peak power</td>
<td>200 W</td>
</tr>
<tr>
<td>Data rate</td>
<td>30 kbps</td>
</tr>
<tr>
<td>Absolute calibration accuracy</td>
<td>0.6 K</td>
</tr>
<tr>
<td>Maximum nonlinearity</td>
<td>0.35 K</td>
</tr>
<tr>
<td>Frequency stability</td>
<td>0.5 MHz</td>
</tr>
<tr>
<td>Pointing knowledge</td>
<td>0.03 degrees</td>
</tr>
<tr>
<td>NEΔT</td>
<td>0.3/0.5/1.0/2.0 K</td>
</tr>
</tbody>
</table>
ATMS Prelaunch Testing

• A variety of prelaunch testing is performed to assess performance and reliability
  – EMI/RFI
  – Mechanical
  – Radiometric
  – Antenna

• Sensor parameters characterized during testing will be used in the calibration and retrieval algorithms
  – Linearity, frequency passbands, antenna patterns, etc.
• Fully characterize the radiometric performance of the sensor over a range of operating temperatures
• Access the stability and repeatability of radiometer performance
• Measure the calibration parameters that are needed by the SDR algorithm (e.g., non-linearity correction factor)
• Validate that the sensor meets performance requirements
• Provide pre-launch performance validation in a flight-like environment