S-NPP ATMS: Antenna Temperature (TDR) Conversion to Brightness Temperature (SDR)

ATMS SDR Team

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College Park, MD

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• TDR-to-SDR Conversion Objective

• Team’s Conversion Approach

• ATMS SDR Algorithm Implementation

• Verification Results
  – CRTM & NWP/GPS-RO dataset
  – NAST-M aircraft observations
  – CRTM & ECMWF dataset

• Analysis of the S-NPP Pitchover Maneuver Scan Bias

• Path Forward
Objective

• The ATMS Temperature Data Record (TDR), i.e., the antenna temperature, is converted to a Sensor Data Record (SDR), i.e., the brightness temperature

• The general TDR-to-SDR relationship for microwave radiometers is

\[ T_A = \frac{1}{4\pi} \int G(\theta, \phi) \cdot T_B(\theta, \phi) \, d\Omega \]

• Other contributions include polarization twist, ant. pattern spillover, and sensor self emission

• The objective is to express and then invert the above relationship to convert the measured TDR into an SDR using first principles:
  – Antenna pattern measurements made in a Compact Antenna Test Range
  – S-NPP spacecraft pitchover maneuver data
  – Assumptions of the radiometric environment
Contributions to the TDR:

a) Main lobe
b) Side lobe viewing the Earth
c) Side lobe viewing deep space
d) Near-field satellite radiation

\[ T_b^{Qv} = T_b^v \cos^2 \theta + T_b^h \sin^2 \theta \]

\[ T_a^{Qv} = \eta_{me} T_b^{Qv} + \eta_{me} T_b^{Qh} + \eta_{se} E_b^{Qv} + \eta_{se} E_b^{Qh} + \eta_{sv} C_b^{Qv} + \eta_{sv} C_b^{Qh} + S_a^{Qv} \]
S-NPP Eta Derivation

- Used S-NPP ATMS antenna pattern measurements made in CATR
- Main lobe was 2.5x the channel’s beamwidth
- S-NPP G-band did not have enough dynamic range in CATR to properly calculate beam efficiency (fixed for J1)
- W-band had a high cross-pol. antenna pattern

<table>
<thead>
<tr>
<th>Principal or Co</th>
<th>Cross</th>
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<tbody>
<tr>
<td>Ch.</td>
<td>$\eta_{pp} + \eta_{sp}$ (%)</td>
</tr>
<tr>
<td>B1</td>
<td>97.82</td>
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<tr>
<td>B2</td>
<td>98.52</td>
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<td>B3</td>
<td>97.94</td>
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</tr>
<tr>
<td>B15</td>
<td>98.47</td>
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</table>

W- & G-band channels did not use the antenna pattern measurements to convert TDR to SDR
S-NPP vs J1 G-band CATR Measurements

- SDR team has several options for S-NPP
  - Option 1: don’t use the S-NPP measurements
  - Option 2: model the side lobes under the noise floor
  - Option 3: replace the S-NPP measurements under the noise floor with the J1 measurements
Near-field Satellite Radiation

- S-NPP spacecraft pitchover maneuver showed an unexpected result
- The homogenous unpolarized cosmic background radiation was not flat across scan angle
- For the TDR-to-SDR conversion, this was attributed to near-field satellite contamination (other explanations discussed later)

\[
S_a^{QV} = \beta_0^v + \beta_1^v \cdot \sin^2(\theta) \\
S_a^{QH} = \beta_0^h + \beta_1^h \cdot \cos^2(\theta)
\]

<table>
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<tr>
<th>Channel</th>
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<th>$\beta_1$</th>
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<td>7</td>
<td>0.0730</td>
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<td>19</td>
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<tr>
<td>20</td>
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<tr>
<td>22</td>
<td>-0.0689</td>
<td>1.0274</td>
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Implementing the Conversion in the Operational Code
The IDPS ATMS SDR Algorithm has a simple linear conversion from antenna temperature to brightness temperature.

BeamEffCorr is the multiplicative conversion factor for each channel and beam position (22 x 96).

ScanBias is the additive conversion factor for each channel and beam position (22 x 96).

Operational code does not distinguish between land/ocean surfaces, but it is a proposed enhancement to match NOAA heritage data products.
## Latest Coefficients in Operational PCT

The equations for BeamEffCorr and ScanBias are given as:

\[
\text{BeamEffCorr} = \frac{1 - a \times \eta_{me}^{cr}}{\eta_{me}^{co} + \eta_{se}^{co} + \eta_{se}^{cr}}
\]

\[
\text{ScanBias} = -\frac{S_a + b \times \eta_{me}^{cr}}{\eta_{me}^{co} + \eta_{se}^{co} + \eta_{se}^{cr}}
\]

<table>
<thead>
<tr>
<th>ATMS Channel</th>
<th>BeamEffCorr</th>
<th>ScanBias</th>
<th>a</th>
<th>b</th>
</tr>
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<tbody>
<tr>
<td>1 – 5</td>
<td>See above</td>
<td>See above</td>
<td>regressed</td>
<td>regressed</td>
</tr>
<tr>
<td>6 - 15</td>
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<td>See above</td>
<td>1</td>
<td>0</td>
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<tr>
<td>16 - 22</td>
<td>1</td>
<td>-Sa</td>
<td>N/A</td>
<td>N/A</td>
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</table>
Example Correction Coefficients

Beam Efficiency Correction (Multiplicative)

Scan Bias Correction (Kelvin)
Verification Results
• Validation datasets used CRTM simulations using GFS (mainly for window channels) and GPS RO (mainly for sounding channels) as inputs

• Clear skies where determined using ATMS Cloud Liquid Water retrievals (< 0.03 g/cm³)

• Collocated COSMIC GPS RO
  – +/- 60° latitude
  – About 3000 collocated measurements/month

• NWP dataset
  – GFS 64-level forecasts
  – December 20-26 2012 (7 days)
• Over ocean under dry, clear-sky, and calm conditions
• 20-26 December 2011
• Theoretical approach
S-NPP Mission Cal/Val Campaign

10 May 2013 Sortie over Gulf of CA

ATMS spot center points
NAST-M spot center points

Red: NAST-M
Green: ATMS V-band
Blue: ATMS G-band

Nadir Footprints (Spots 48 & 49)

NAST-M calibration at MIT LL

Calibration Target
TDR-to-SDR Results: K and Lower V Band

Residuals of SDR and TDR against ECMWF/CRTM for May 24, 2013 over ocean and under clear skies

* NAST-M Result from 10 May 2013; clear skies over ocean with limited # of high quality matchups
TDR-to-SDR Results: Upper Air Sounding

NAST-M Result from 10 May 2013; clear skies over ocean
TDR-to-SDR Results for W/G Band

- NAST-M Result from 10 May 2013; clear skies over ocean with limited # of high quality matchups
S-NPP Pitchover Data Analysis & ATMS Scan Bias
S-NPP Pitchover ATMS Scan Angle Bias

**Channel 1**
- QV 23.8 GHz

**Channel 16**
- QV 89 GHz

**Channel 3**
- QH 50.3 GHz

**Channel 4**
- QH 53.596 GHz
Potential Explanations

- With the Earthview sector viewing deep space, the radiometric scene is a homogenous and unpolarized source that fills the entire field of view of ATMS.

- As an unpolarized scene, the polarization twist or cross-pol. impurity issues are not the primary explanation.

- Alignment/pointing errors are unlikely due to strict subsystem quasi-optical alignment requirements that were verified during assembly.

- Skimming or spillover is a possibility, but the bias symmetry is difficult to justify.

- The bias asymmetry in the response is explained by near-field emission from the satellite, but the ATMS is positioned on the edge of the spacecraft, which doesn’t justify the cosine or sine relationship.
Potential Explanation: Flat Reflector Emissivity Model

- ATMS scanning reflector is a gold-plated beryllium flat plate, oriented 45 degrees relative to the wavefront.
- Conductive gold surface is a thin layer composed of microcrystalline granules, the emissivity can exceed the theoretical (Hagen-Rubens) emissivity of a perfectly flat bulk material.
- The layered and rough surface is difficult to accurately model or simulate.
- Values of the two polarization components can be expressed in terms of the normal emissivity derived from the Fresnel equations for reflections from a plane interface.
- Reflector is scanned relative to a fixed linear polarization feed horn, the resulting Quasi-Vertical (QV) and Quasi-Horizontal (QH) components of emissions are scan angle-dependent (Eq. 1).
- Resulting antenna temperature in Equation 2
  - \( \varepsilon_x \) is the quasi-V (QV) or quasi-H (QH) emissivity
  - \( T_{\text{refl}} \) is the physical temperature of the flat reflector

\[
\begin{align*}
\varepsilon_{\text{QV}} &= \frac{\varepsilon_n}{\sqrt{2}} \times \sin^2(\phi_{\text{scan}}) \\
\varepsilon_{\text{QH}} &= \frac{\varepsilon_n}{\sqrt{2}} \times \cos^2(\phi_{\text{scan}}) \\
T_{\text{measured}} &= (1 - \varepsilon_x) \times T_{\text{scene}} + \varepsilon_x \times T_{\text{refl}}
\end{align*}
\]
On-orbit Derivation of the Normal Emissivity

• Swept the normal emissivity in a emissivity-corrected calibration algorithm until the Earth View Sector during the pitchover was flat

• Top figure presents the radiometric EVS results of stepping the emissivity for Channel 1
  – Cyan: original uncorrected result
  – Blue: corrected results at various emissivity steps
  – Green: tuned emissivity that had the lowest EVS standard deviation metric

• Bottom plot gives the derived emissivity for each channel
  – K- and V-band flat reflector is on the left
  – W- and G-band flat reflector is on the right
  – Tuning method was not sensitive to emissivity steps less than 0.05%

• Derived emissivity explained TVAC calibration anomaly
Future Work

• TDR to SDR theoretical approach:
  – Review other options for derivation of eta (antenna pattern contributions), e.g., agree on use of W/G band measurements or utilize S-NPP roll maneuvers
  – Evaluate other options for modelling radiation sources like the opposite quasi-polar and Earth radiation

• The TDR to SDR conversion in IDPS:
  – Enhance SDR algorithm to handle ocean and land surfaces separately for the scan bias correction
  – Investigate how the IDPS correction can implement the theoretical approach more accurately

• Flat reflector emissivity:
  – Characterize emissivity by measuring flat reflectors, which is presently underway at NGES
  – The TDR (not SDR) emissivity-corrected algorithm has been developed
  – The above corrected TDR algorithm needs to be implemented in IDPS and a LUT of coefficients added to the ATMS SDR PCT
Backup Slides
Utility of the S-NPP Spacecraft Maneuvers

- The S-NPP pitchover maneuver provided crucial data that is extremely difficult to replicate in pre-launch testing.

- Pitchover data is helping characterize the scan bias on ATMS, and potentially providing insight into other heritage cross-track microwave instruments.

- Pitchover data was used for the striping investigation to determine if the root cause was related to the scene radiance and for determining a striping metric.

- Roll maneuvers provided value data for the selection of the ATMS space view sector.

- Additional efforts are underway to utilize the roll maneuvers to characterize beam efficiency and scan bias.
Estimating Contribution Parameters For Theoretical Expression

\[ T_a^{Q_v} = \eta_{me}^{vv} T_b^{Q_v} + \eta_{me}^{hv} T_b^{Q_h} + \eta_{se}^{vv} E_b^{Q_v} + \eta_{se}^{hv} E_b^{Q_h} + (\eta_{sc}^{vv} + \eta_{sc}^{hv}) T_{c,RJ} + S_a^{Q_v} \]

Solve for SDR in the above equation:

\[ \begin{align*}
T_b^{Q_h} &= A^v(\theta) T_b^{Q_v} \\
E_b^{Q_v} &= T_b^{Q_v} \\
E_b^{Q_h} &= T_b^{Q_h} \\
S_a^{Q_v} &= \beta_v^0 + \beta_v^1 \cdot \sin^2(\theta) \\
S_a^{Q_H} &= \beta_h^0 + \beta_h^1 \cdot \cos^2(\theta)
\end{align*} \]

Assumptions and caveats summarized next.

\[ T_b^{Q_v} = \begin{bmatrix} T_a^{Q_v} - (\eta_{sc}^{vv} + \eta_{sc}^{hv}) T_c - S_a^{Q_v} \end{bmatrix} / \begin{bmatrix} \eta_{me}^{vv} + \eta_{se}^{vv} + A^v (\eta_{me}^{hv} + \eta_{se}^{hv}) \end{bmatrix} \]

Assumptions and caveats summarized next.

\[ me = \text{main lobe earth}; \ se = \text{side lobe earth}; \ sc = \text{side lobe deep space} \]
Theoretical Expression’s Assumptions & Caveats

• The etas were calculated from the Compact Antenna Test Range measurements of the S-NPP ATMS antenna patterns

• The Earth $T_b$ seen by the side lobe is approximated as the same as the main lobe Earth $T_b$
  \[ E_b^{Qy} = T_b^{Qy} \]

• Because ATMS only measures a single quasi-polarization, the opposite polarization $T_b$ was estimated as a linear estimate of the measured quasi-pol. $T_b$
  – Regression used ocean simulations (CRTM)
  – Regression was only applied to window channels (1-5 & 16)
  – Upper sounding and G-band channels used their measured quasi-pol. $T_b$ instead

• The near-field satellite radiation was modelled using the S-NPP pitchover maneuver data
  \[ S_a^{Qy} = \beta_0^y + \beta_1^y \cdot \sin^2(\theta) \]
Sidelobe Intercept with Deep Space

- Side lobe intercept of deep space was estimated using the CATR antenna pattern measurements.

- G-band measurements at far angles (which side lobes would intercept deep space) was limited by noise floor of the CATR and set to zero.

- W-band measurements of the cold space contributions resulted in unrealistic values and were not used.
Quasi-pol. Approximation

• Simulated Ocean Radiances
  – CRTM (fastem v4)
  – US std atmosphere
  – 5 m/s wind speed
  – 290 K surface temp.

• Linear regression between the two quasi-polarizations provided the conversion factor $A(\theta)$
  
  \[ T_b^{Oh} = A^v(\theta)T_b^{Ov} \]
  
  \[ T_b^{Ov} = A^h(\theta)T_b^{Oh} \]

• Contribution in conversion:

\[ A^v(\eta_{me}^{hv} + \eta_{se}^{hv}) \]

<table>
<thead>
<tr>
<th>Ch.</th>
<th>(\eta_{me}^{hv} + \eta_{se}^{hv}) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<tr>
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<td>0.99 1.02 0.86</td>
</tr>
<tr>
<td>3</td>
<td>1.46 1.56 1.33</td>
</tr>
<tr>
<td>4</td>
<td>1.38 1.39 1.03</td>
</tr>
<tr>
<td>5</td>
<td>1.35 1.41 1.37</td>
</tr>
</tbody>
</table>

Circle = horizontal pol.
Asterisk = vertical pol.
Solid = quasi-pol.
Dashed = pure pol.
Implementing the Contribution Parameters in IDPS

\[
T_a^{Qv} = \eta_{me}^{vv}T_b^{Qv} + \eta_{me}^{hv}T_b^{Oh} + \eta_{se}^{vv}E_b^{Qv} + \eta_{se}^{hv}E_b^{Oh} + (\eta_{sc}^{vv} + \eta_{se}^{hv})T_c,_{RJ} + S_a^{Qv}
\]

\[
T_b^{Oh} = a(\theta) \cdot T_a^{Qv} + b(\theta)
\]

\[
E_b^{Qv} = T_b^{Qv}
\]

\[
E_b^{Oh} = T_b^{Qv}
\]

Solve for SDR in the above equation (but with two changes above in red):

\[
T_b = \left( T_a - S_a - (a \cdot T_a + b) \cdot \eta_{me}^{cr} \right) / \left( \eta_{me}^{co} + \eta_{se}^{co} + \eta_{se}^{cr} \right)
\]

Assumptions and caveats summarized next.

\[ co = vv \text{ or } hh \]
\[ cr = vh \text{ or } hv \]

\[ me = \text{main lobe earth}; se = \text{side lobe earth}; sc = \text{side lobe deep space} \]
Implementation Assumptions & Caveats

• Differences from theoretical approach:
  – Side lobe intercept with deep space was removed
  – Opposite quasi-pol. of Earth sidelobe is treated as SDR
  – Opposite quasi-pol. is estimated from measured quasi-pol. antenna temperature (instead of treating it as a brightness temperature)

\[ E_{b}^{Oh} = T_{b}^{Qv} \]

• Parts that were kept the same as the theoretical approach:
  – The Earth \( T_b \) seen by the side lobe is approximated as the same as the main lobe

\[ E_{b}^{Qv} = T_{b}^{Qv} \]

  – Opposite polarization \( T_b \) was estimated as a linear equation of the measured quasi-pol. \( T_a \) (theoretical did use \( T_b \))

\[ T_{b}^{Oh} = a(\theta) \cdot T_{a}^{Qv} + b(\theta) \]

  – The near-field satellite radiation was modelled using the S-NPP pitchover maneuver data

\[ S_{a}^{Qv} = \beta_{0}^{v} + \beta_{1}^{v} \cdot \sin^{2}(\theta) \]
Observations, Simulations and Angular Biases (CRTM & GFS/GPS-RO)

Ch. 2

Ch. 8

Scan Angle

TDR (K)  O - B (K)

Scan Angle

TDR (K)  O - B (K)

Scan Angle

TDR (K)  O - B (K)

Scan Angle

TDR (K)  O - B (K)

 Scan Angle

O  B - - - O-B
Radiance Versus Modeling Verification

Radiance to Radiance Comparisons

- Separate sensors measuring nearly the same point at the same time
- Examples include Simultaneous Nadir Observations (SNO) or aircraft underflights
- Pros: same atmosphere and surface conditions with similar instrumentation
- Cons: Different spectral or spatial characteristics and small data sets

Radiance to Model Comparisons

- Model the sensor and the atmosphere
- Examples include using state-of-the-art NWP, radiative transfer, and surface models
- Pros: large amounts of data
- Cons: Idealized or measured spectral or spatial characteristics; and modeling errors in the models
V-band ATMS vs NAST-M: 10 May 2013

- Used nadir spots only
- ATMS is the mean of spots 48 and 49
- NAST-M is the mean of spots 13, 14, 15
- For each ATMS “pseudo nadir spot,” the average of all NAST-M spots are taken within the 2.2 deg. beam (31.6 km)
Used nadir spots only

ATMS is the mean of spots 48 and 49

NAST-M is the mean of spots 12 through 16

For each ATMS “pseudo nadir spot,” the average of all the NAST-M spots are taken within the 1.1 deg. beam (15.8 km)

G-band ATMS vs NAST-M: 10 May 2013
NOAA-14 MSU Deep Space Scan Bias

MSU Ch. 1 50.36 GHz

MSU Ch. 2 53.74 GHz

MSU Ch. 3 54.96 GHz

MSU Ch. 4 57.95 GHz

NOAA-14 Pitch Over Maneuver

ATMS Ch. 3

ATMS Ch. 6

ATMS Ch. 8

ATMS Ch. 10
Emissivity Correction Parameters

• First parameter is the physical temperature of the flat reflector
  – No temperature sensor is on the reflector, but used a nearby sensor on the scan drive mechanism
  – Calibration algorithm is fairly insensitive to the reflector temperature (i.e., temp. is multiplied by the emissivity), which was confirmed by a sensitivity study (i.e., adding 10° C showed marginal impact)

• Second parameter is the normal emissivity for each band (or channel)
  – Difficult to model or derive a theoretical equation
  – Plans are in preparation to measure angle-dependent emissivity on spare flight-like reflectors
  – Used pitchover maneuver to “fit” a normal emissivity value to each channel
Calibration Algorithm Correction

Correction impacts three parts of the calibration equation:

\[ T_{measured} = g \times (C_{scene} - C_{sv}) + T_{sv} \quad \text{(Eq. 3)} \]

SV = Space View

1. The deep space radiometric counts are corrupted by the reflector’s physical temperature and must be corrected in the deep space brightness temperature:

\[ T_{sv} = \rho \times T_{DS} + \varepsilon_{SV} \times T_{refl} = T_{DS} + \frac{\varepsilon_n}{\sqrt{2}} \times \sin^2(\phi_{SV}) \times (T_{refl} - T_{DS}) \quad \text{(Eq. 4)} \]

2. Since the hot and cold calibration views are at different angles, the gain must be corrected for the reflector emissivity contribution:

\[ g = \frac{T_{HC} + \varepsilon_{HC} \times (T_{refl} - T_{HC}) - T_{sv} - \varepsilon_{SV} \times (T_{refl} - T_{SV})}{C_{HC} - C_{SV}} \quad \text{(Eq. 5)} \]

HC = Hot Cal (i.e., ambient)

3. Finally, the scene brightness temperature is corrupted and this correction must be applied:

\[ T_{scene} = \frac{T_{measured} - \varepsilon_x \times T_{refl}}{1 - \varepsilon_x} \quad \text{(Eq. 6)} \]

\[ \varepsilon_x \] is the quasi-V (QV) or quasi-H (QH) emissivity

SV = Space View

T_{DS} = Deep Space T_b
K- & W-Band Error Plots (Kelvin)

ICVS TDR Histogram ranges from 140 to 240 K
(no strong peak)
Worst case: ~0.4 K at nadir

ICVS TDR Histogram ranges from 200 to 280 K
(no strong peak)
Worst case: ~0.4 K at nadir
V- and G-Band Error Plots (Kelvin)

ICVS TDR Histogram ranges from 210 to 265 K (peak ~230 K)  
Worst case: ~0.1 K at nadir

ICVS TDR Histogram ranges from 240 to 290 K (peak ~285 K)  
Worst case: ~0.15 K
• The error of quasi-V channels moved close to zero at the two calibration points
• V-band quasi-H channels also moved closer to zero
• Next chart shows W- and G-band results
The two bands measuring the same external variable target now measure a similar radiometric signature after correction.

Analysis of external variable target indicates a ~1.3 K gradient across target, which might explain remaining cal. target discrepancy.
Nonlinearity Over Full Dynamic Range

Did not significantly impact nonlinearity measurement
ATMS TDR-to-SDR Conversion

- ATMS antenna temperature to brightness temperature conversion
  - NOAA STAR has identified a TDR-to-SDR conversion approach for ATMS utilizing:
    - Pre-launch antenna pattern measurements
    - S-NPP pitchover maneuver data
  - NOAA STAR implemented the conversion in the ATMS SDR Algorithm
  - Verified approach and implementation using:
    - CRTM & GFS/GPS-RO
    - CRTM & ECMWF
    - Aircraft measurements

- Investigating the S-NPP pitchover maneuver scan bias
  - Primary explanation is higher than expected flat reflector emissivity
  - Emissivity measurements under way at NGES
  - TDR algorithm correction prepared
  - Correction needs to be coded for IDPS