ATMS Algorithm Verification and Improvements to Reduce Radiometric Biases

V. Leslie, B. Blackwell, M. DiLiberto, I. Osaretin, J. Meyer, and M. Tolman (MIT LL)

Kent Anderson (NGES)

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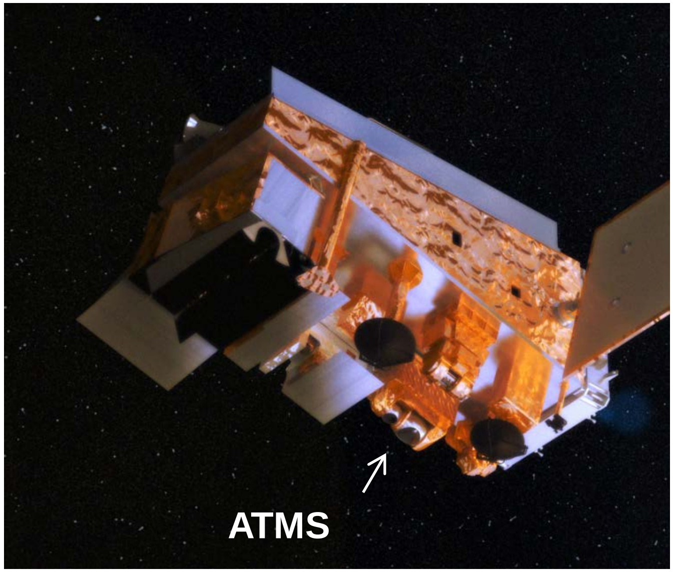
Outline

- Update on the Flat Reflector Emissivity
- Icelandic S-NPP Aircraft Cal/Val Campaign
- Radiometric Environment Characterization
- On-orbit Single Events Upsets
- Future Work

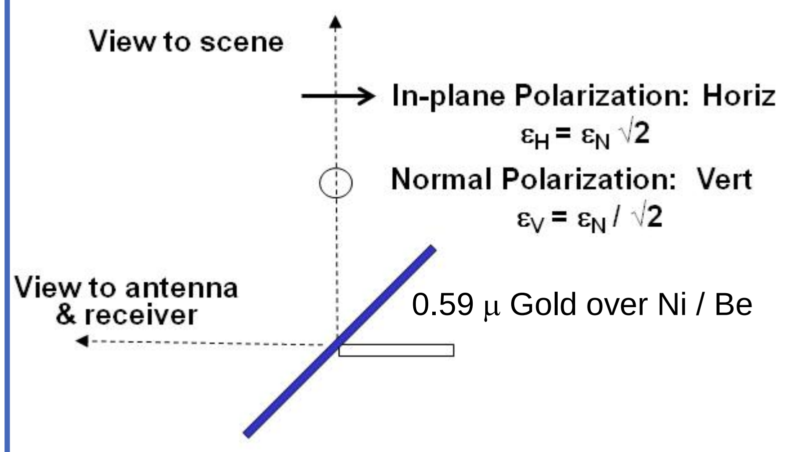
Pitchover Bias: Potential Explanations

- 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 (a nickel layer bonds the two)**
- **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**



Scanning Reflector Geometry

Vertical and Horizontal brightness temperatures will be:

$$T_{BV} = \rho_V T_{SV} + \varepsilon_V T_R$$

$$T_{BH} = \rho_H T_{SH} + \varepsilon_H T_R$$

where : ρ_V = **reflectivity of the reflector** = $1-\varepsilon_V$,
$T_{SV,SH}$ = **brightness temperature of the scene, viewed by the reflector**
T_R = **physical temperature of the reflector**

SV = Scene Vertical Pol.
SH = Scene Horiz. Pol.

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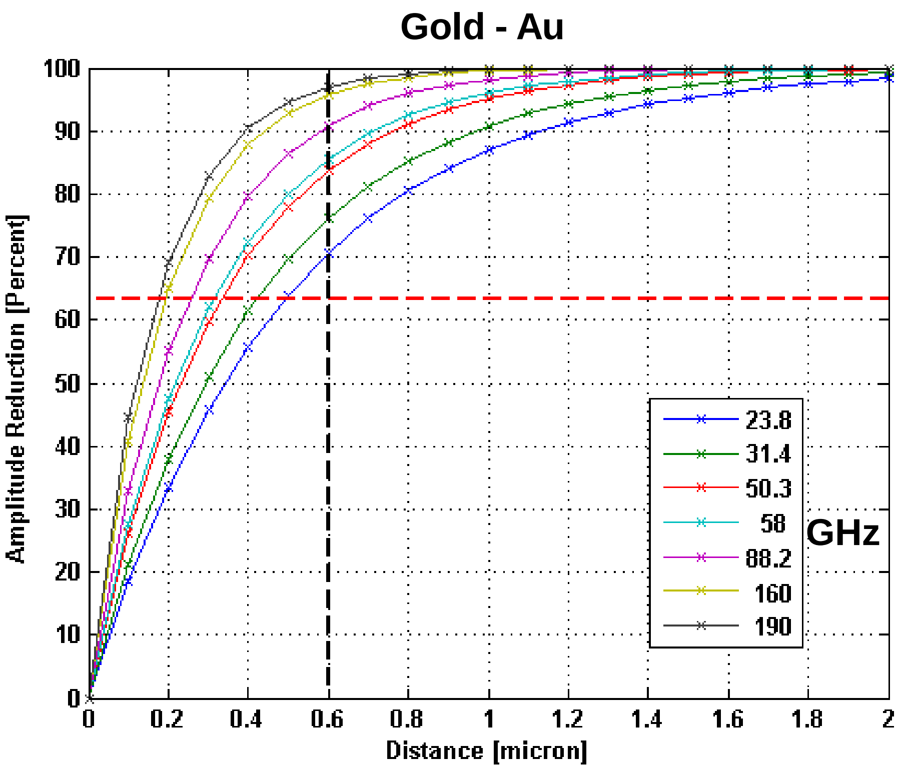
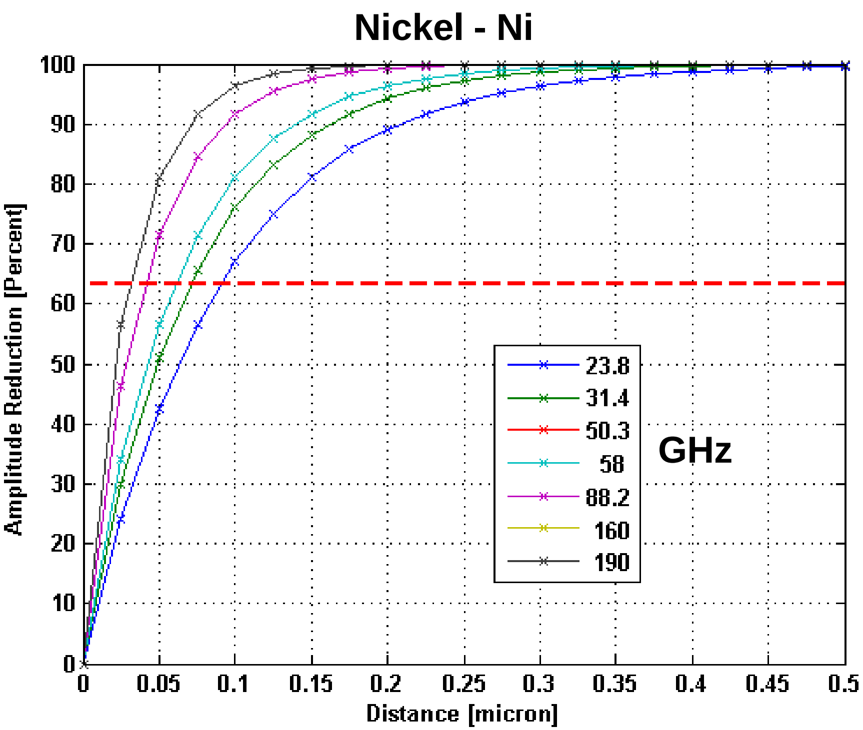
Penetration Depth in Metal





Adding The Scanning Flat Reflector

When the reflector scans to an angle ϕ, the resulting Quasi-Vertical (QV) and Quasi-Horizontal (QH) outputs:

$$T_{QV} = T_{BV}\cos^2\phi + T_{BH}\sin^2\phi$$

Substitute T_{BV} and T_{BH}

$$T_{QV} = T_{SV}\cos^2\phi + T_{SH}\sin^2\phi + \frac{\varepsilon_N}{\sqrt{2}}\left[T_R + T_{SV} - 2T_{SH}\right]\sin^2\phi + \frac{\varepsilon_N}{\sqrt{2}}\left(T_R - T_{SV}\right)$$

$$T_{QH} = T_{BV}\sin^2\phi + T_{BH}\cos^2\phi$$

$$T_{QH} = T_{SV}\sin^2\phi + T_{SH}\cos^2\phi + \frac{\varepsilon_N}{\sqrt{2}}\left[T_R + T_{SV} - 2T_{SH}\right]\cos^2\phi + \frac{\varepsilon_N}{\sqrt{2}}\left(T_R - T_{SV}\right)$$

For the case of an unpolarized ($T_{SH} = T_{SV} = T_{CS}$) scene, at T_{CS}:

$$T_{QV} = T_{CS} + \frac{\varepsilon_N}{\sqrt{2}}\left[T_R - T_{CS}\right]\sin^2\phi + \frac{\varepsilon_N}{\sqrt{2}}\left(T_R - T_{CS}\right)$$

$$T_{QH} = T_{CS} + \frac{\varepsilon_N}{\sqrt{2}}\left[T_R - T_{CS}\right]\cos^2\phi + \frac{\varepsilon_N}{\sqrt{2}}\left(T_R - T_{CS}\right)$$

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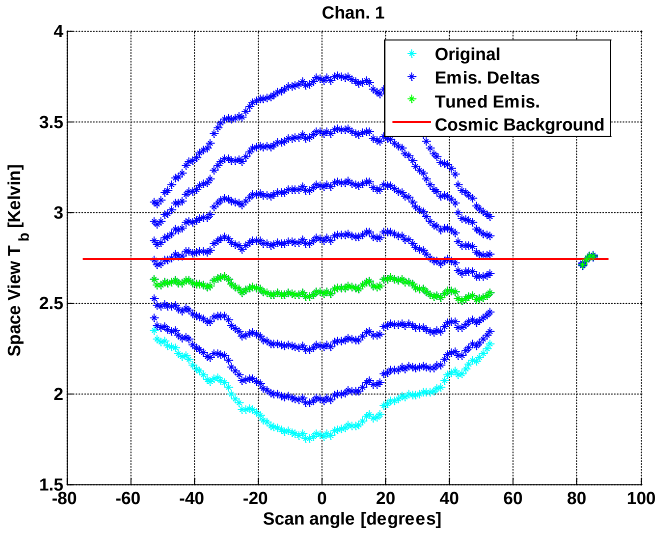
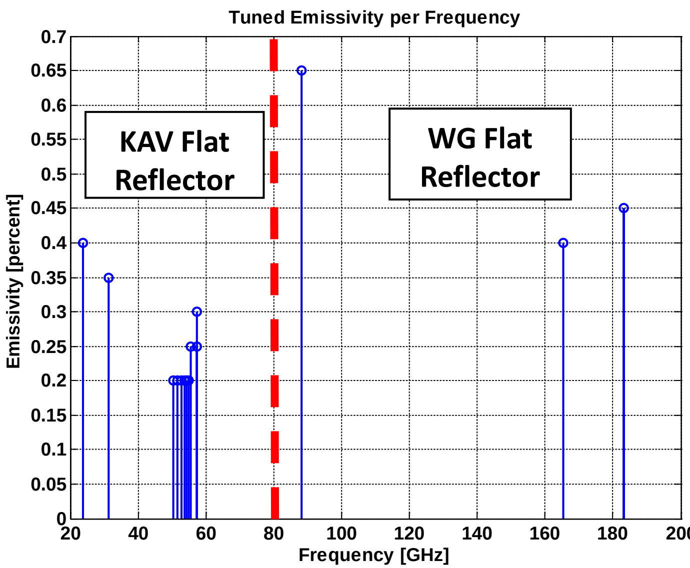
Emissivity Correction Parameters

- First parameter is the physical temperature of the flat reflector
  - There is no temperature sensor on the reflector, but there is on the Scan Drive Motor (SDM) and NGES has a thermal model to adjust the SDM temp. to a reflector temp.
  - Calibration algorithm is fairly insensitive to the reflector temperature (i.e., temp. is multiplied by the emissivity), which was confirmed by a rough sensitivity study
- Second parameter is the normal emissivity for each band (or channel)
  - Difficult to model or derive a theoretical equation
  - Three empirical methods were used to derive emissivity:
    - Used pitchover maneuver to "fit" a normal emissivity value to each channel
    - Derived from two precision calibration targets at similar temperatures but different angles during TVAC calibration
    - Measured the emissivity of flight-like spares (NGES)

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**





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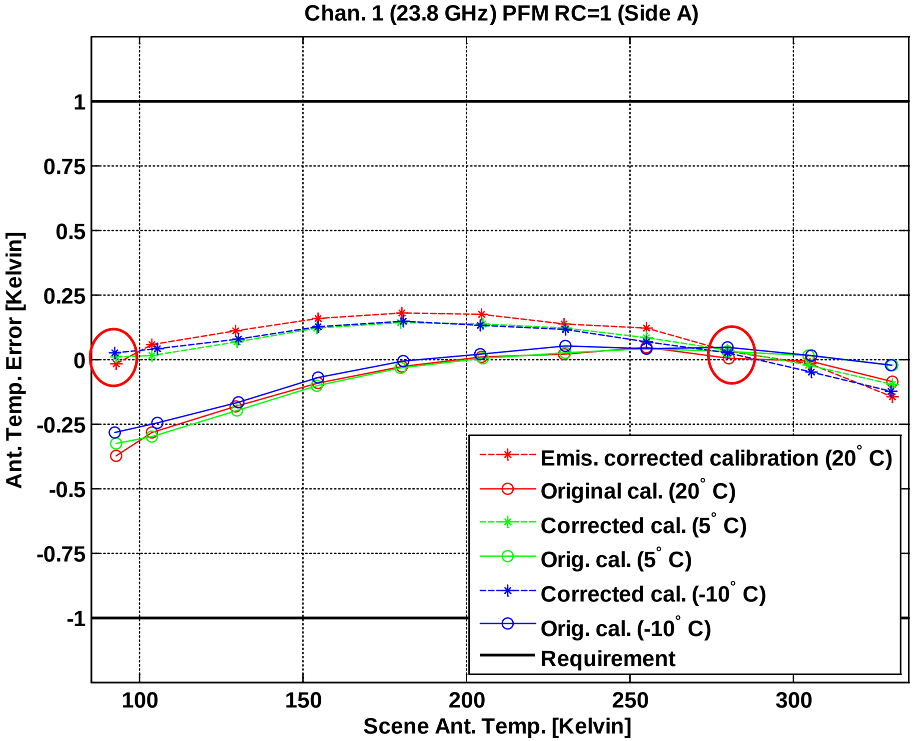
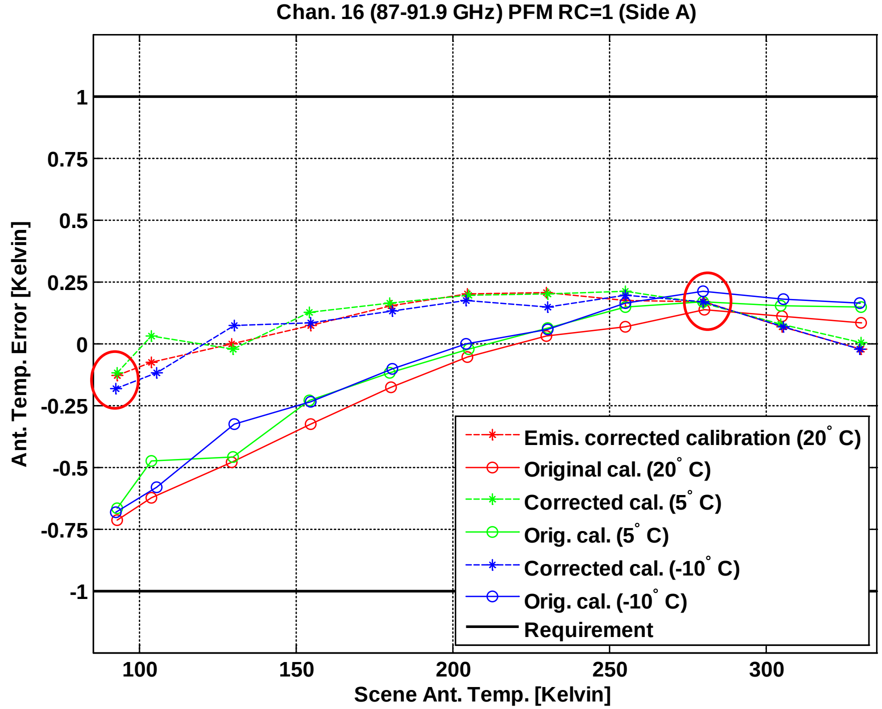
Applying Correction to Calibration Testing





- **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**

NGES Emissivity Measurement

- **NOAA/NASA asked NGES to measure the emissivity of the flight spare flat reflector to confirm on-orbit measurements**
- **NGES measured the emissivity of three flat reflectors:**
  - **Spare flight reflector (Au/Ni/Be)**
  - **Bulk Aluminum (6061)**
  - **Stainless Steel (304)**
- **Setup and more details coming up:**
  - **Flight spare's emissivity trend across bands (i.e., frequency) was verified**
  - **Absolute values were different than on-orbit measurements**
  - **Analytical (i.e., Hagen-Rubens) values did not match**

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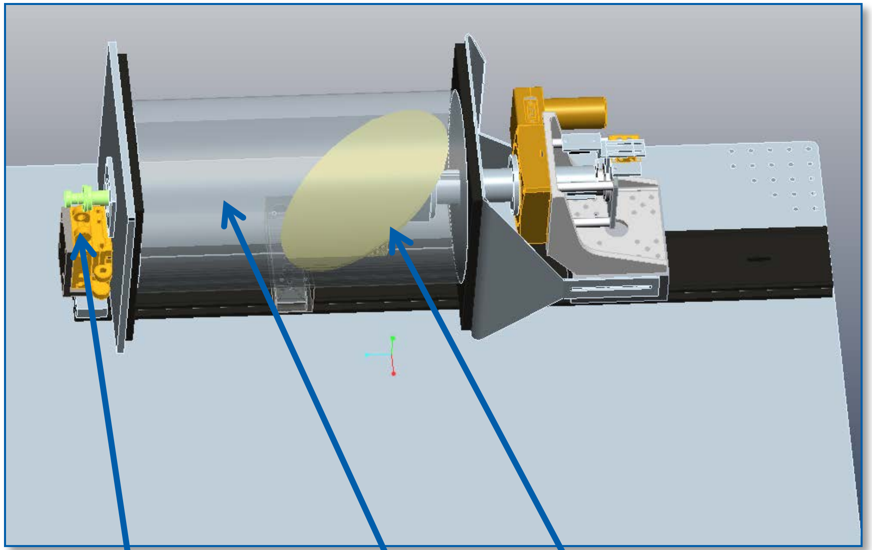
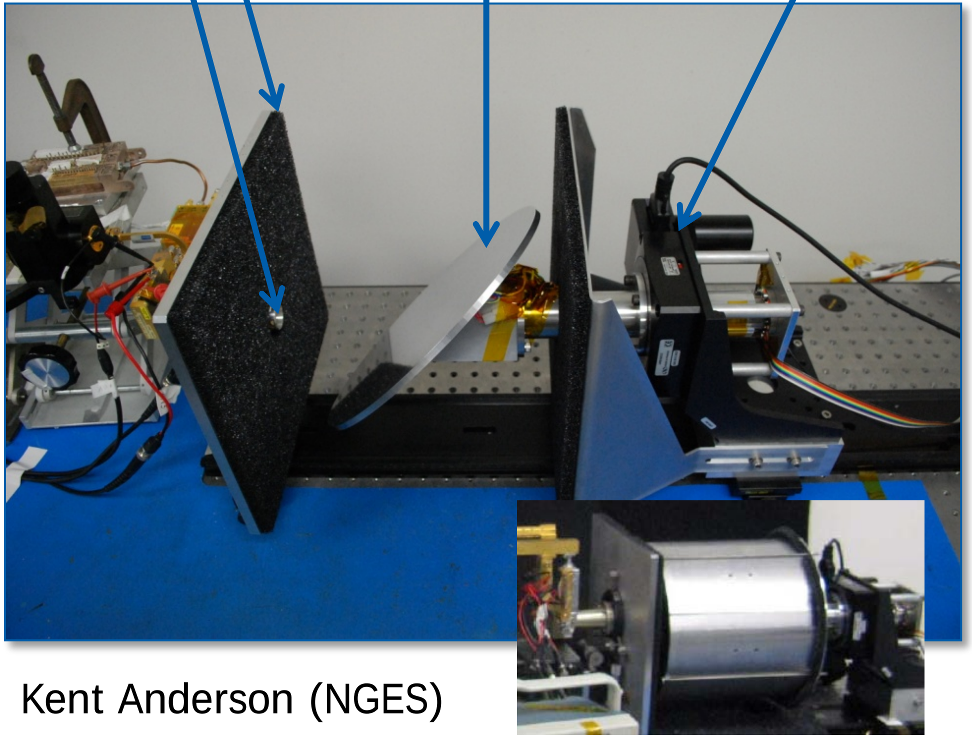
Special Test for Reflector Emissivity

- A special test was performed using a spare flight reflector to make a direct measurement of its polarized emissivity
  - Reflector was heated to produce contrast between reflector emission and energy reflected from a blackbody shroud
  - Reflector rotated at constant rate (1 Hz) and data processing extracted the 2 Hz sinusoidal component due to emissivity





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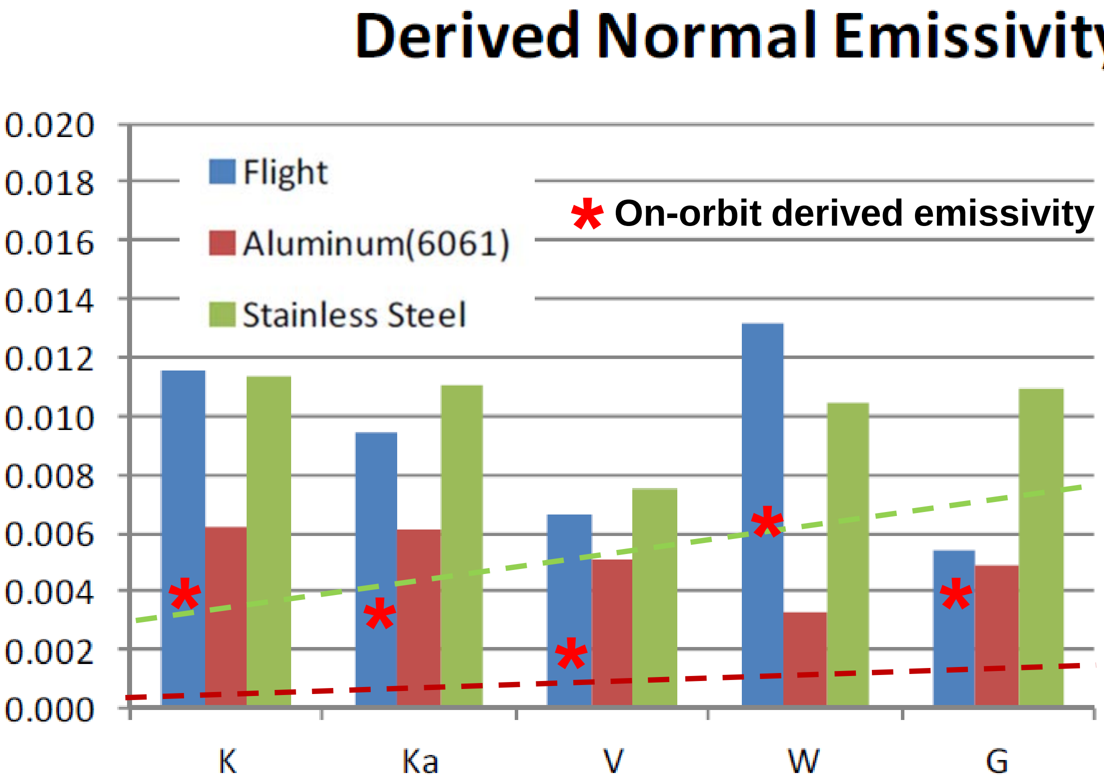
NGES Test Results



Results:

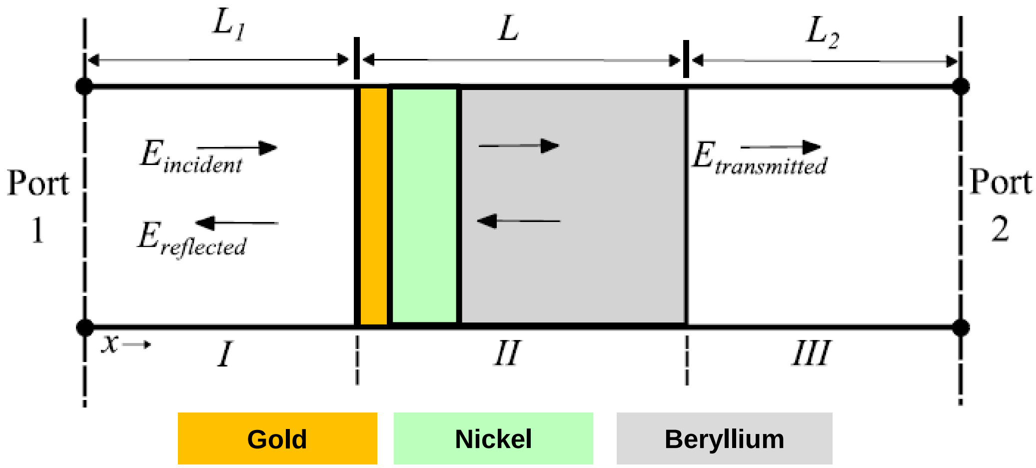
- Flight trend matches on-orbit trend
- No freq. trend with Al or SS
- SS is higher than Al

- **Hagen-Rubens expects 2.8 times the emissivity between K and G-band**
  - **Smooth bulk Al = 0.0005 to 0.0015**
  - **Smooth bulk SS = 0.0027 to 0.0076**
- **Hagen-Rubens expects 5 times the emissivity between SS and Al**

K. Anderson NGES RE-19494 "Reflector Emissivity Test Report"

Simulating the Normal Emissivity

- **Non-resonant characterization method using rectangular waveguide**



- **Numerical computation via HFSS FEA modeling**
- **Scattering parameters are obtained for waveguide**
- **Application of Nicolson-Ross-Weir Algorithm is used on computed S-parameters to obtain reflection coefficient**
- **HFSS Huray roughness model had 10 µm nodule radius and 2.9 Hall-Huray surface ratio**

Idahosa Osaretin (MIT LL)

Simulated Emissivity Results for Aluminum and Stainless Steel (WIP)

% emissivity

<table>
<tr><th>Channel</th><th>Freq. (GHz)</th><th>Analytical Emissivity (Al)</th><th>Numerical Emissivity (Smooth Al)</th><th>Numerical Emissivity (Rough Al)</th><th>NGES Measured Al</th><th>Analytical Emissivity (SS)</th><th>Numerical Emissivity (Smooth SS)</th><th>Numerical Emissivity (Rough SS)</th><th>NGES Measured SS</th></tr>
<tr><td>1 (QV)</td><td>23.8</td><td>0.05464</td><td>0.054665</td><td>0.054666</td><td>0.622</td><td>0.27046</td><td>0.05652</td><td>0.05659</td><td>1.131</td></tr>
<tr><td>2 (QV)</td><td>31.4</td><td>0.06276</td><td>0.222123</td><td>0.222126</td><td>0.608</td><td>0.31066</td><td>0.22458</td><td>0.22468</td><td>1.102</td></tr>
<tr><td>3 (QH)</td><td>50.3</td><td>0.07944</td><td>0.043947</td><td>0.043950</td><td rowspan="5">0.514</td><td>0.39319</td><td>0.18071</td><td>0.66068</td><td rowspan="5">0.753</td></tr>
<tr><td rowspan="2">6 (QH)</td><td rowspan="2">53.596</td><td rowspan="2">0.08199</td><td rowspan="2">0.052666</td><td rowspan="2">0.052668</td><td>0.40586</td><td>0.20756</td><td>0.75451</td></tr>
<tr><td rowspan="2">0.40890</td><td rowspan="2">0.21316</td><td rowspan="2">0.77502</td></tr>
<tr><td>7 (QH)</td><td>54.4</td><td>0.08061</td><td>0.054264</td><td>0.054267</td></tr>
<tr><td>10 (QH)</td><td>57.29</td><td>0.08476</td><td>0.066365</td><td>0.066368</td><td>0.41962</td><td>0.23857</td><td>0.85063</td></tr>
<tr><td>16 (AV)</td><td>88.2</td><td>0.10519</td><td>0.093227</td><td>0.093225</td><td>0.325</td><td>0.52065</td><td>0.10177</td><td>0.10167</td><td>1.041</td></tr>
<tr><td>17 (QH)</td><td>165</td><td>0.14409</td><td></td><td></td><td rowspan="2">0.490</td><td>0.71320</td><td></td><td></td><td rowspan="2">1.092</td></tr>
<tr><td>18 center (QH)</td><td>183.3</td><td>0.15164</td><td>0.271500</td><td>0.271504</td><td>0.75058</td><td>0.27663</td><td>0.27657</td></tr>
</table>

Still working on modeling surface roughness

Still working on modelling stainless steel

Before analyzing layered flight reflector, simulating Al, SS, and teflon to build confidence

What it means for J1 & J2?

- **For J1, Kent Anderson's (NGES) initial evaluation of the emissivity from the May 2013 TVAC calibration indicated the emissivity was significantly smaller, but a J1 pitchover maneuver is a more reliable measurement because**
  - **It's independent of potential Calibration Test Equipment issues**
  - **Gives multiple angles (i.e., more data) to derive the emissivity**

- **For J2, NGES and NASA added these changes:**
  - **Specifying 8 micro-inches profile arithmetic mean (R_a) surface roughness for the Be surface prior to nickel plating**
  - **Polish the nickel-plated surface to < 100 Angstroms surface quality**
  - **Thicker gold plating (increased from > 0.5 micron to > 1.3 micron)**

Review of Calibration Algorithm Changes

- Correction biases for an observed unpolarized brightness temperature T_B are computed as below:

$$\Delta T_{QV} = \frac{\varepsilon_N}{\sqrt{2}}\left[T_R - T_B\right]\sin^2\phi + \frac{\varepsilon_N}{\sqrt{2}}\left(T_R - T_B\right) \qquad \Delta T_{QH} = \frac{\varepsilon_N}{\sqrt{2}}\left[T_R - T_B\right]\cos^2\phi + \frac{\varepsilon_N}{\sqrt{2}}\left(T_R - T_B\right)$$

- Algorithm steps:

1. Add the biases due to reflector emissivity to the cold and warm calibration brightness temperatures
    - Scan angles are at 83.3° and 195° respectively
    - Use T_R derived from temperature telemetry
2. Add biases to correct for any other error sources
3. Compute gain and offset for the radiometric transfer function
4. Compute uncorrected scene temperatures, based on transfer function gain and offset
5. Add emissivity bias correction for each scene sample (function of scan angle and scene temperature)

Kent Anderson (NGES)

Polarized Scenes

- **Calibration targets and opaque channels use this scene correction term:**

Use uncorrected T_B

$$\Delta T_{QV} = \frac{\varepsilon_N}{\sqrt{2}}\left[T_R - T_B\right]\sin^2\phi + \frac{\varepsilon_N}{\sqrt{2}}\left(T_R - T_B\right)$$

Use model-adjusted SDM temperature

Left out quasi-horiz.

- **Channels sensitive to the surface (i.e., window channels) *should* use this scene correction term (Ch. 1, 2, 3, 4, 16 & 17):**

$$\Delta T_{QV} = \frac{\varepsilon_N}{\sqrt{2}}\left[T_R + T_{SV} - 2T_{SH}\right]\sin^2\phi + \frac{\varepsilon_N}{\sqrt{2}}\left(T_R - T_{SV}\right)$$

Need to model relationship between vertical and horizontal polarizations

- **Implementing the surface correction for the window channels requires:**
  - **Ability to differentiate between sea and land (e.g., land/sea mask)**
  - **A model to estimate the brightness temperature difference between the vertical and horizontal polarization, which is a function of scan angle, surface wind speed, and sea surface temperature**
  - **May not be worth the effort**

Status of Implementing Reflector Emissivity in IDPS

- Implementing the algorithm in IDPS requires making the Processing Coefficient Table (PCT) larger to hold the additional instrument-specific calibration parameters

- Implementation requires a relatively minor code change to the TDR/SDR calibration algorithm

- Plan to implement change in ADL, then compare the TDR scan bias against NWP and GPS-RO (Tiger NOAA STAR has implemented it in ARTS and have presentation available)

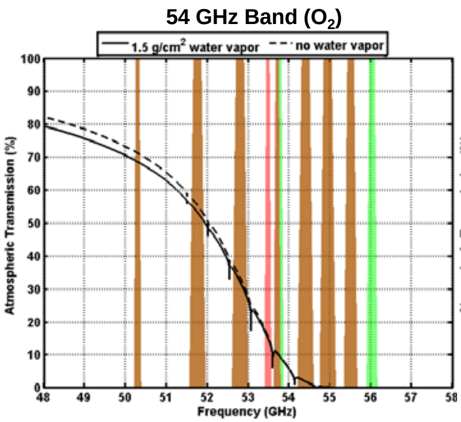
- The TDR-to-SDR conversion, i.e., the scan bias correction from antenna pattern measurements, will have to be reevaluated

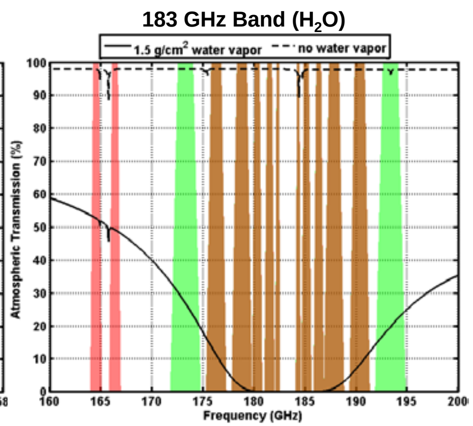
ATMS Calibration Validation Mission March 2015

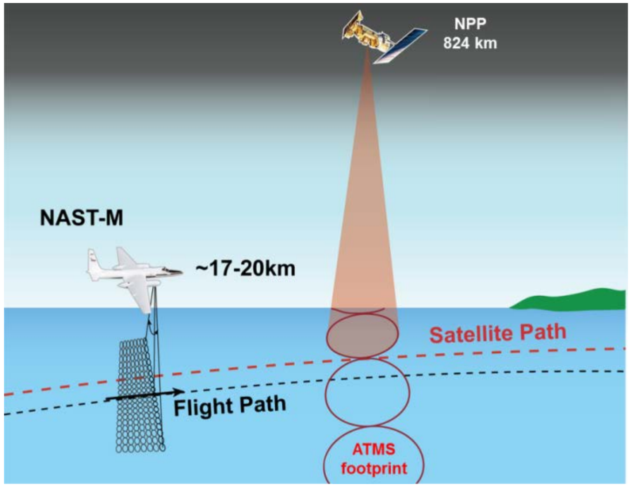
NAST-M

Dual-band, 15-channel microwave sounder similar to ATMS (54, 183) GHz

NAST-M
ATMS
Both

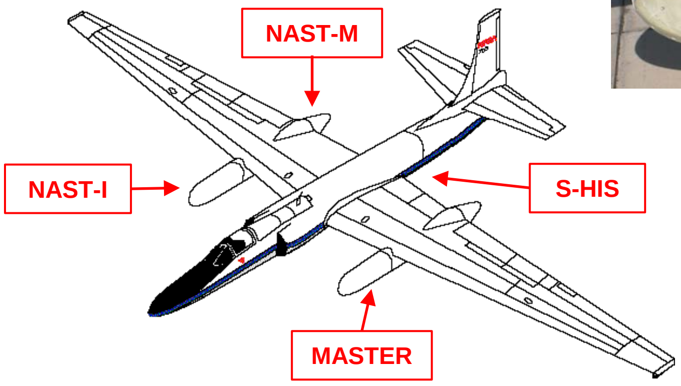






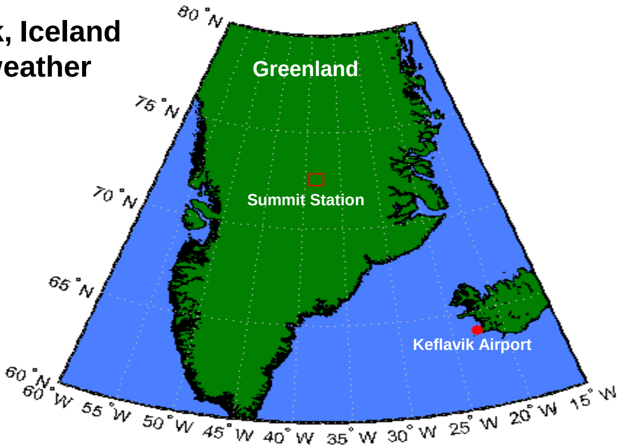
Mission

NASA ER-2 Aircraft



http://www.nasa.gov/

- **Sorties from Keflavik, Iceland**
- **Greenland Summit weather station**



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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

2015 Science Sorties Over Greenland

NAST-M has data from 7 flights ~41 hours

	Full Data Collected
*	Partial Data Collected
	No Data Collected

Data Source	15-Mar	19-Mar	23-Mar	24-Mar	25-Mar	28-Mar	29-Mar
NAST-M		*					
GPS							
Video	*	*					
ER-2 NAV							
SS Ozonesondes							
ECMWF							
Overpass							
NPP	2	1	1	1	1	2	1
Aqua			1		1	1	1
Metop-A			1		1	1	1
Metop-B	1		1		1	1	1
Conditions							
Time Of Day	Day	Day	Day	Day	Day	Day	Day
Surface type	Land	Mixed	Land	Mixed	Land	Land	Land
Weather	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy
Flight Time (H)	5.92	4.58	6.23	4.12	7.45	7.35	6.08

Collected data from 9 S-NPP overflights

2013 Science Sorties Over the Pacific Next to Mexico

NAST-M has data from 12 flights ~81 hours

Data Collected
No Data Collected

Data Source	May 7th	May 10th	May 15th	May 16th	May 18th	May 20th	May 22nd	May 23rd	May 24th	May 30th	May 31th	June 1st
NAST-M												
GPS												
Video												
ER-2 NAV												
Drop Sonde												
Radioondes												
Salton Sea												
NAM												
ECMWF												
Overpass												
NPP												
Aqua												
Metop-A												
Metop-B												
Conditions												
Time Of Day	Day	Day	Day	Day	Day	Day	Day	Day	Day	Night	Night	
Surface type	Ocean	Mixed	Mixed	Mixed	Land	Land	Land	Ocean	Land	Ocean	Mixed	
Weather	Cloudy	Clear	Clear	Scattered	Thin Cirrus	Scattered	Clear	Cloudy	Scattered	Scattered	Clear	
Flight Time (H)	6.35	5.98	7.63	8.13	6.25	8.47	9.2	6.58	8.03	6.22	8.18	0

Collected data from 9 S-NPP overflights

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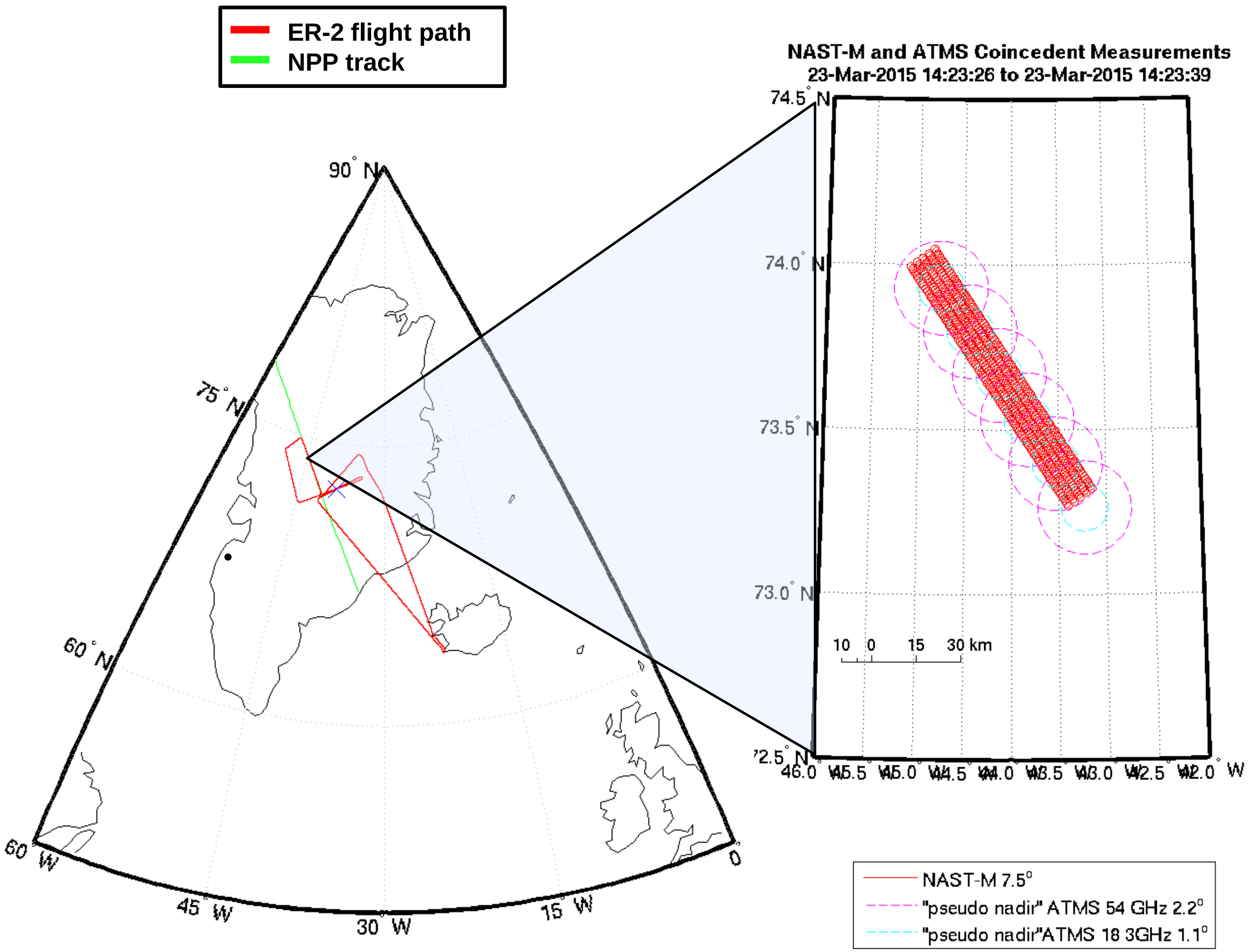
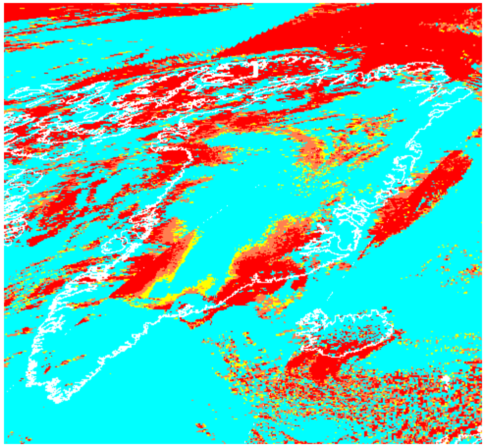
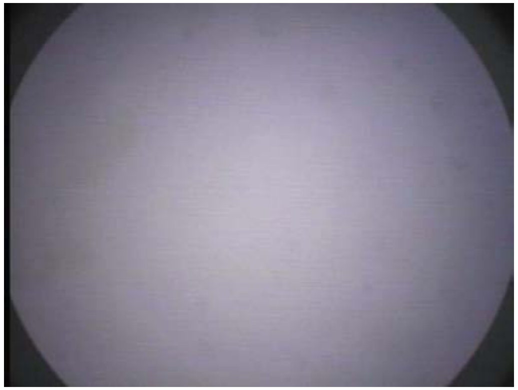
23 March ER-2 Flight Path and NPP Track





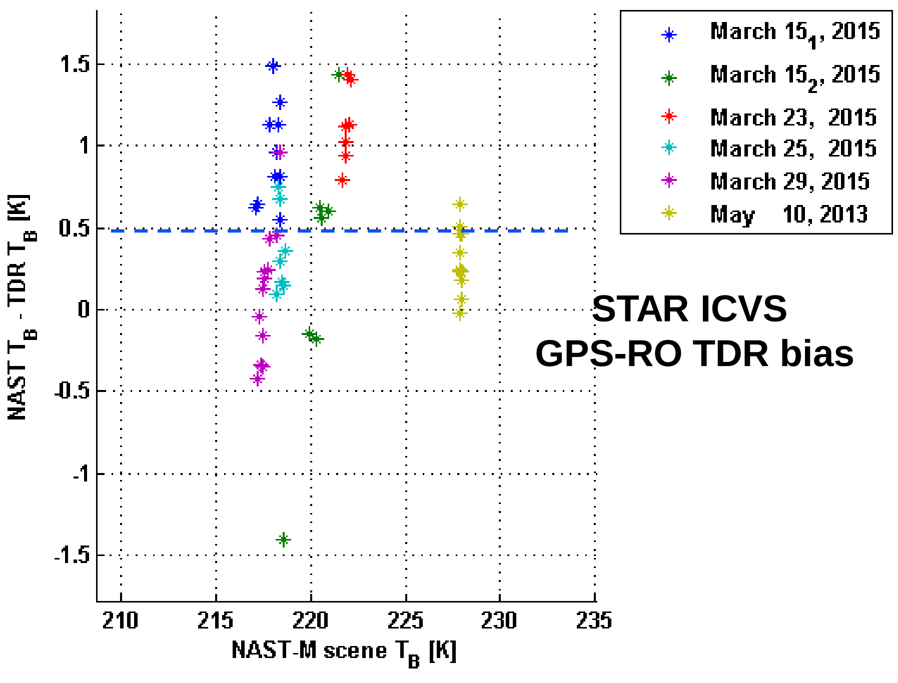
VIIRS Cloud Mask (blue is cloudy)



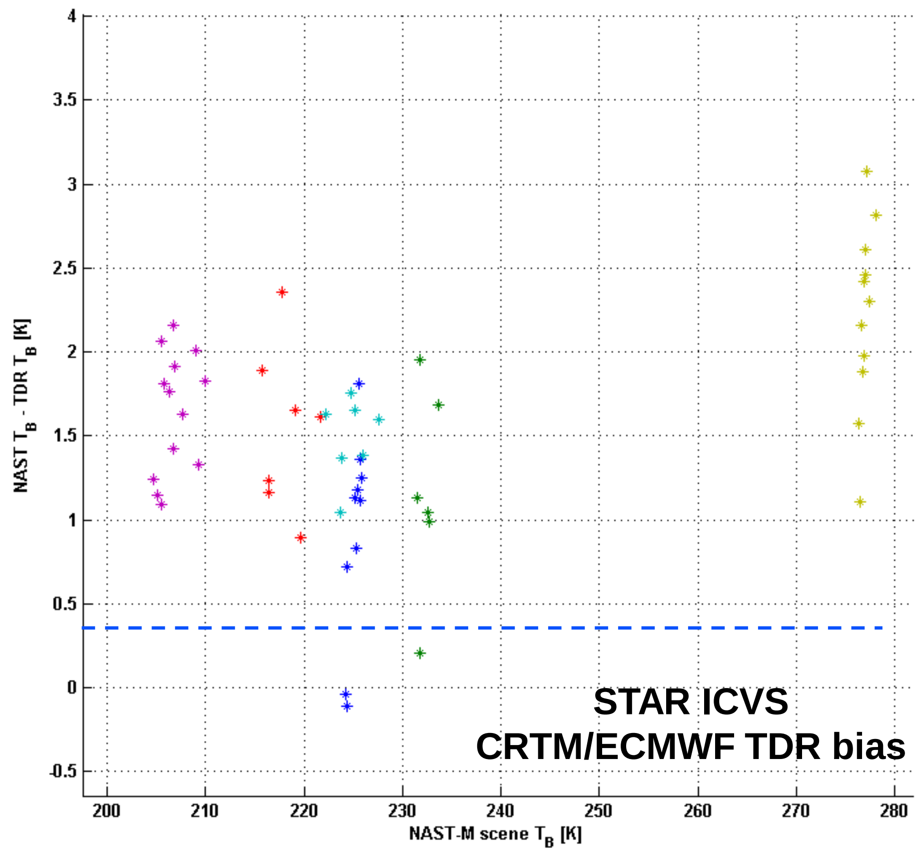
NAST-M Camera image from underpass

Examples of NAST-M TDR Bias

Ch. 8: 54.94 GHz

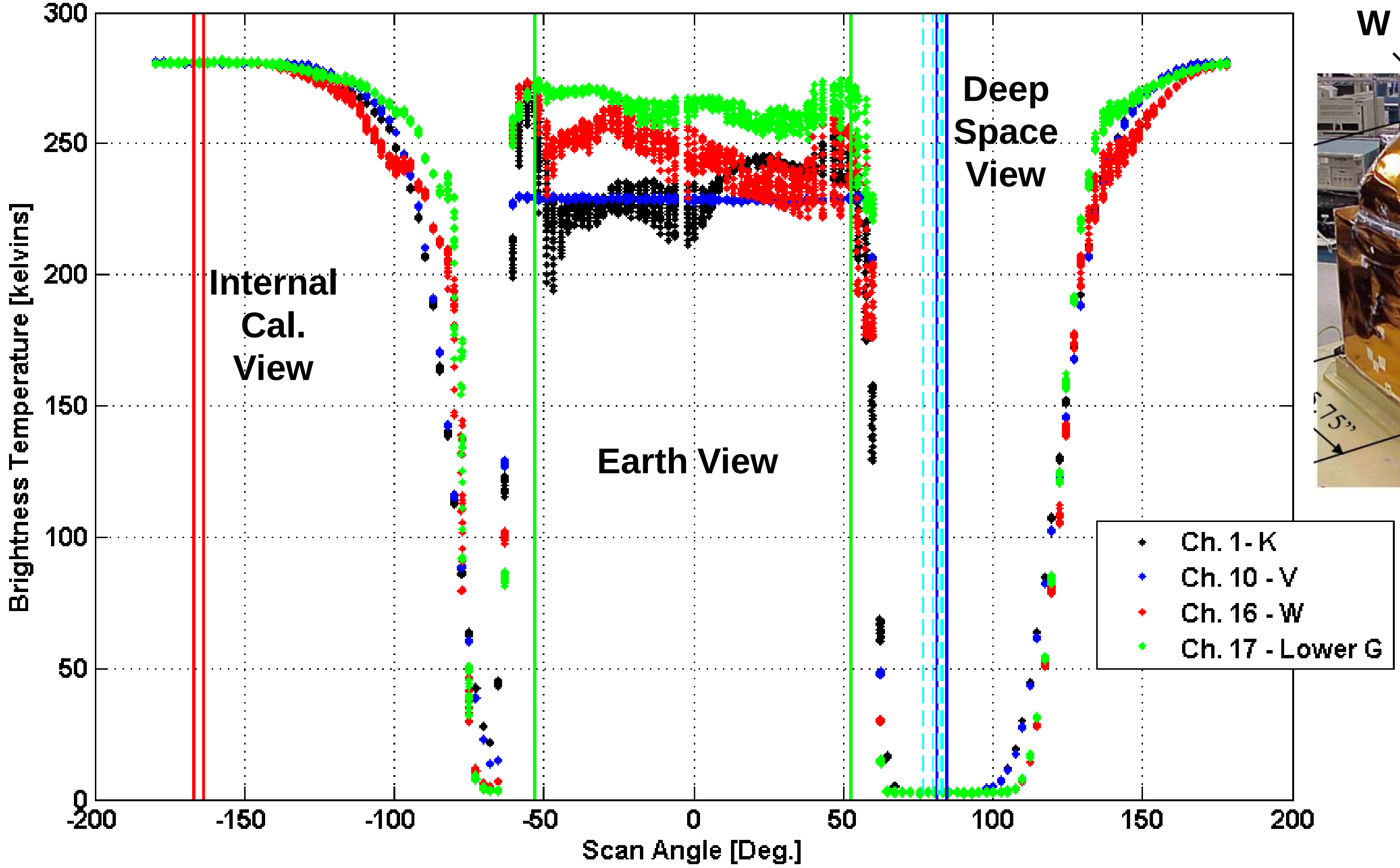


Ch. 19: 183 +/- 4.5 GHz



S-NPP Radiometric Environmental Characterization

Resulted from S-NPP ATMS Scan Reversal, which has contiguous sampling

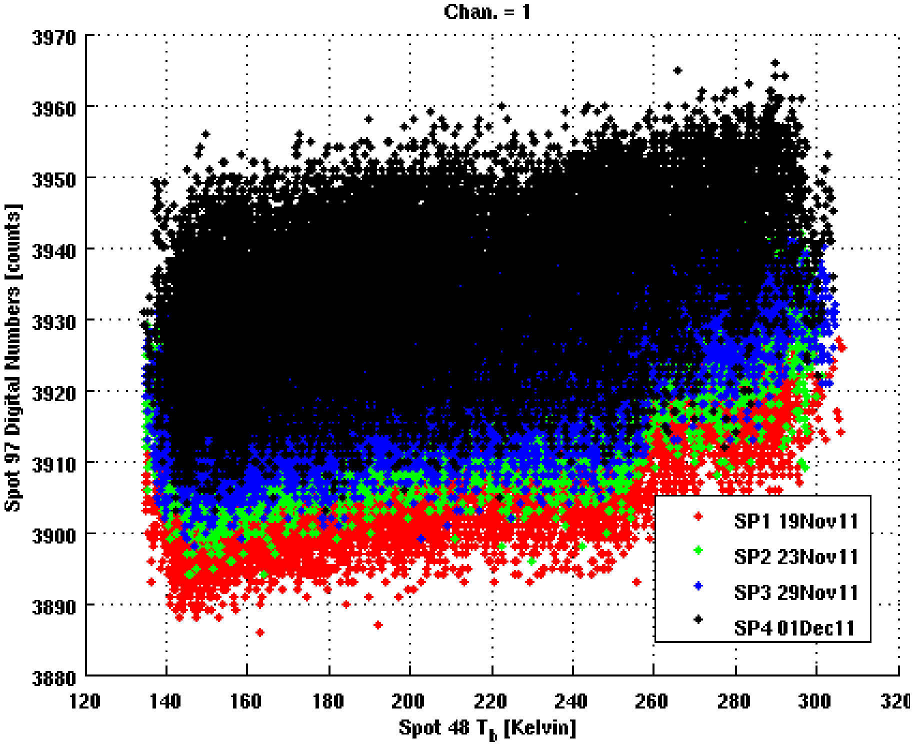


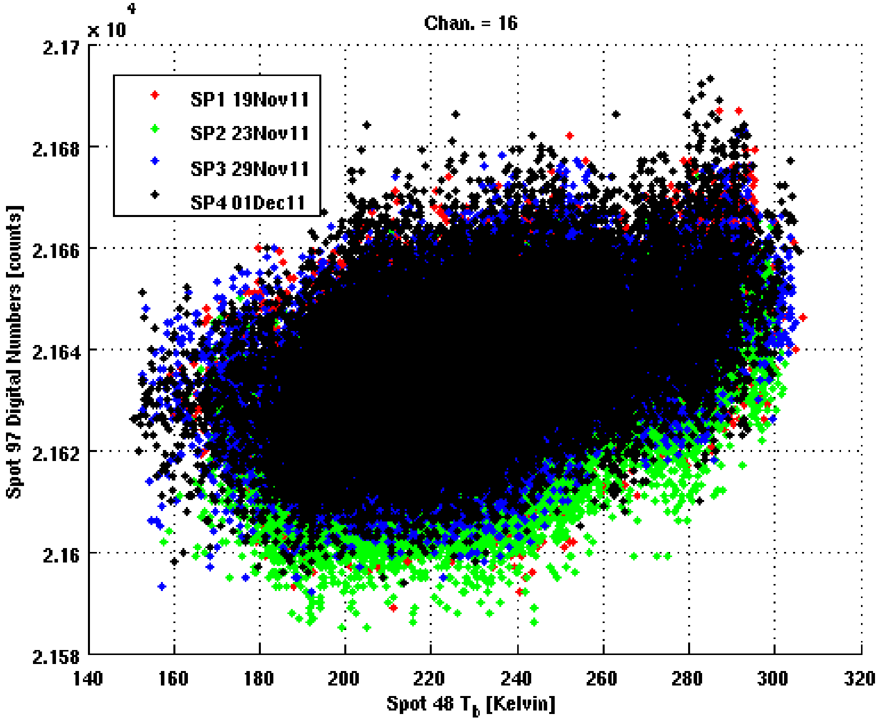
Anti-sun side

K/Ka 5.2° BW
V 2.2°
W 2.2°
G 1.1°

Diagnostic mode in continuous sampling gives 2.43° spacing (360/148)

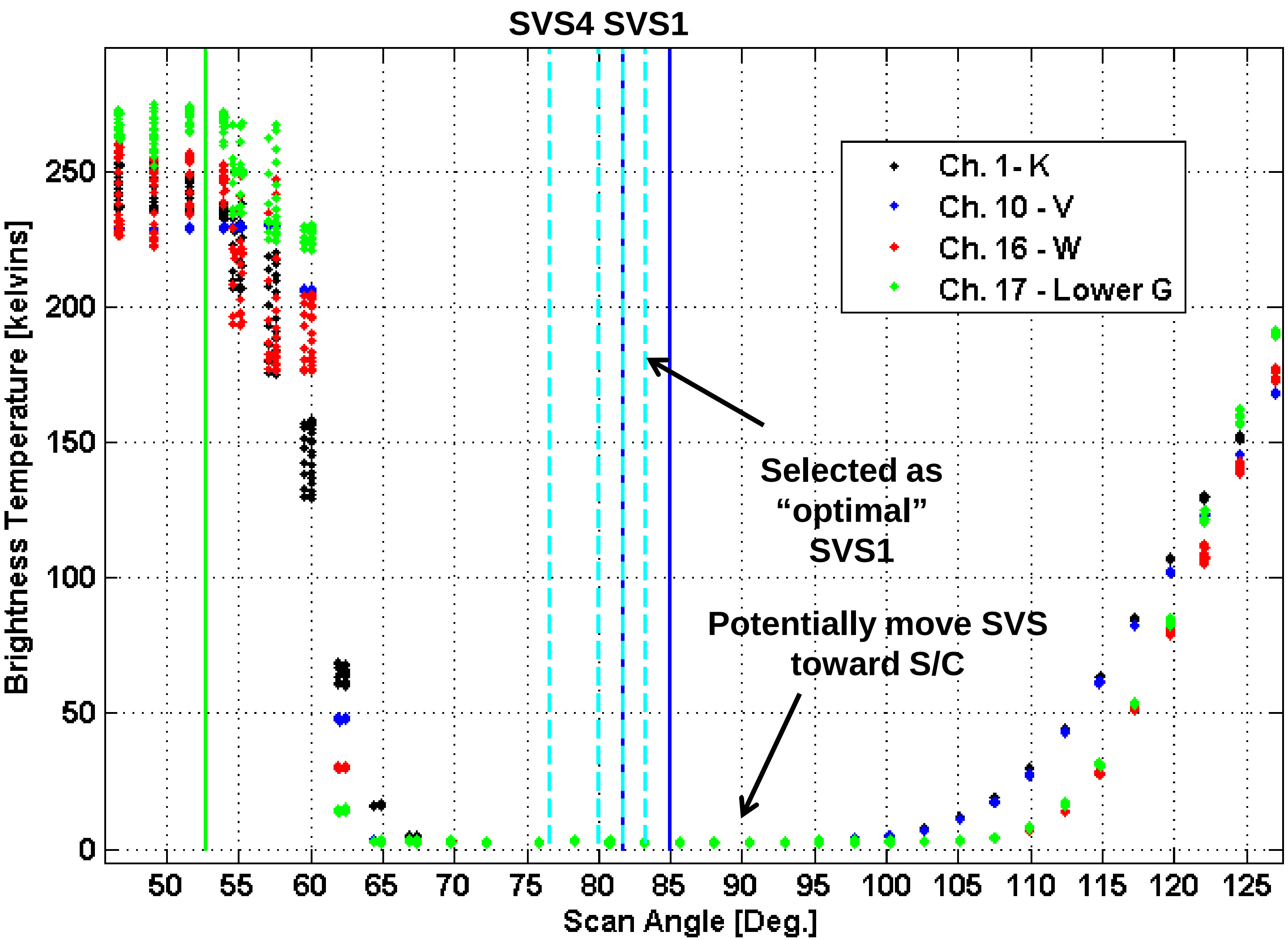
Scatter Plots: SV Spot 97 Cnts vs EV 48 Tb





- Plots above indicate a correlation between EV Tb and SV counts
- Disclosure: Tb calibrated using all 8 calibration measurement (4 SV & 4 HC)
- Channels affected seem to be the quasi-V polarized channels (Ch. 1, 2, & 16)
- May be some correlation in V-band window channel (Ch. 3).
- Spot 100 of the SVS had similar response
- Correlation coefficient about the same for all SVS spot 97 (between 0.4 to 0.55)

Potential to Move Space View Sector



Review of ATMS Single Event Upsets

- **Two types of SEU have been identified**
- **One type of event impacts the radiometric counts**
- **Another type of event impacts the Scan Drive Motor & resolver**
- **All events found are either in or near the South Atlantic Anomaly or near the polar regions**
- **ATMS recovers very quickly with minimum number of pixels impacted, but TDR/SDR Quality Flags (QFs) were not tripped**
- **Team should investigate altering QF to inform user of these events**

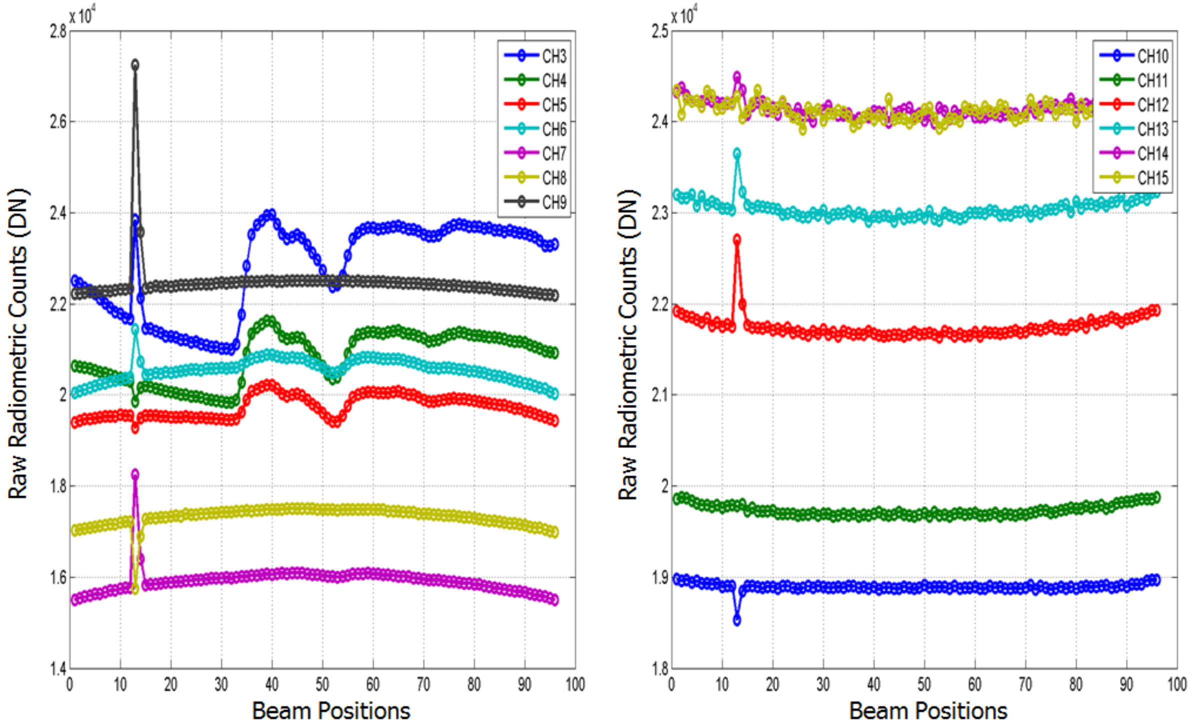
Radiometric SEU

- **NGAS Sept. 8, 2014 investigation showed "random" positive and negative spike pattern per V-band Channels**

Only V Band Channels Are Affected and the Anomaly can be both Positive and Negative

NORTHROP GRUMMAN

V band channel raw radiometric counts of the affected scan



5

Degui Gu & Alex Foo (NGAS)

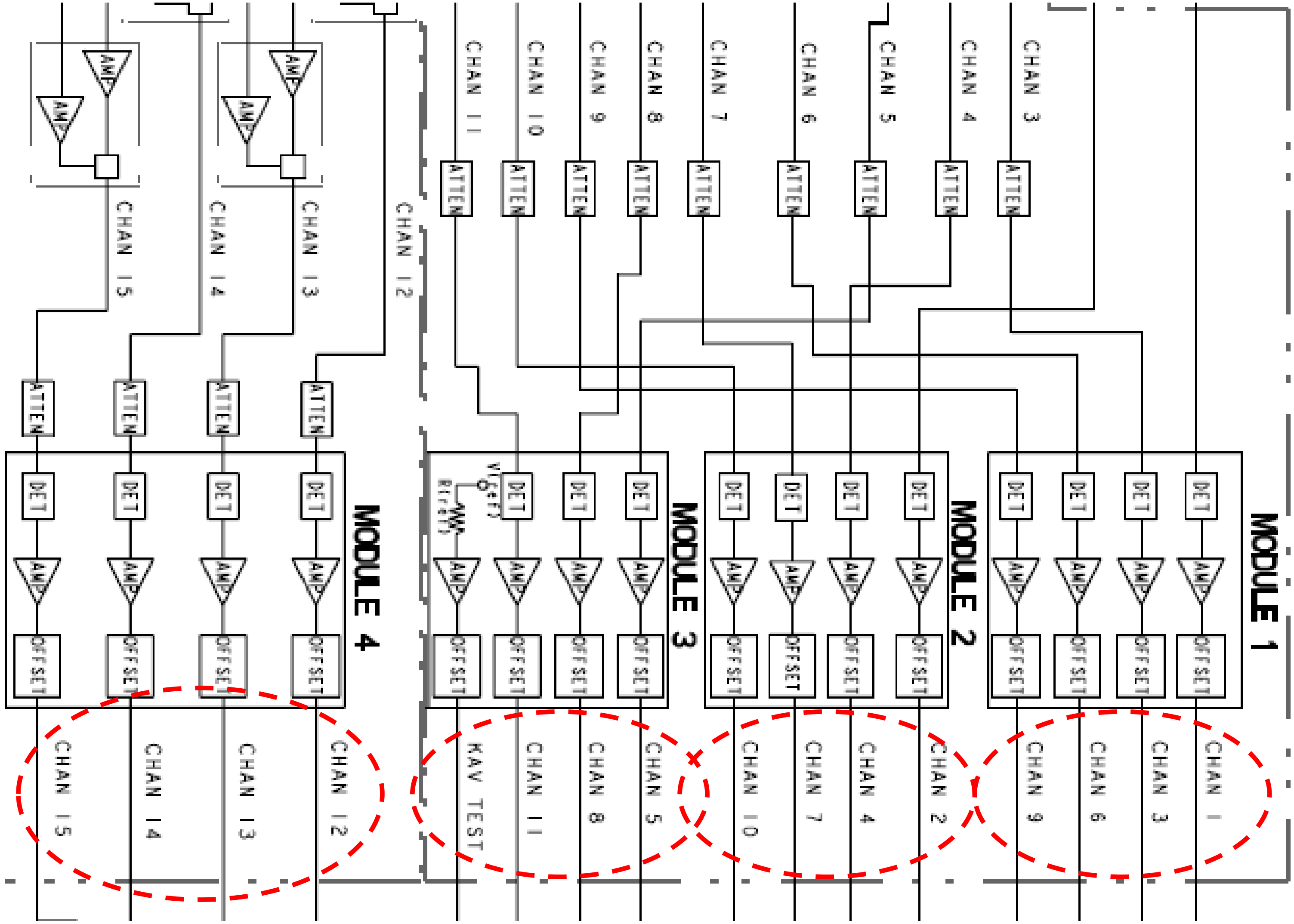
Positive Spikes: Channels 3, 6, 7, 9, 12, 13, 14, 15

Negative Spikes: Channels 4, 5, 8, 10

Undetermined: Channel 11

Initially characterized by Sung-Yung Lee (NASA JPL)

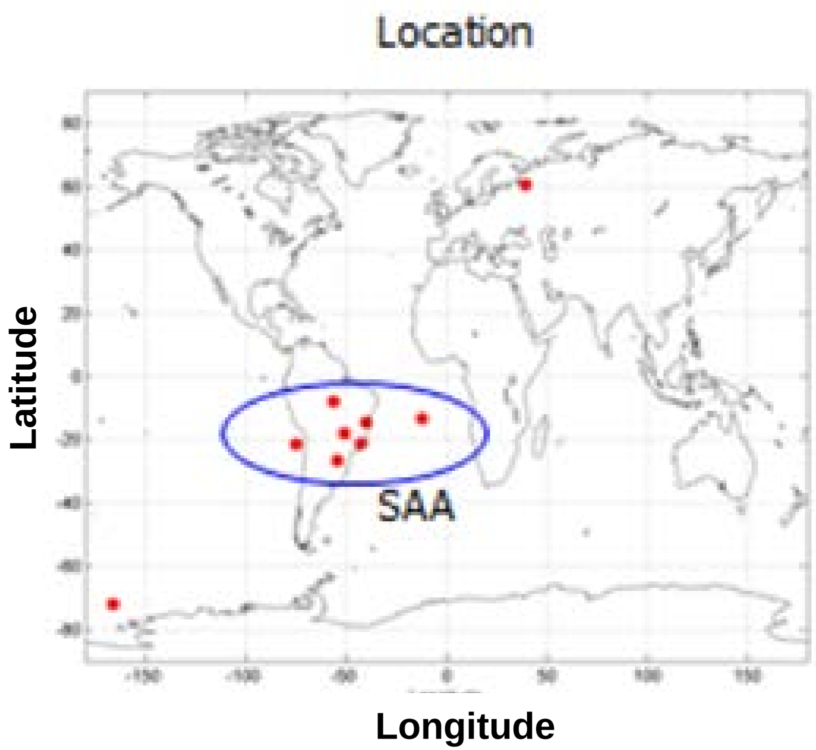
Section of ATMS Flow Diagram

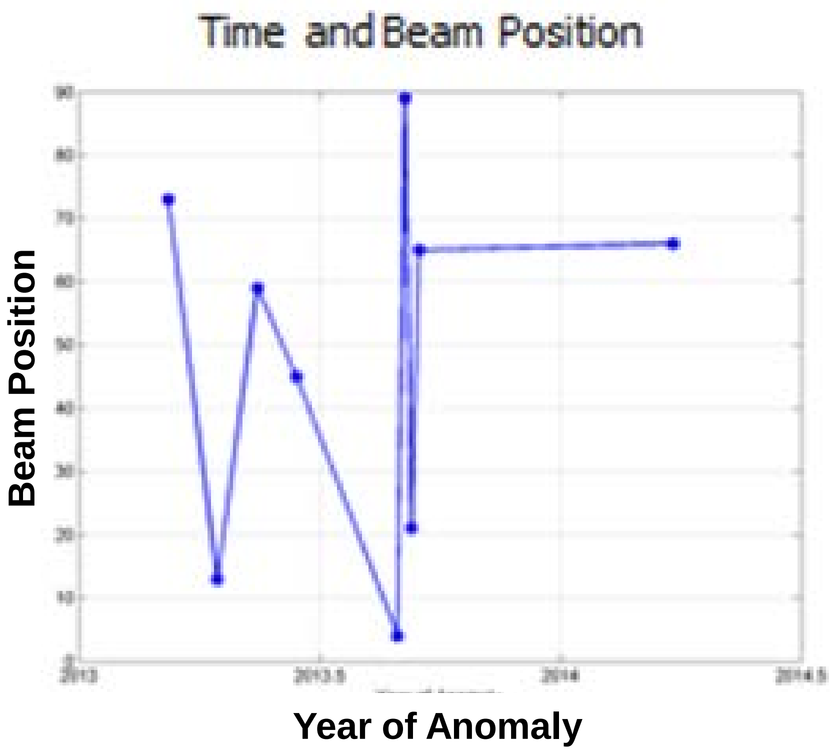


NGAS SEU Characterization of Radiometric Event

Spatial Characteristics

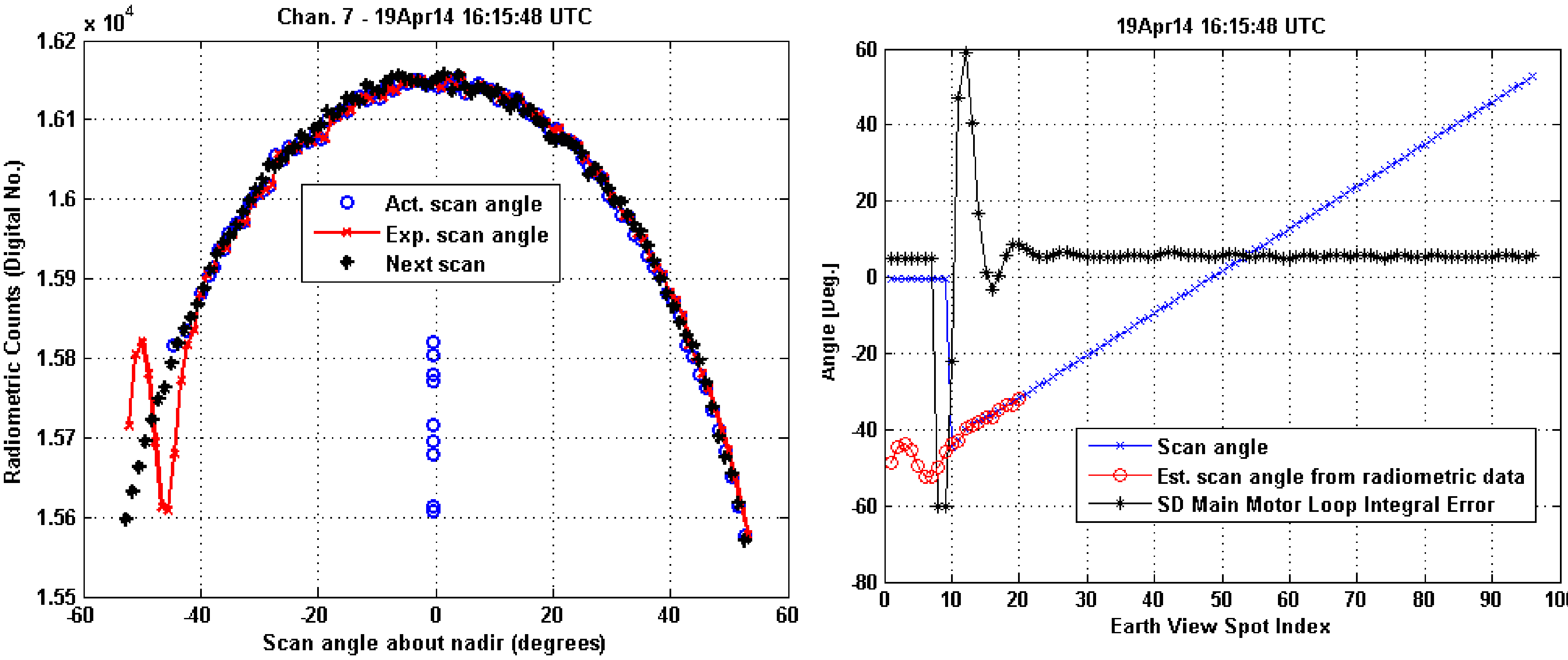
NORTHROP GRUMMAN





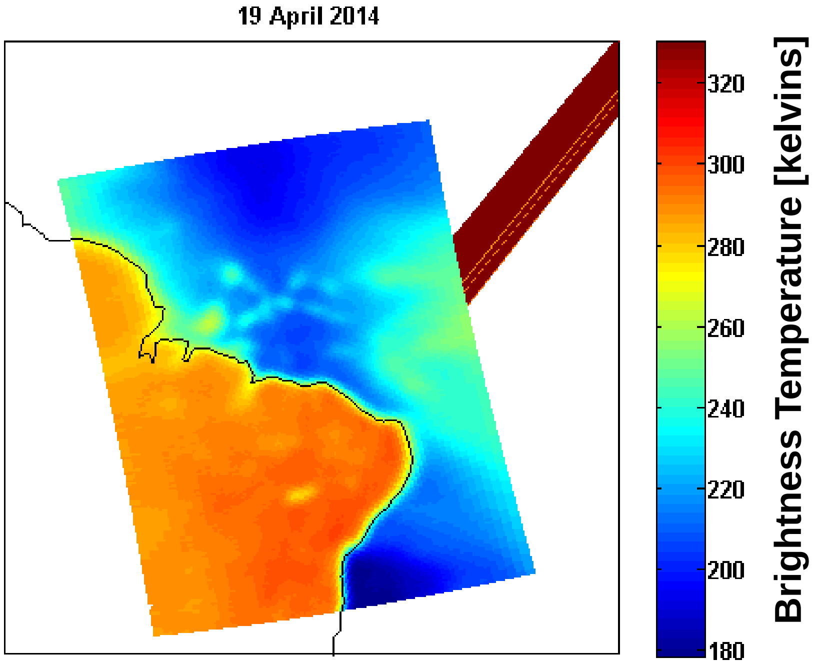
Degui Gu and Alex Foo (NGAS)

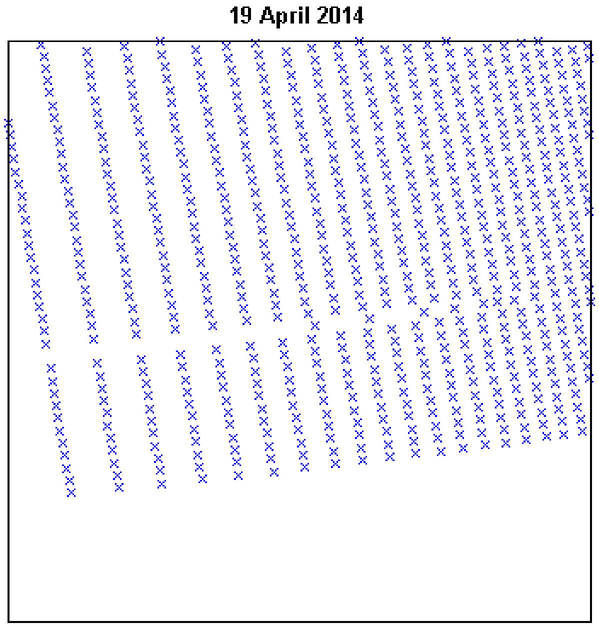
Scan Drive Motor SEU

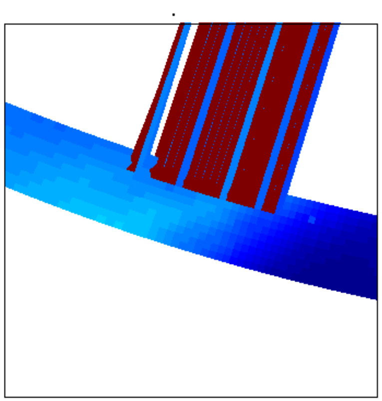


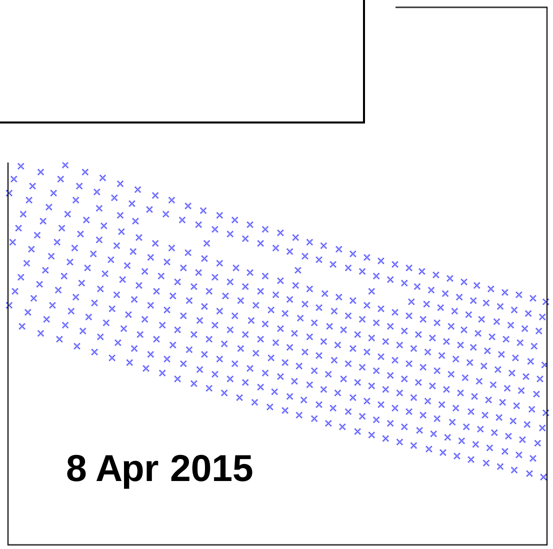
Reconstructed scan angles during event does seem to indicate that the SDM continues toward nadir, but starts to react to the zero resolver values (i.e., goes in reverse) before correcting itself.

Radiance & Geolocation (SDR) Data Products



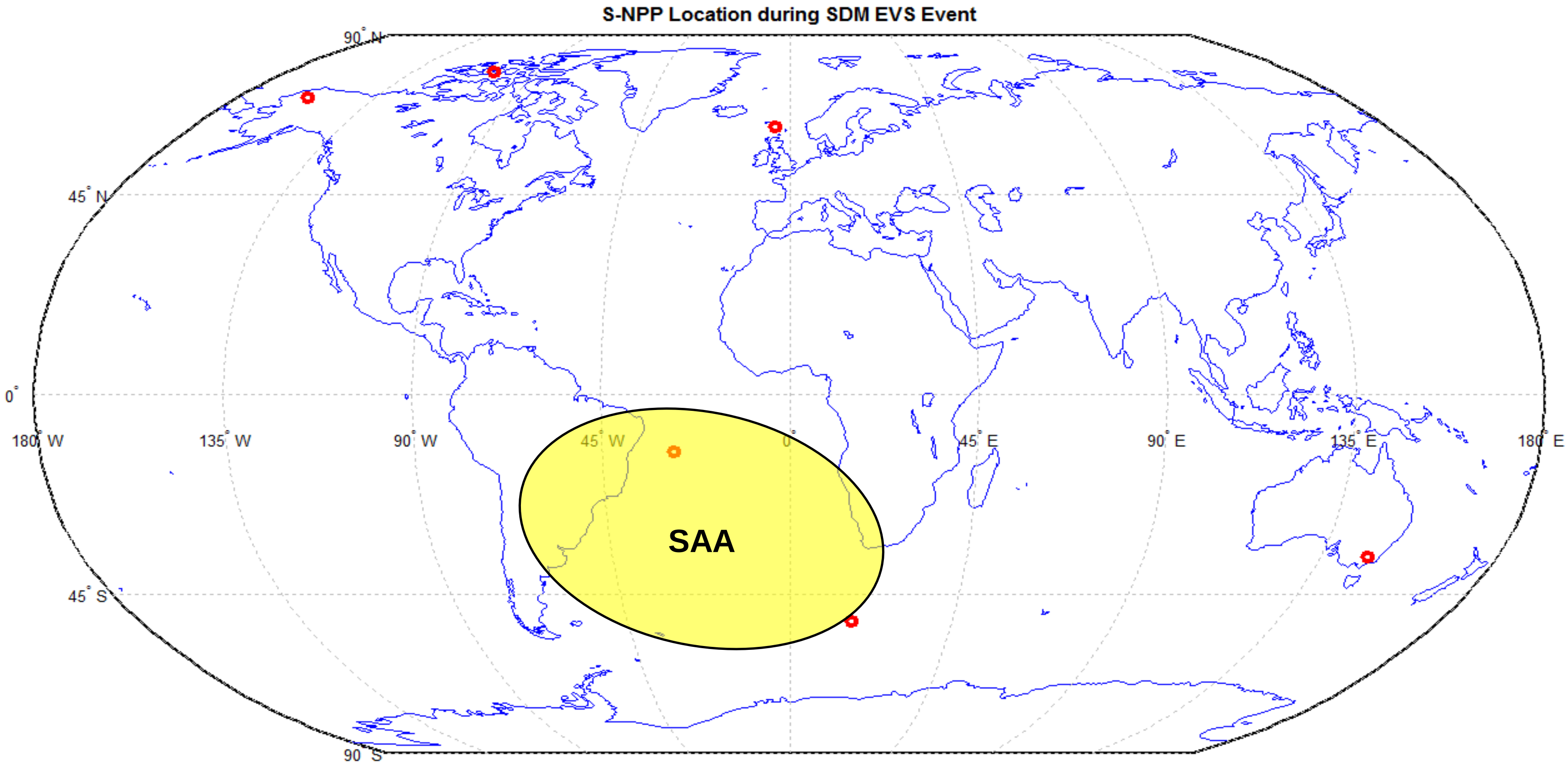






Radiance "fill" values also had latitude and longitude fill values (-999.5)

S-NPP Location at Start of SDM Event



About one or two SDM SEUs occur per month

Future Work

- **Flat reflector emissivity**
  - **Continue to investigate emissivity with modeling**
  - **Implement the emissivity correction in IDPS and add coefficients to the ATMS SDR PCT**
  - **Get user and science community sign off**
- **NAST-M**
  - **Return to 2013 campaign to increase the data set**
  - **Continue with NAST-M upgrade that will add K & Ka channels**
- **Advocate for J1 spacecraft maneuvers and radiometric environment characterization in the PLT**
- **Investigate developing data product quality flags for ATMS Single Event Upsets**

Backup Slides

Comparison to Previous ATMS Emissivity Study Results

Channel	Frequency	Analytical Emissivity (Bulk Ni Layer)	Numerical Emissivity	Analytical Emissivity (Bulk Au Layer)	PFM Pitch-Over Derived Emissivity LL	PFM Ground Calibration Derived Emissivity (NGES)
1 (QV)	23.8 GHz	0.0008545	0.0007060	0.0005083	0.004	0.0038
2 (QV)	31.4 GHz	0.0009815	0.0024944	0.0005838	0.0035	0.00363
3 (QH)	50.3 GHz	0.0012422	0.0004398	0.0007389	0.002	0.0025
6 (QH)	53.596 GHz	0.0012830	0.0004143	0.0007627		
7 (QH)	54.4 GHz	0.0012919	0.0004438	0.0007684		
10 (QH)	57.29 GHz	0.0013257	0.0005008	0.0007885		
16 (AV)	88.2 GHz	0.0016450	0.0014246	0.0009784	0.0065	0.00662
17 (QH)	165 GHz	0.0022533	0.0008428	0.0013403	0.004	0.00354
18 min (QH)	176.3 GHz	0.0023257	0.0008060	0.0013833	0.0045	0.0043
18 center (QH)	183.3 GHz	0.0023714	0.0006445	0.0014105		
18 max (QH)	190.3 GHz	0.0024163	0.0011150	0.0014372		

Calibration Algorithm Correction

Correction impacts three parts of the calibration equation:

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

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_{DS} = Deep Space T_b

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

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

$$g = \frac{T_{HC} + \varepsilon_{HC} \times \left(T_{refl} - T_{HC}\right) - T_{DS} - \varepsilon_{SV} \times \left(T_{refl} - T_{DS}\right)}{C_{HC} - C_{SV}} \quad \text{(Eq. 5)}$$

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

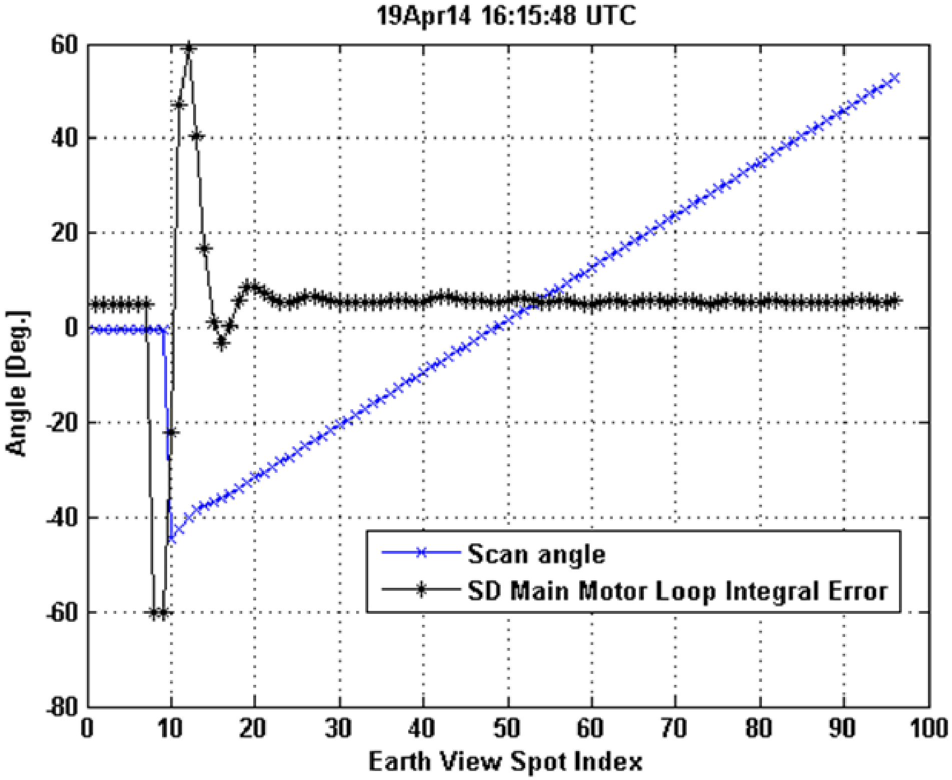
3. **Finally, the scene brightness temperature is corrupted and this correction must be applied:**

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

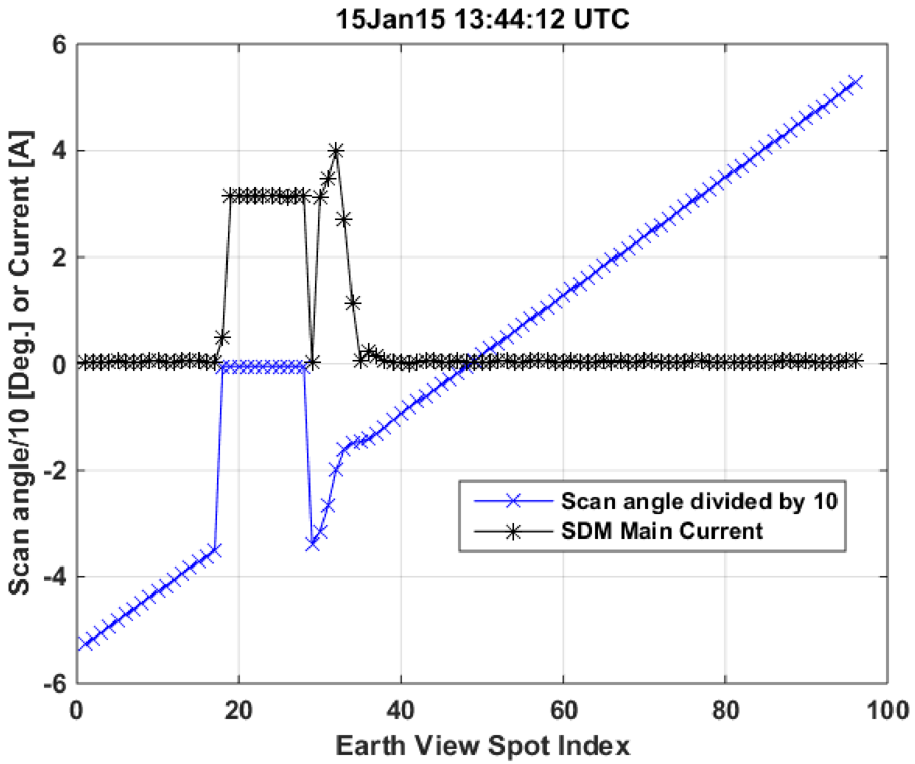
ε_x is the quasi-V (QV) or quasi-H (QH) emissivity

Loop Integral Error & Main Motor Current During an Event

19Apr2014



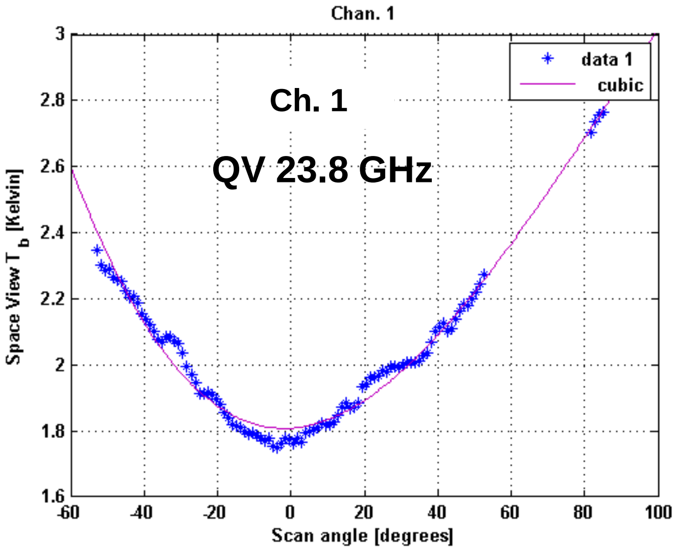
15Jan2015

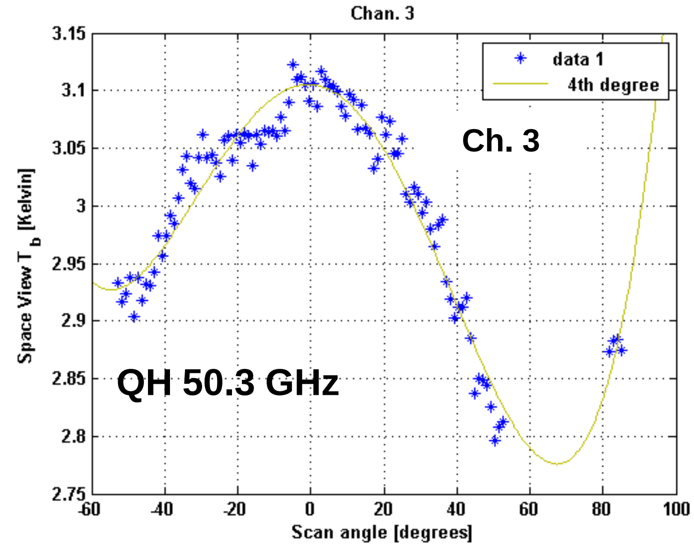


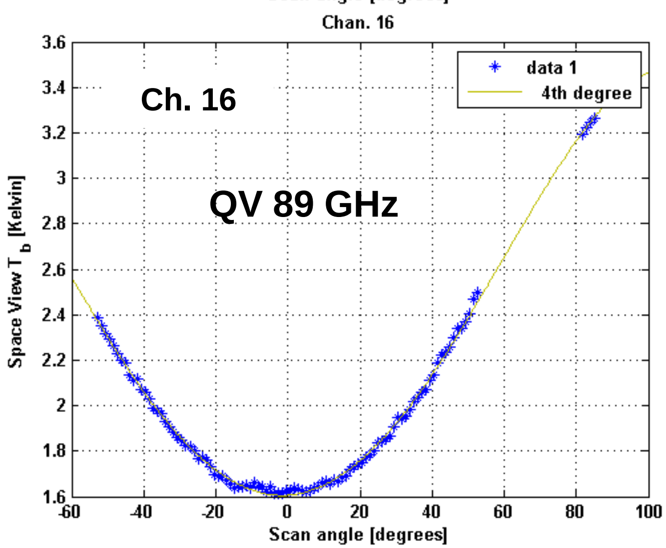
Once the scan angle returns (see left), the scan angle value is in approximately the same location as it left off.

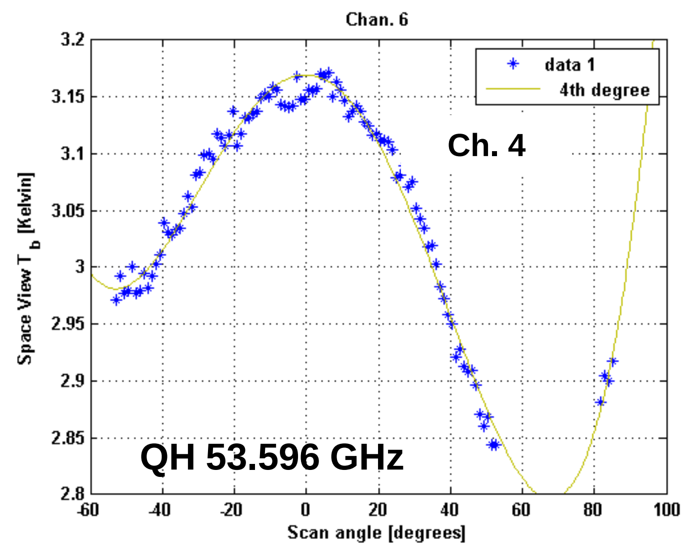
The Loop Integral Error changes before the resolver (i.e., scan angle) returns to correct values

S-NPP Pitchover ATMS Scan Angle Bias



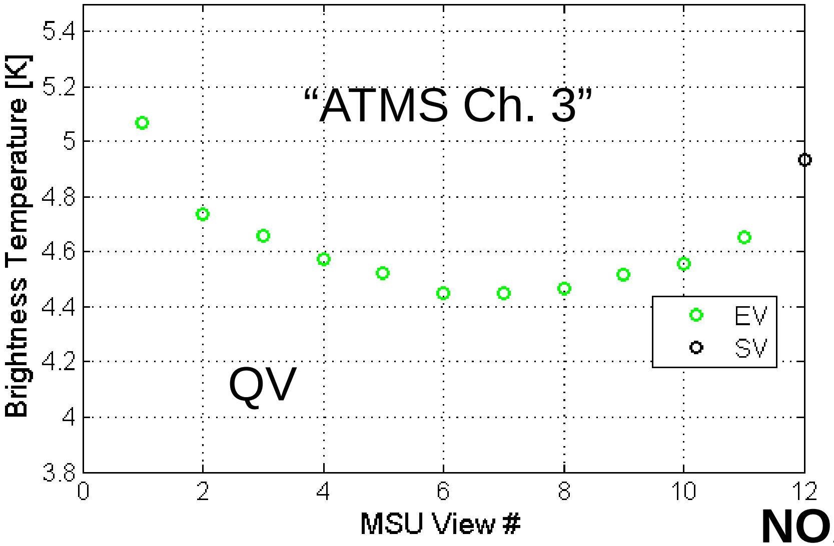






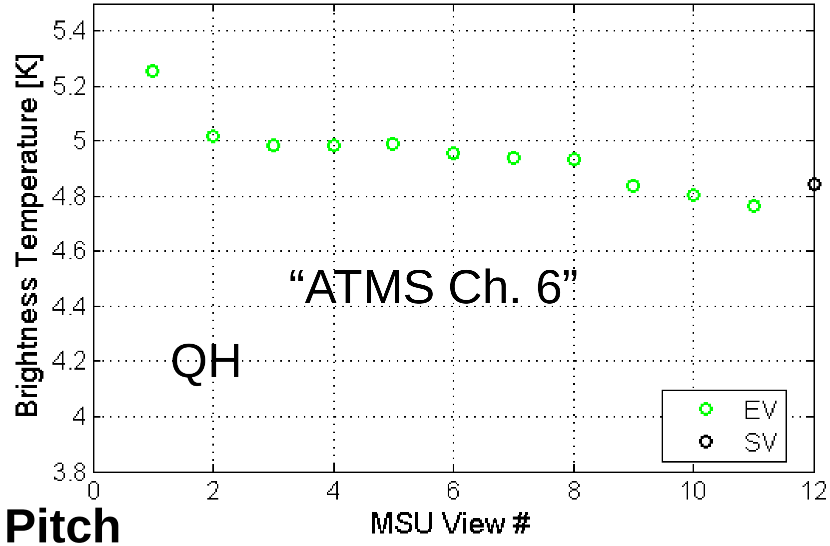
NOAA-14 MSU Deep Space Scan Bias

MSU Ch. 1 50.36 GHz



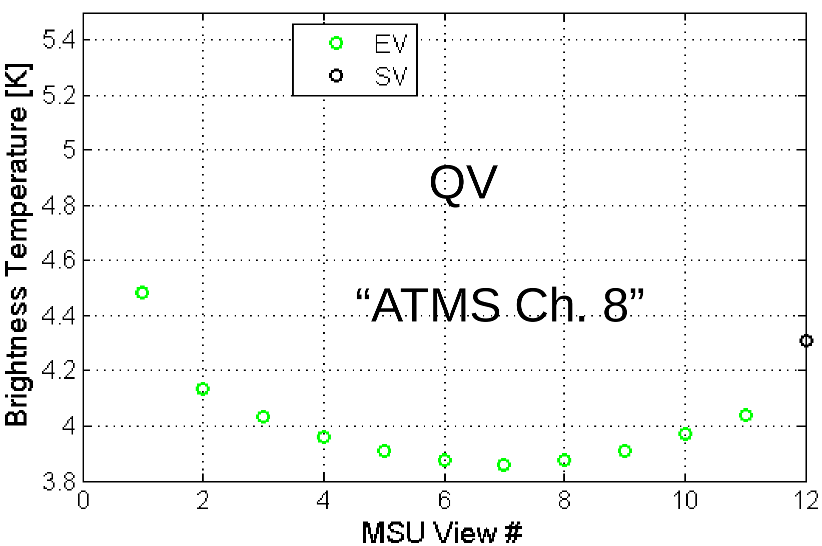
Ant. 1

MSU Ch. 2 53.74GHz



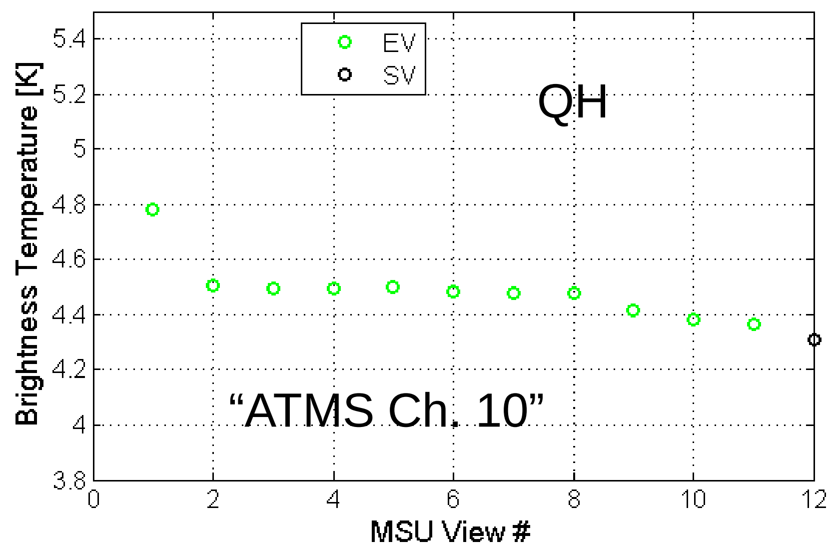
NOAA-14 Pitch Over Maneuver

MSU Ch. 3 54.96 GHz



Ant. 2

MSU Ch. 4 57.95 GHz



S-NPP Mission Cal/Val Campaign

10 May 2013 Sortie over Gulf of CA