An On-Orbit Calibration Procedure For Spaceborne Microwave Radiometers Using Special Spacecraft Attitude Maneuvers

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Presentation Outline

- Purpose of this Dissertation
- TRMM, TMI, & the Inertial Hold
- Analyses Discussed:
  - Reflector Emissivity
  - Second Stokes Analysis using a Nadir-Look
- Recommendations
- Conclusion
- Future Work

Dissertation Objectives

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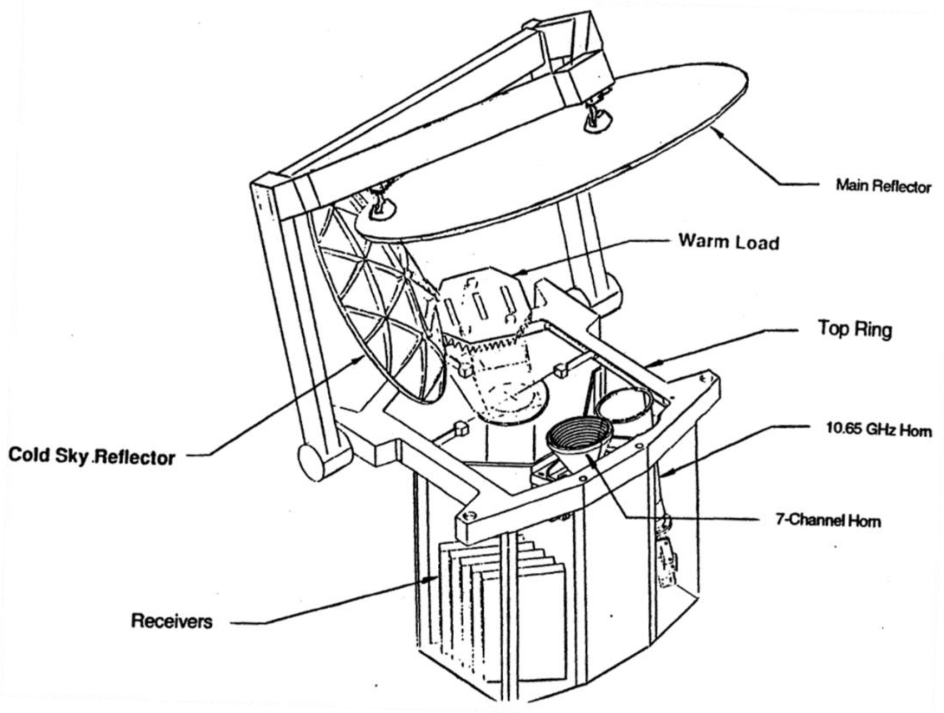
- Develop & document methods for post-launch calibration of spaceborne microwave radiometers
  - Using Calibration Attitude Maneuvers (CAM)
  - Use pre-existing & new CAMs
- Use TRMM Deep Space Calibration (DSC) maneuvers for developing this plan
  - Jan & Sept 1998 (7 maneuvers) and July 2014 (3 maneuvers)
- Calibrate TRMM Microwave Imager (TMI)
  - Use this information for the final version of the TB data product (Archived/Legacy)

Why CAMs?

- Common post-launch calibration methods:
  - Uses Earth observations which requires months of the instrument observations to detect biases
  - Inter-satellite calibration requires the other instrument to be stable
  - Heavily dependent on (imperfect) radiative transfer models that require ancillary data (weather models)
- Calibration Attitude Maneuvers (CAMs):
  - Provide early & accurate results on the performance of the instrument
  - Deep Space Calibration (DSC) Maneuvers (DSCM) use the known homogenous non-polarized cosmic microwave background (CMB)
  - Sharp transitions in TB at Earth's Horizon
  - Nadir-Look: Instruments Line of sight aligned to geodetic vector
- Overall, uses simpler well known scenes

TMI

- TRMM Microwave Imager (TMI)
  - TRMM was launched on Nov 28, 1997
  - Conically scanning radiometer
  - Main reflector is emissive
  - Over 17 Years of operation
  - Will be turned off on April 8, 2015
  - Re-enters Earth atmosphere on June 11, 2015

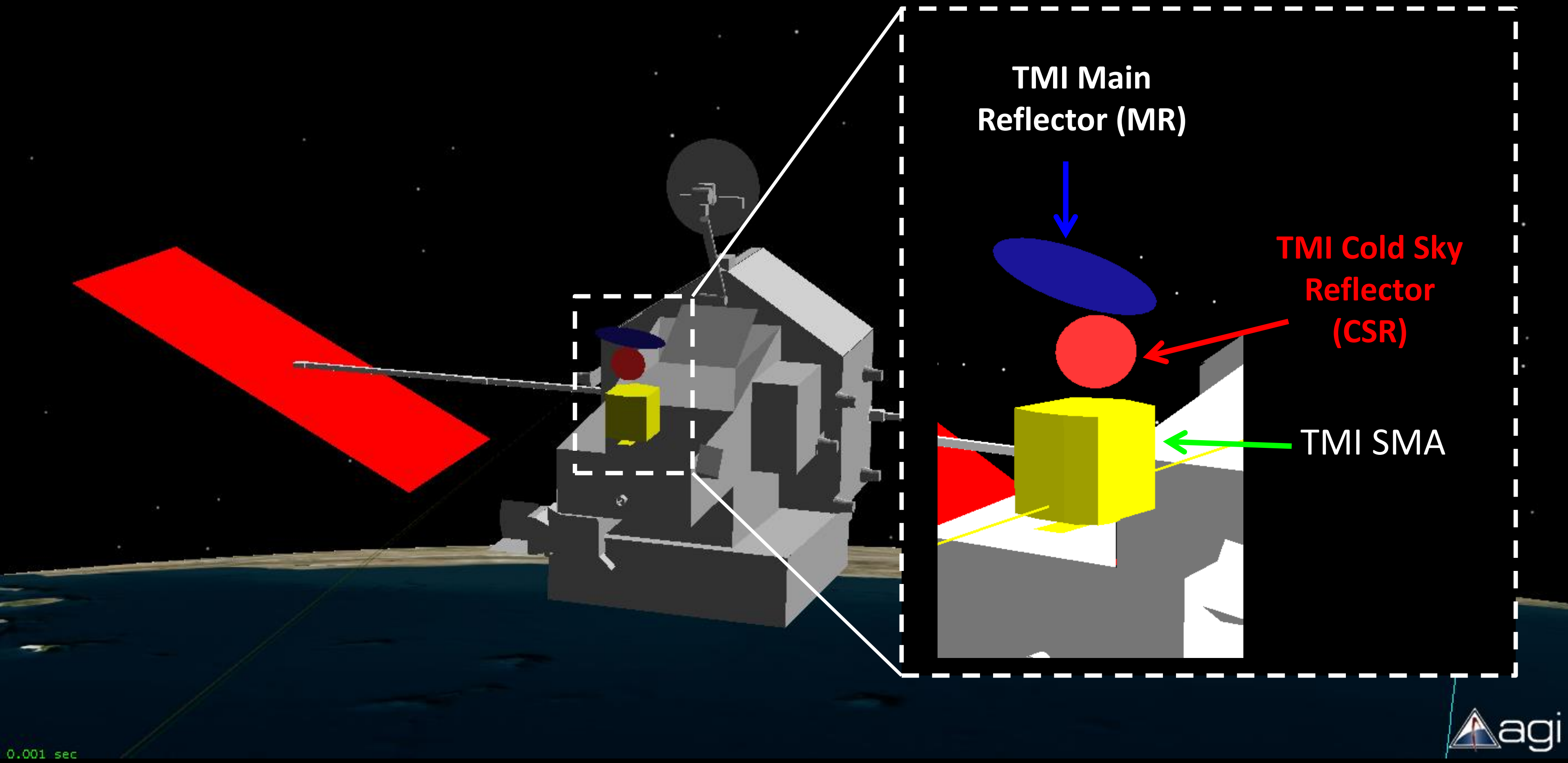


Red Boxes: Channels we can confidently reconstruct T_A

Center Frequencies(GHz)	10.65	10.65	19.35	19.35	21.3	37.0	37.0	85.5	85.5
Polarization	V	H	V	H	V	V	H	V	H
Bandwidth (MHz)	100	100	500	500	200	2000	2000	3000	3000
Sensitivity (K)	0.63	0.54	0.50	0.47	0.71	0.36	0.31	0.52	0.93
IFOV (km x km)	63 x 37	63 x 37	30 x 18	30 x 18	23 x 18	16 x 9	16 x 9	7 x 5	7 x 5
Sampling Interval (km x km)	13.9x9.1	13.9x9.1	13.9x9.1	13.9x9.1	13.9x9.1	13.9x9.1	13.9x9.1	13.9x4.6	13.9x4.6
Integration Time (msec)	6.6	6.6	6.6	6.6	6.6	6.6	6.6	3.3	3.3

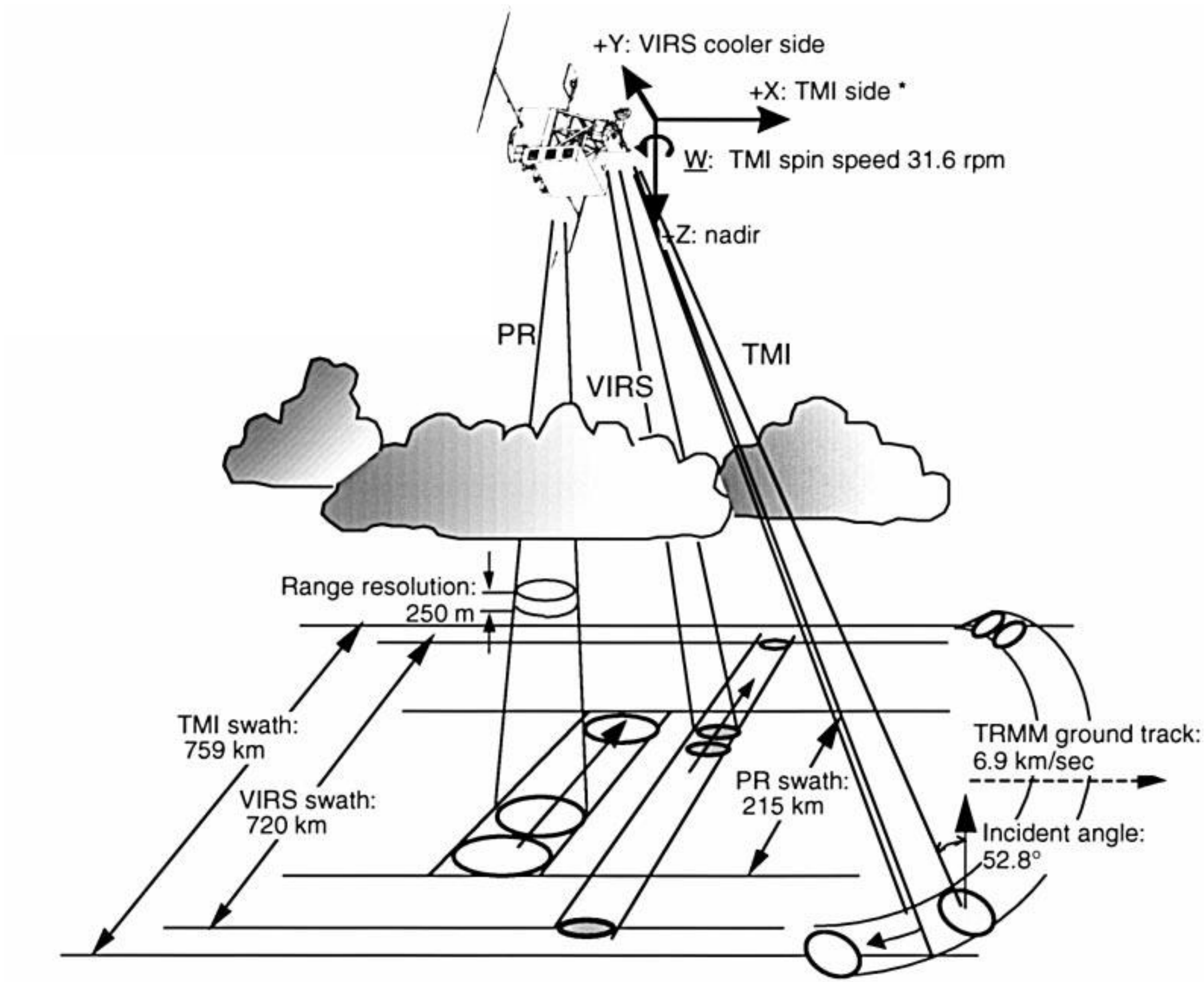
From: http://mrain.atmos.colostate.edu/LEVEL1C/level1C_devtmi.html

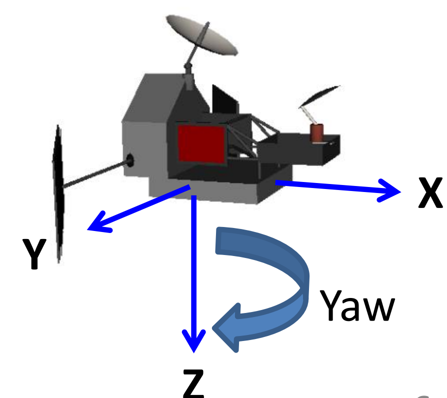
Tropical Rainfall Measuring Mission (TRMM) Spacecraft



CAD of TRMM using AGI's STK Software

TMI Scanning Geometry





Source: **"The Tropical Rainfall Measuring Mission (TRMM) Sensor Package,"** ***Journal of Atmospheric and Oceanic Technology***

Example of an Inertial Hold at Yaw=0°

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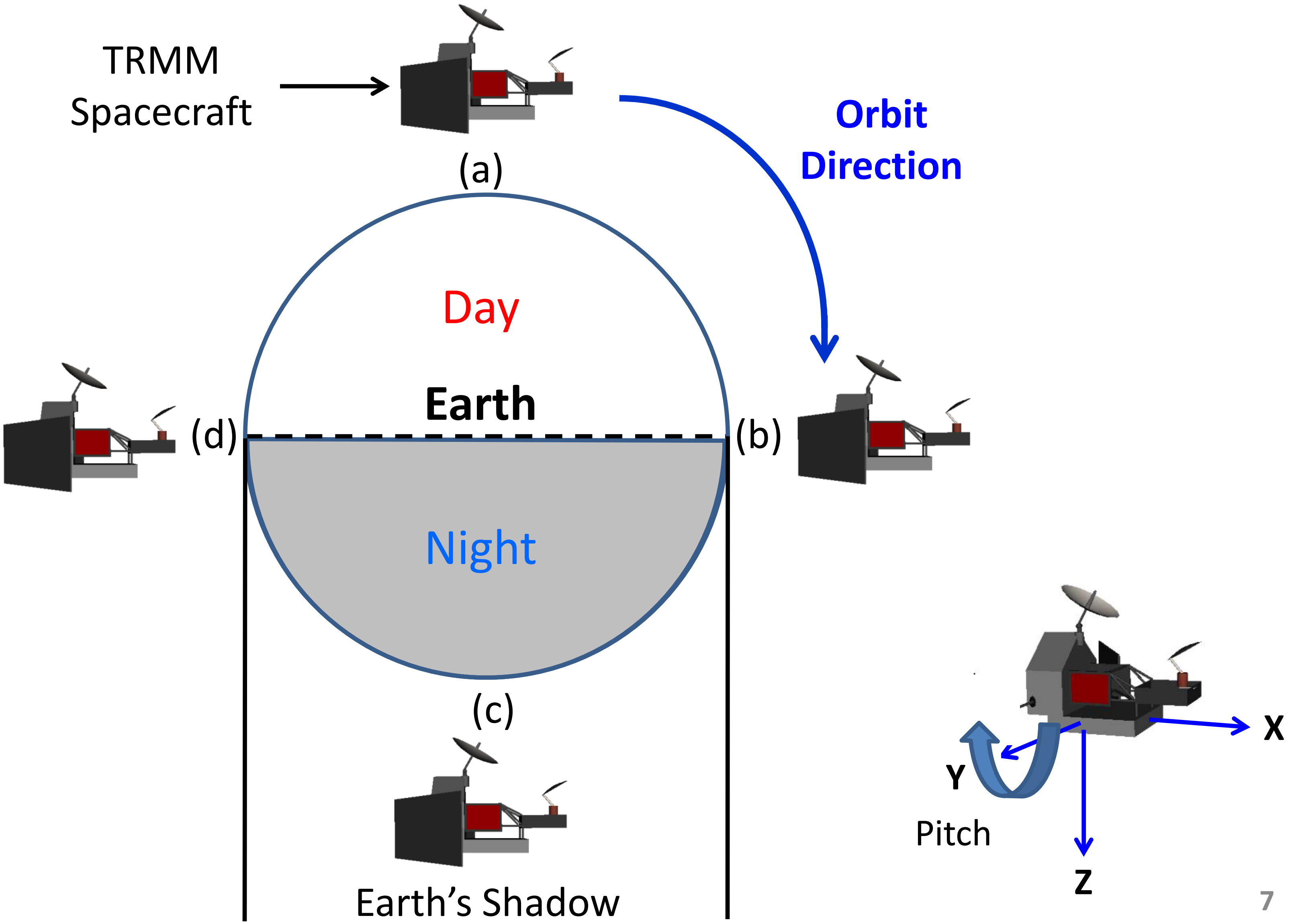
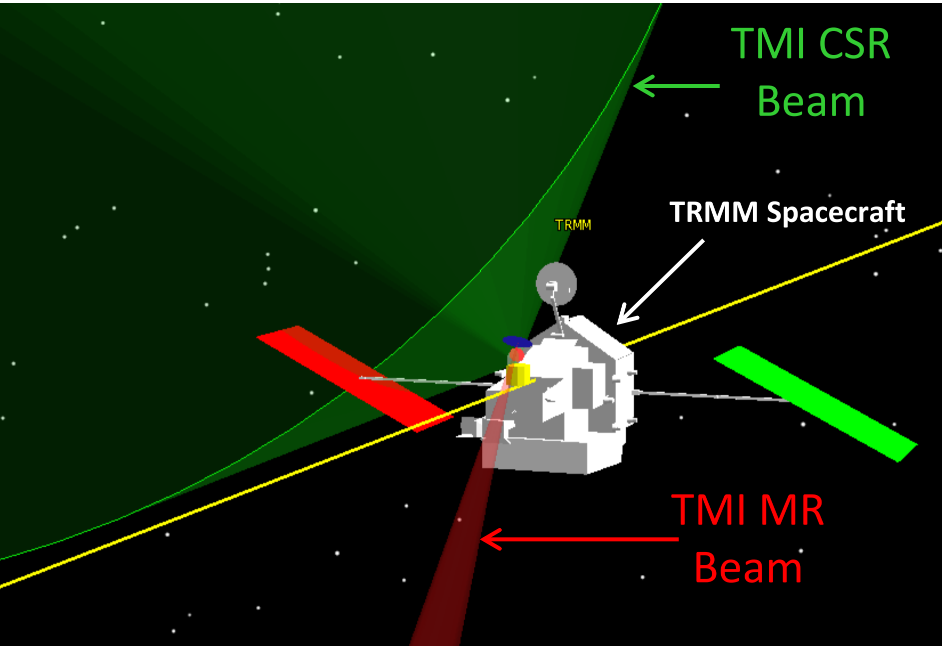


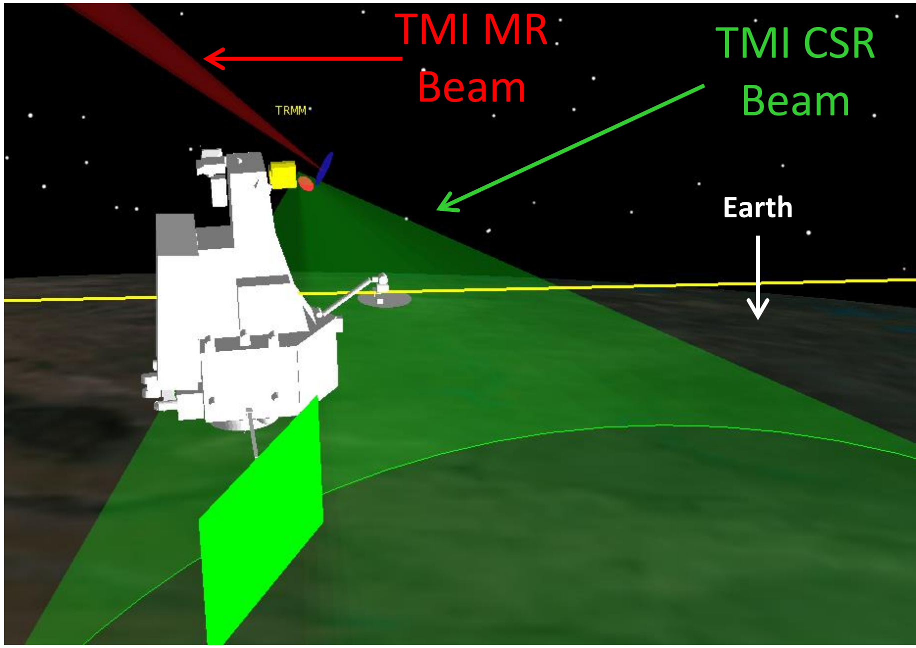
Main Reflector & Cold Sky Reflector Beams

Earth Pointing Mode



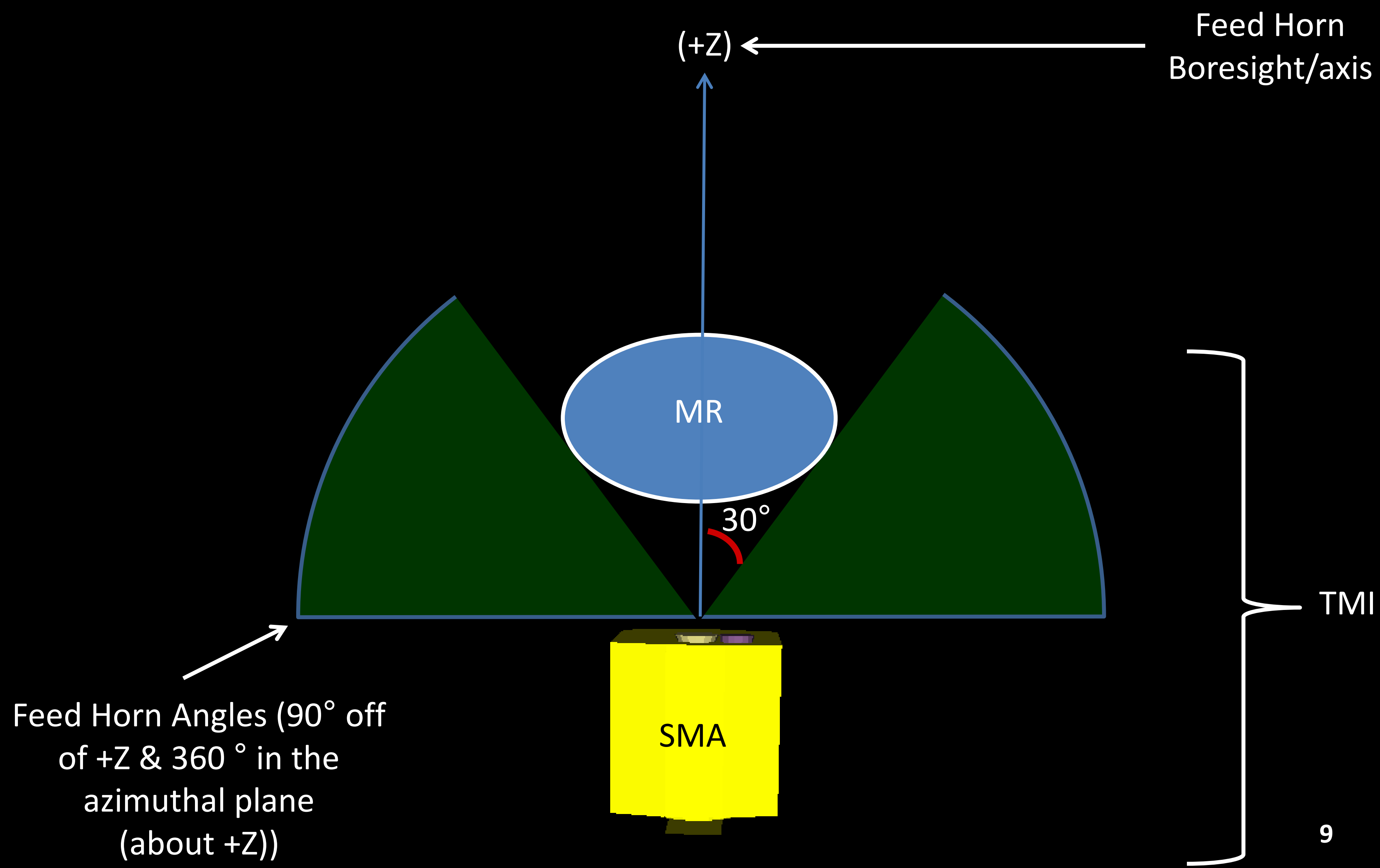
(a)

DSC Mode



(b)

Depicting Spillover Region



Time Series During T_A (10 V-pol) & EIA

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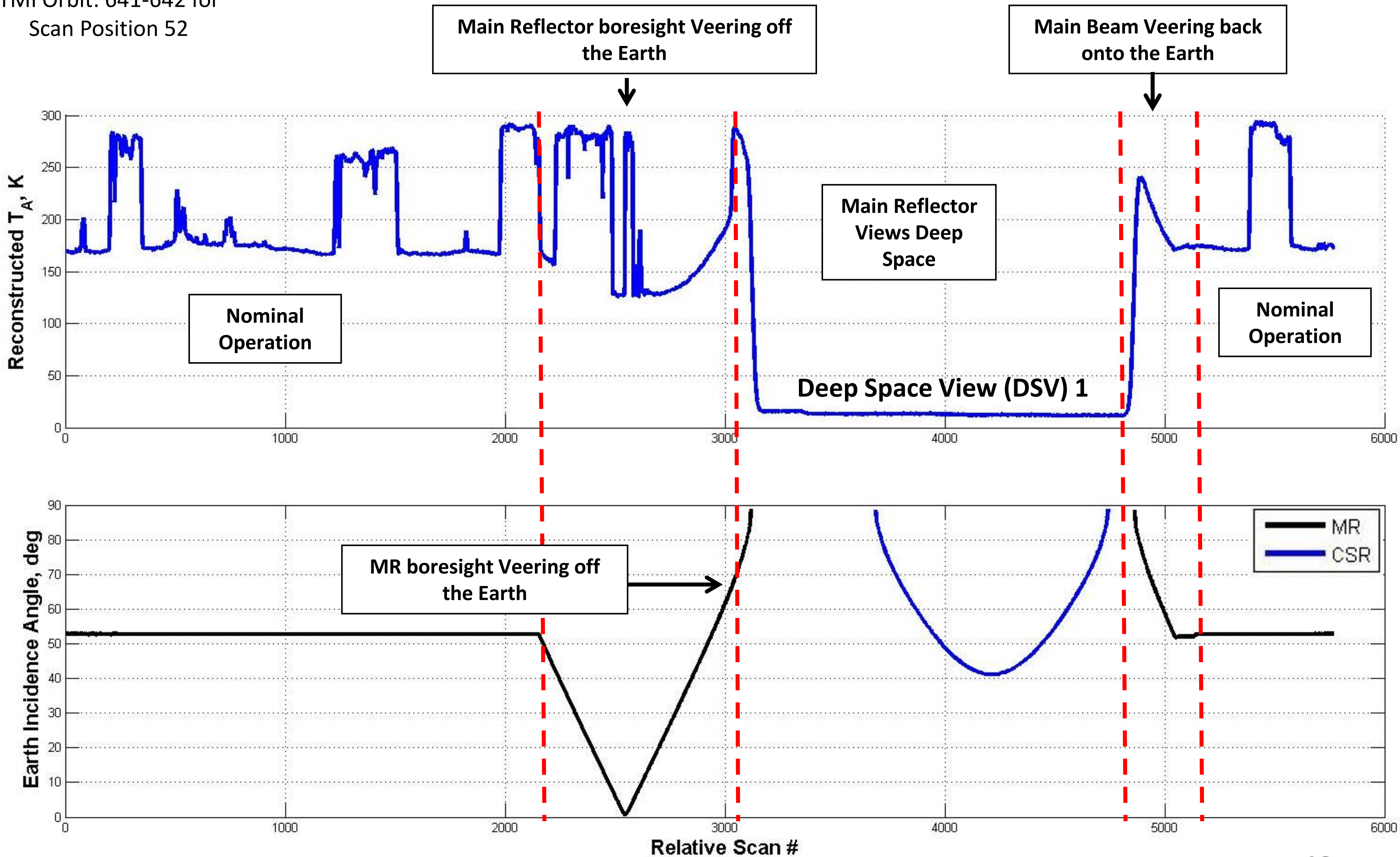
TMI Orbit: 641-642 for Scan Position 52



Analyses Performed

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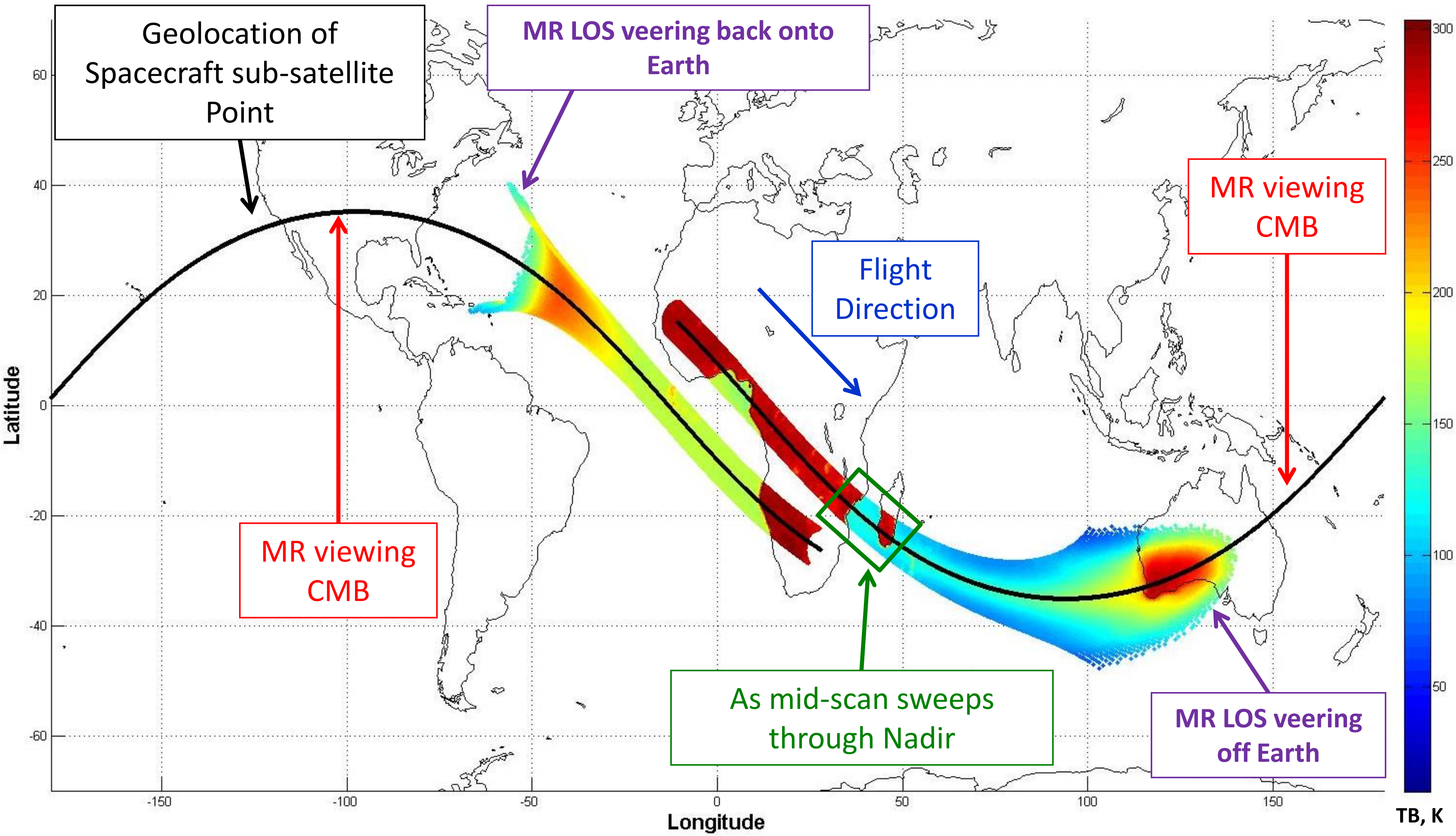
- Data Products Used:
  - TMI 1A11 & Base files: radiometric counts, temperature sensors, geolocation purposes
  - ERA-I from CSU for RTM
- Dissertation Covers:
  - Reconstruction of T_A
    - First presented in Proposal
    - Developed 2nd method
  - Beamwidth & Boresight Point
    - Uses the Earth's Horizon
  - Along-scan Bias
    - Very good agreement with RSS' results
  - TMI Emissive Reflector
  - Second Stokes using Nadir-Look

Discussed within this dissertation

Discussed in Dissertation & is placed in backup slides

Discussed within this Presentation

T_a for 10.65 GHz V-Pol During DSCM 1



DSCM Sets

DSCM Set	DSCM #	Date	Orbit #	Yaw (°)	Altitude (km)
1	1 – 6	Jan 7, 1998 Jan 8, 1998	641-646 657-662	180	349
2	7	Sept 2, 1998	4393-4394	0	350
3	8-10	July 22, 2014	95023-95028	0	400
4	11-16	Feb 26, 2015 Feb 27, 2015	98452- 98457 98468- 98473	0	350
5	17-20	Mar 25-26, 2015	98878-98883 98893-98898	90	341

Analysis

TMI Main Reflector Emissivity

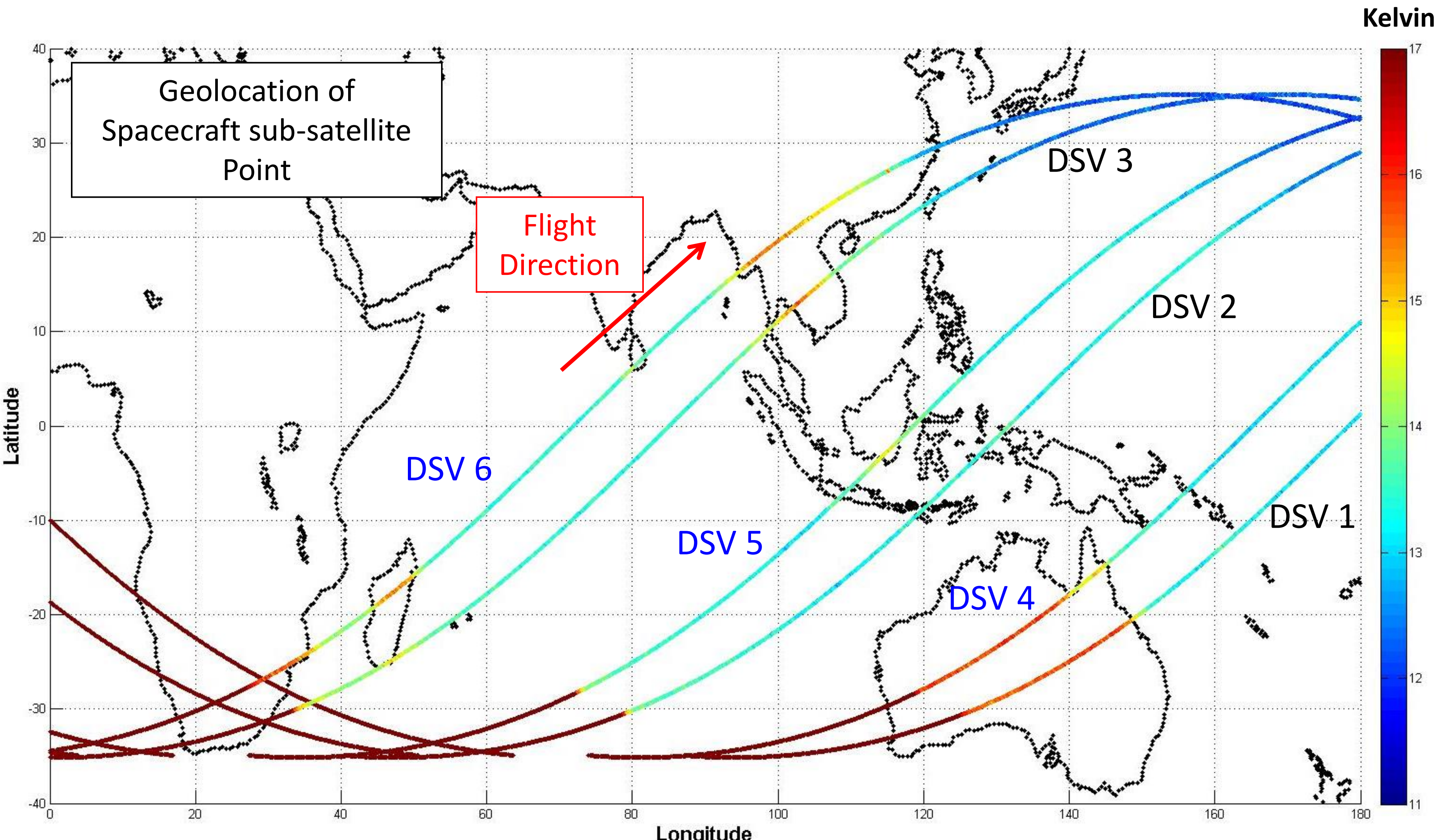
TMI's Emissive Main Reflector

- Since the beginning of the mission, NASA observed a positive bias in TMI's T_Bs
  - One theory was that RFI from TRMM's Precipitation Radar could be root cause (DSCM-7 in 1998 discarded this theory)
  - Since then it has been determined that TMI's MR is emissive as shown in RSS & CFRSL analyzes
    - Dependent on radiative transfer theory & intersatellite calibration
- An emissive reflector will reflect & emit energy

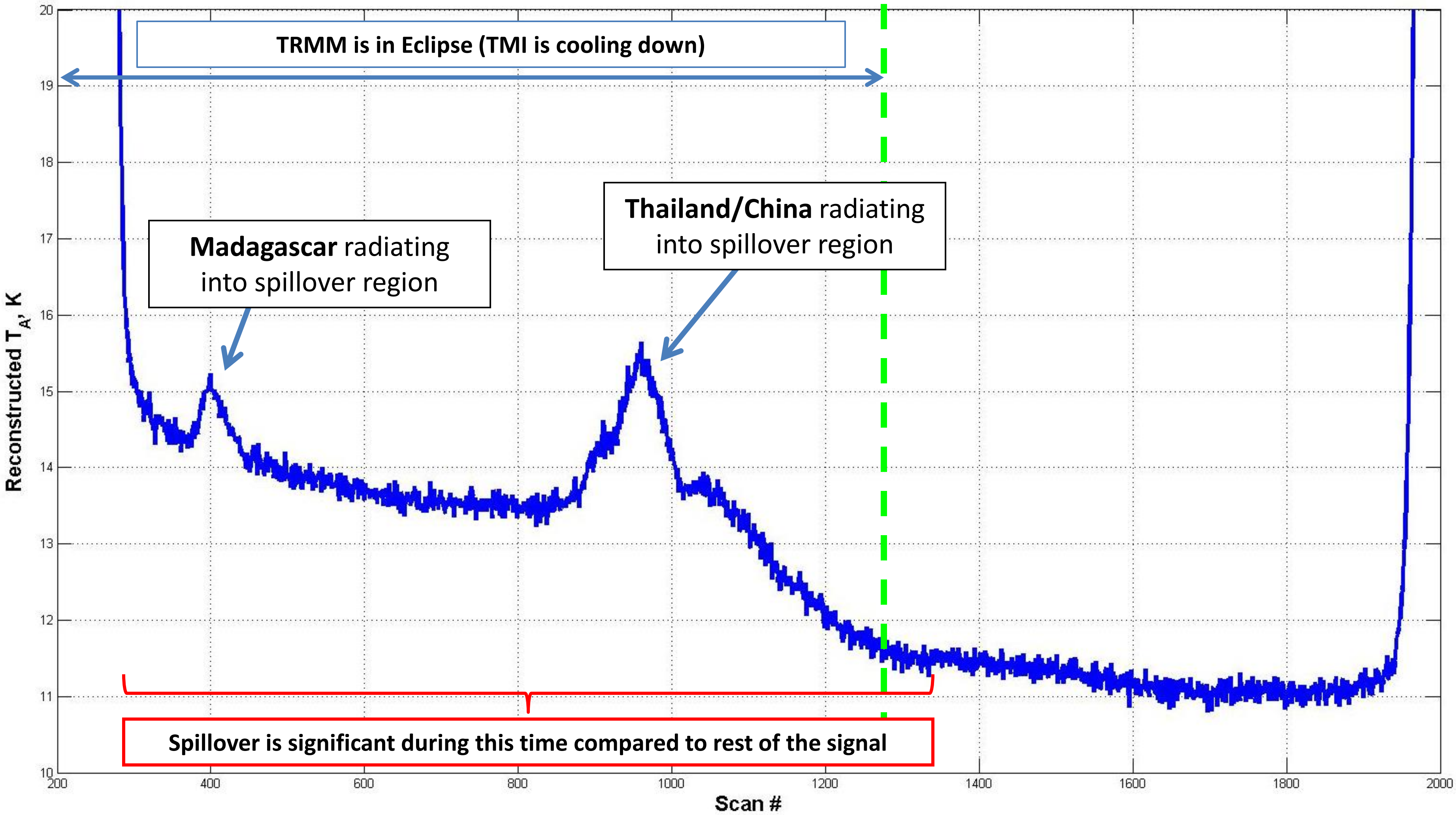
$$T'_{B,MR} = T_B \cdot (1-\varepsilon) + T_{MR\ Physical} \cdot \varepsilon \qquad (Eqn.1)$$

  - T_B energy incident on the reflector, ε & $T_{MR\ Physical}$ is the emissivity & physical temperature of the face of the reflector, respectively
- Goal: Determine the emissivity using the entire DSV time series

T_A (19 V-pol) Earth Contamination (Spillover) for DSV 1-6



Reconstruction of T_A for 10V



Deep Space Calibration Maneuver (DSCM) # 3

Removing Spillover

Removing Spillover Effect

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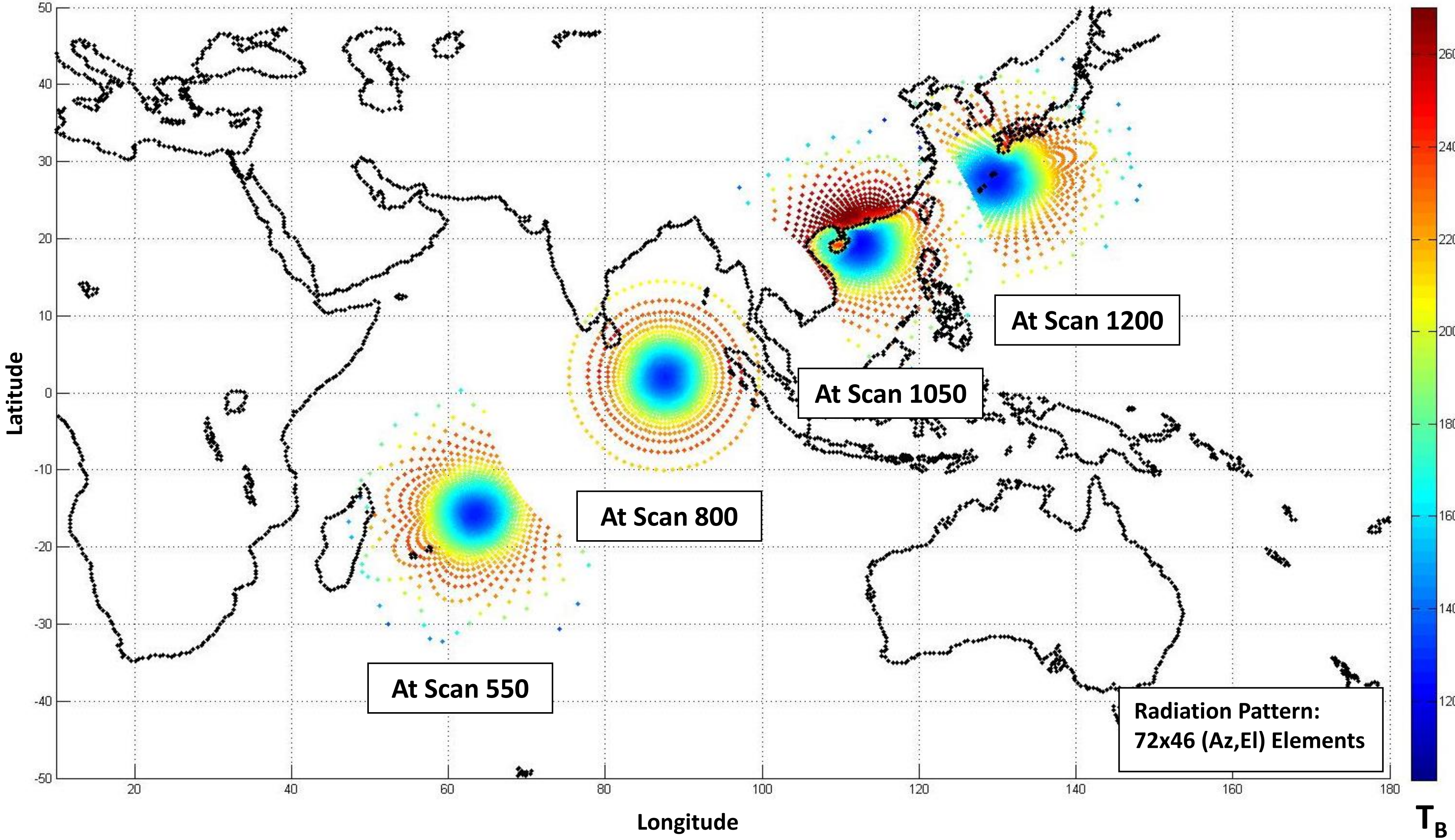
- Overall we need to simulate the signal that the feed radiation pattern (primary pattern) is measuring
- Need to characterize:
  - main reflector signal ($T'_{B,MR}$)
  - the spillover: illuminate parts of TMI & TRMM, Space, Earth (Land/Ocean)

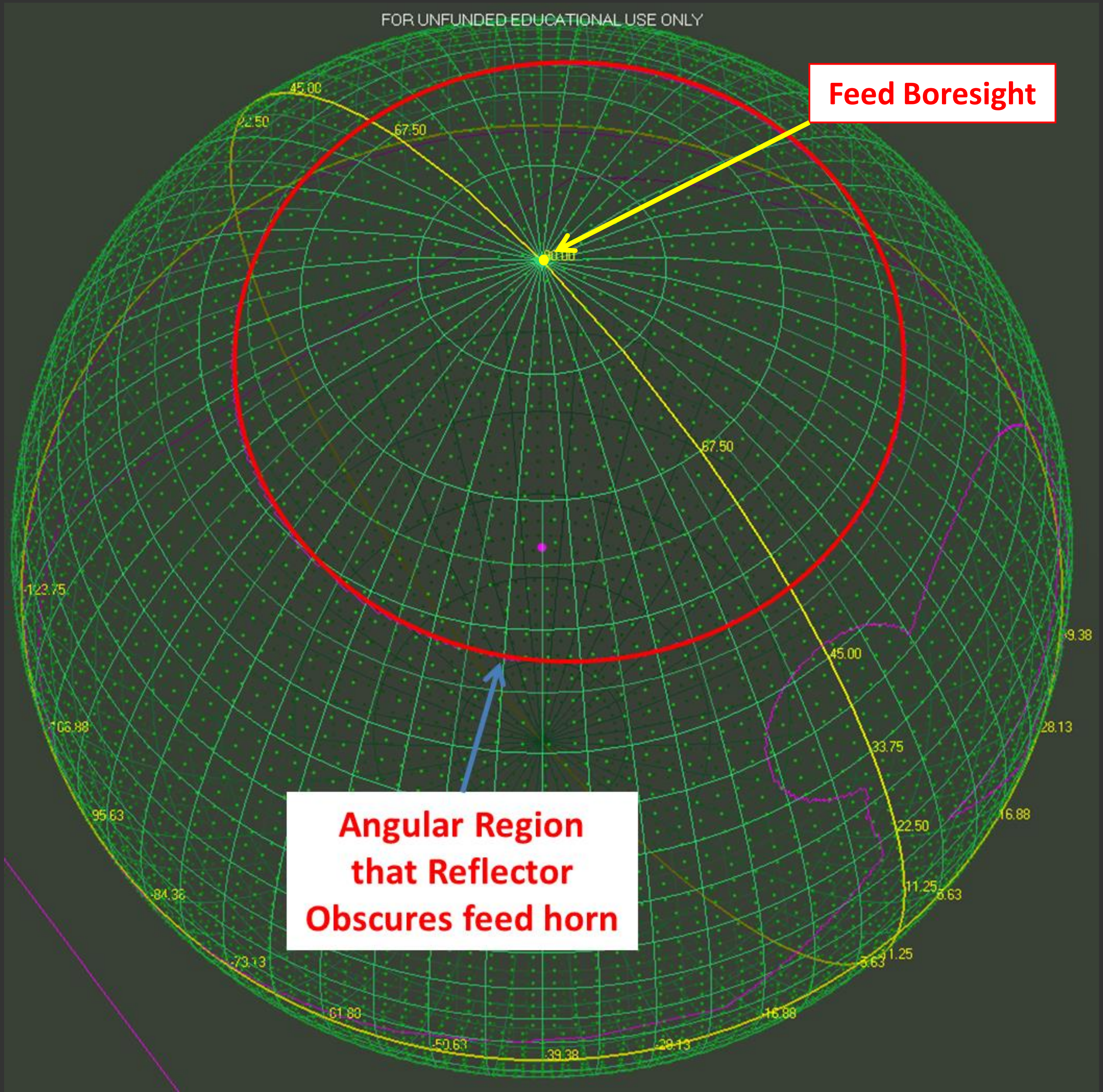
1. Geolocate Radiation Pattern for removal of spillover (modified TMI geolocation code)
   - Obtain Feed Radiation Pattern (Primary) – the weighting function
   - Obscure Feed Pattern
2. Simulate spillover portion that intersects Earth (discussed in Dissertation & Back-up slides)

Projection of Spillover with assigned TB Values (11 V-pol)



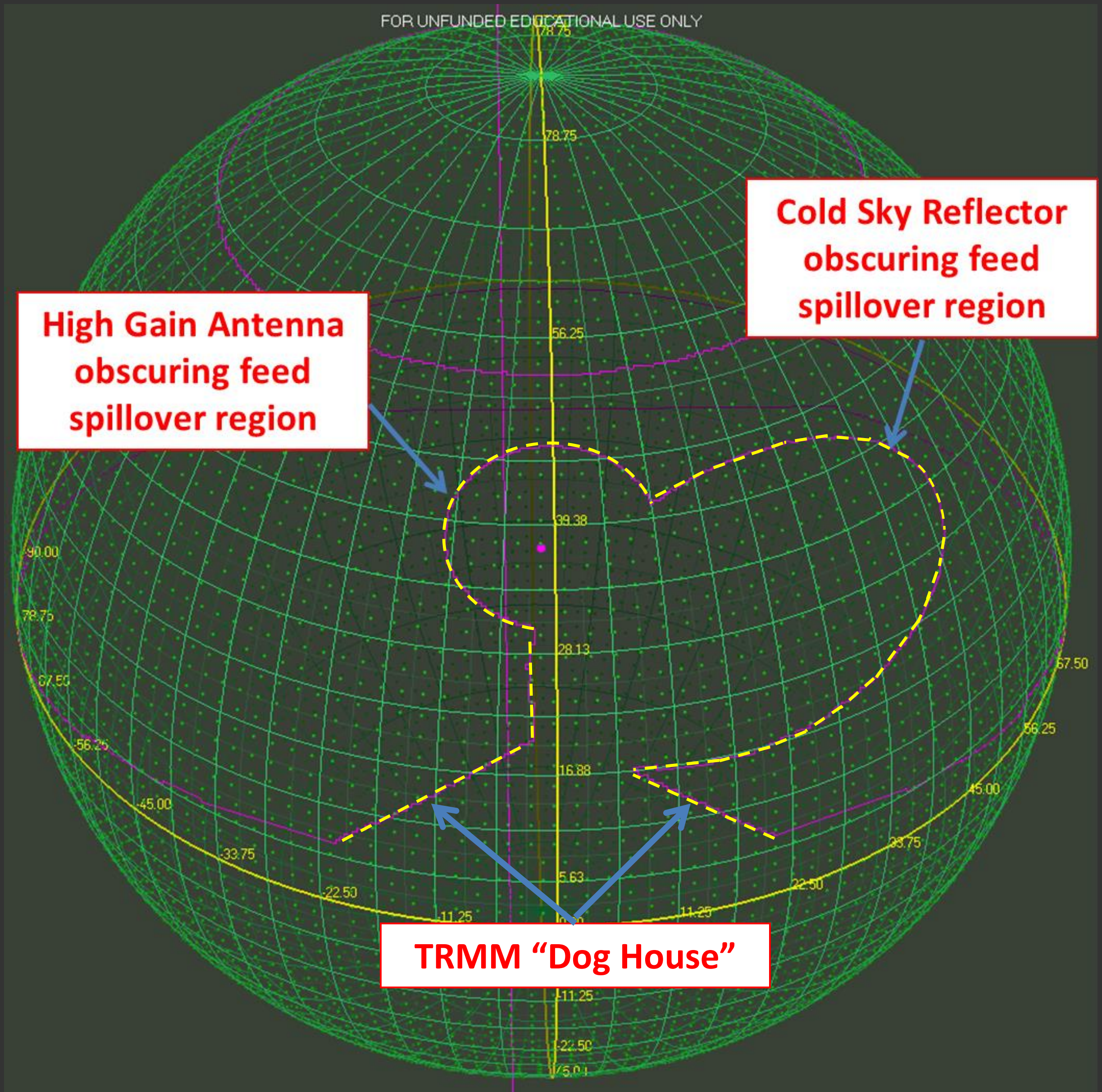
Deep Space Calibration Maneuver (DSCM) # 3

Radiation Mask – Main Reflector



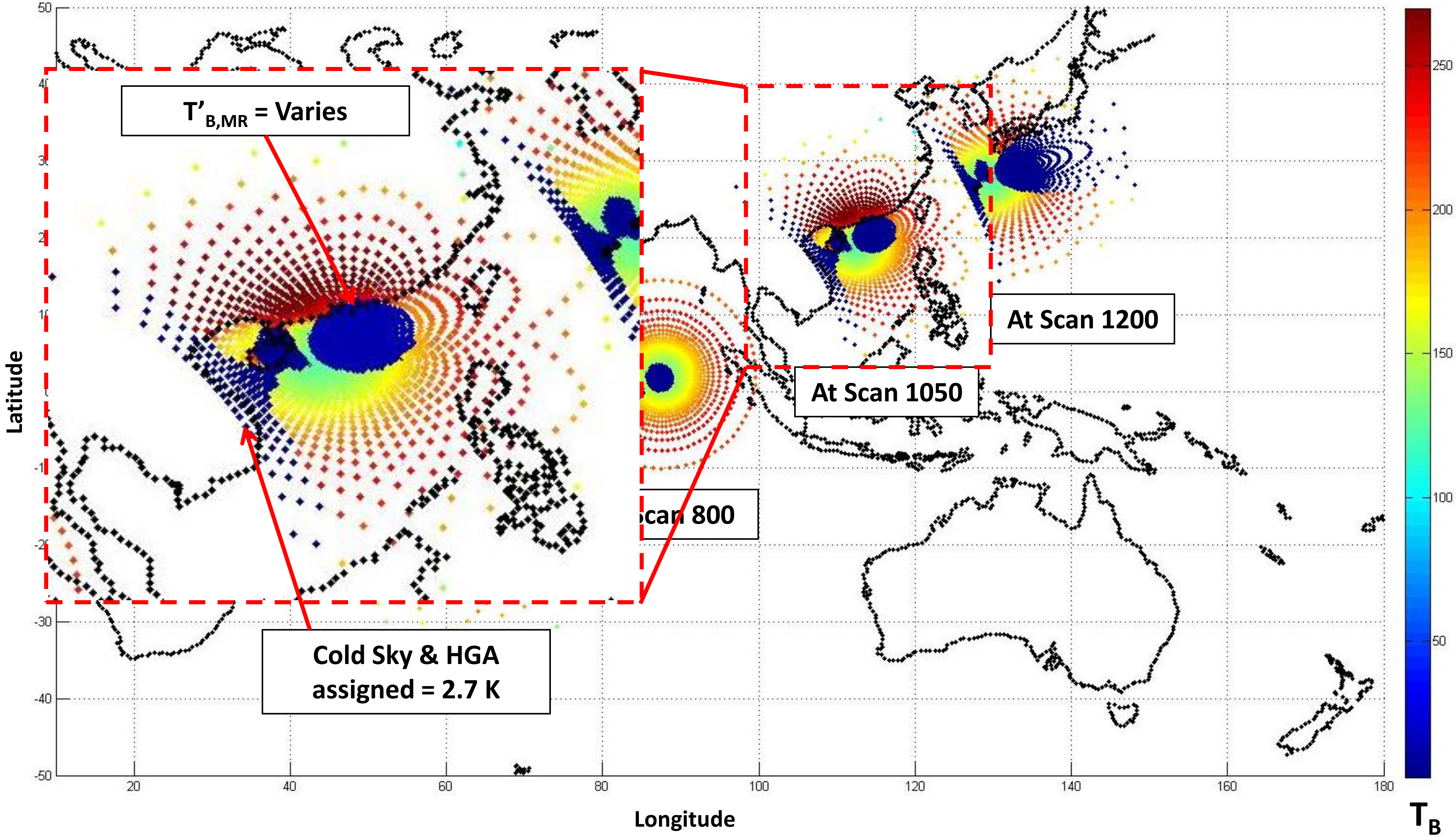
Using TRMM CAD model & AGI STK

Radiation Mask – HGA, CSR, Spacecraft



Using TRMM CAD model & AGI STK

Projection of Spillover with assigned TB Values with Obscuration



Separating Feed Horn T_A: Main Reflector & Spillover Regions

$$T'_A = \frac{\iint_{MR\,Angles} T'_{B,MR}(\Omega_{MR})\,F_{MR}(\Omega_{MR})\,d\Omega}{\iint_{2\pi\,sr} F_{MR}(\Omega_{MR})\,d\Omega} + \frac{\iint_{Spillover\,Region} T_{B,SR}(\Omega_{SR})\,F_{SR}(\Omega_{SR})\,d\Omega}{\iint_{2\pi\,sr} F_{SR}(\Omega_{SR})\,d\Omega} \quad (Eqn.2)$$

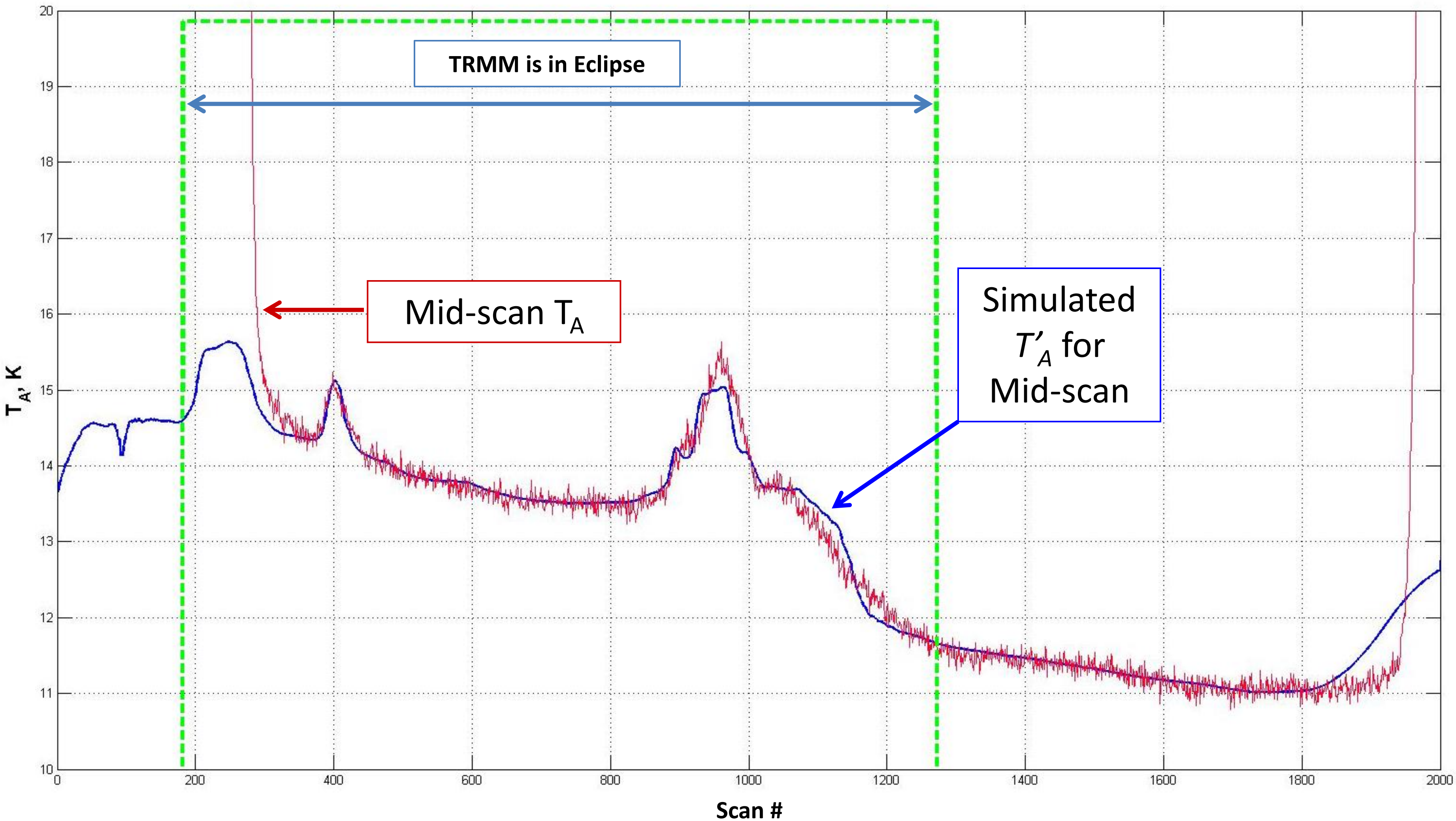
From T'_A reconstruction method

$T'_{B,MR}$ is parametrically varied until right side of eqn matches T'_A

Simulated as discussed in dissertation

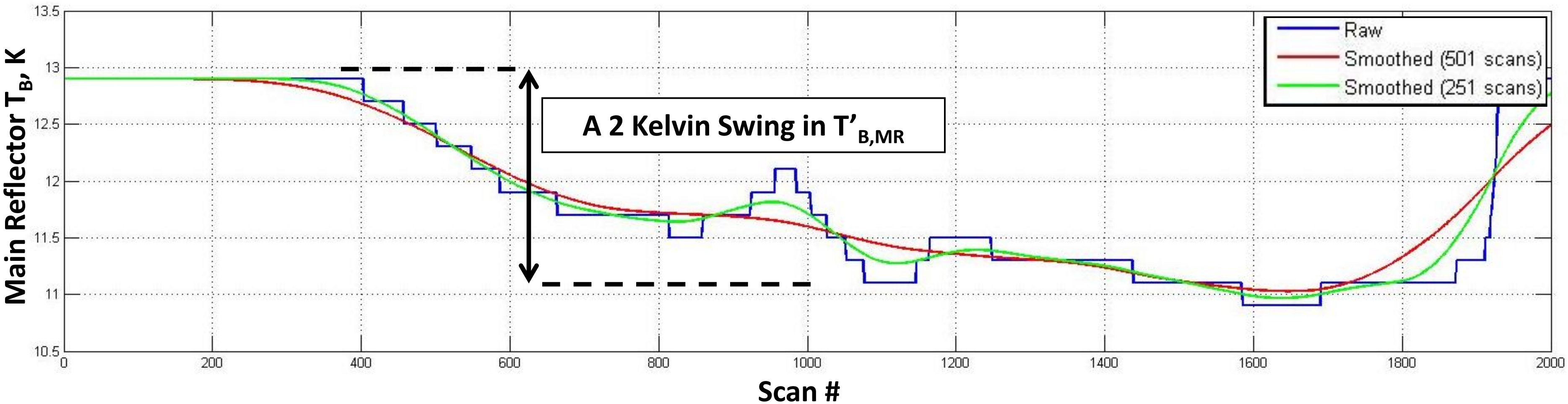
MR: Main Reflector
SR: Spillover Region
F: Feed Radiation pattern

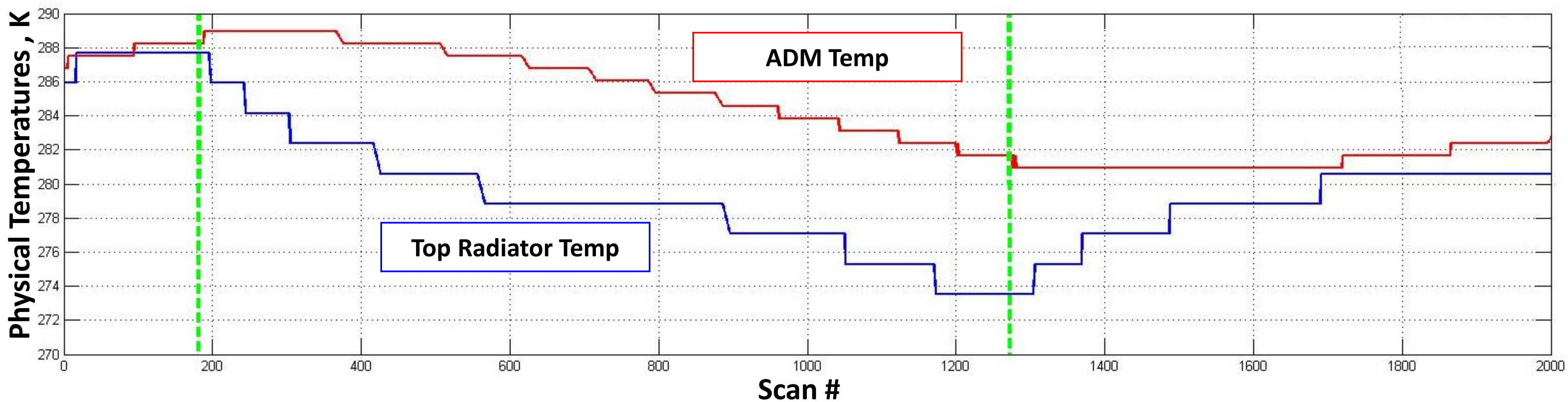
Matching Simulated T_A to Truth: 10V



Deep Space Calibration Maneuver (DSCM) # 3

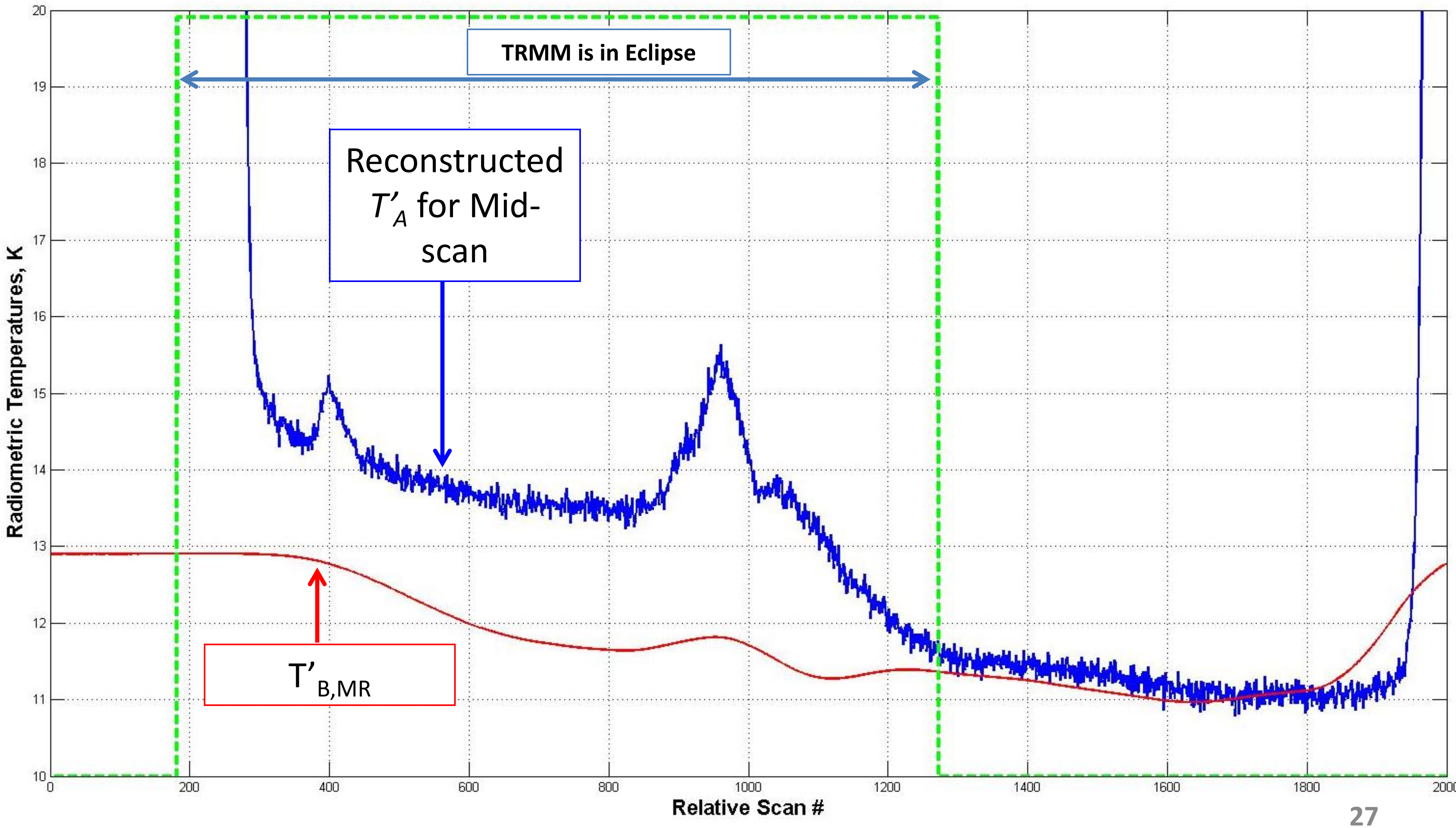
DSCM 3: $T_{B,MR}$ & Physical Temperatures





Deep Space Calibration Maneuver (DSCM) # 3

Comparing 10 V-pol Signals DSV-3



Solving for TMI Emissivity

TMI Main Reflector

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- An emissive MR during DSV:

$$T'_{B,MR} = \underline{T_B} \cdot (1-\varepsilon) + \underline{T_{MR\ Physical}} \cdot \varepsilon, \longrightarrow \varepsilon : emissivity\ \ of\ \ the\ main\ reflector$$

T_B → Depends on frequency (2.7-3.2 K)

$T_{MR\ Physical}$ → Independent of frequency

ε → Depends on frequency

- Unknowns: $T_{MR\ Physical}$ & ε (2 unknowns)
  - *Only TB & ε are unique to each channel*

Research on SSMIS Reflector

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- Special Sensor Microwave Imager/Sounder (SSMIS) is DOD microwave radiometer on the DMSP series
- Using previous work by JPL (Shannon Brown) on SSMIS Emissive Reflector*; where the emissivity for V & H-Pol are:

$$\varepsilon_v \cong \sqrt{\frac{16\pi\upsilon\varepsilon_0}{\sigma_{eff}}}\sec\theta_i \qquad \varepsilon_h \cong \varepsilon_v \cos^2\theta_i \qquad (Eqns.3\&4)$$

  - v = frequency [Hz], ε_0 = free-space permittivity [F/m], σ_{eff} = effective conductivity [S/m], ϑ_i is incidence angle
  - Assuming effective conductivity is constant then emissivity varies due to the operating frequency
  - As MR views Deep Space, a non-polarized signal, incidence angle is neglected sec(θ)=1 & $\varepsilon_v = \varepsilon_h$

*Observed F-16 and F-17 Anomalies Detailed Analysis of the Root Causes, and the Path Forward

Emissivity Response to Frequency

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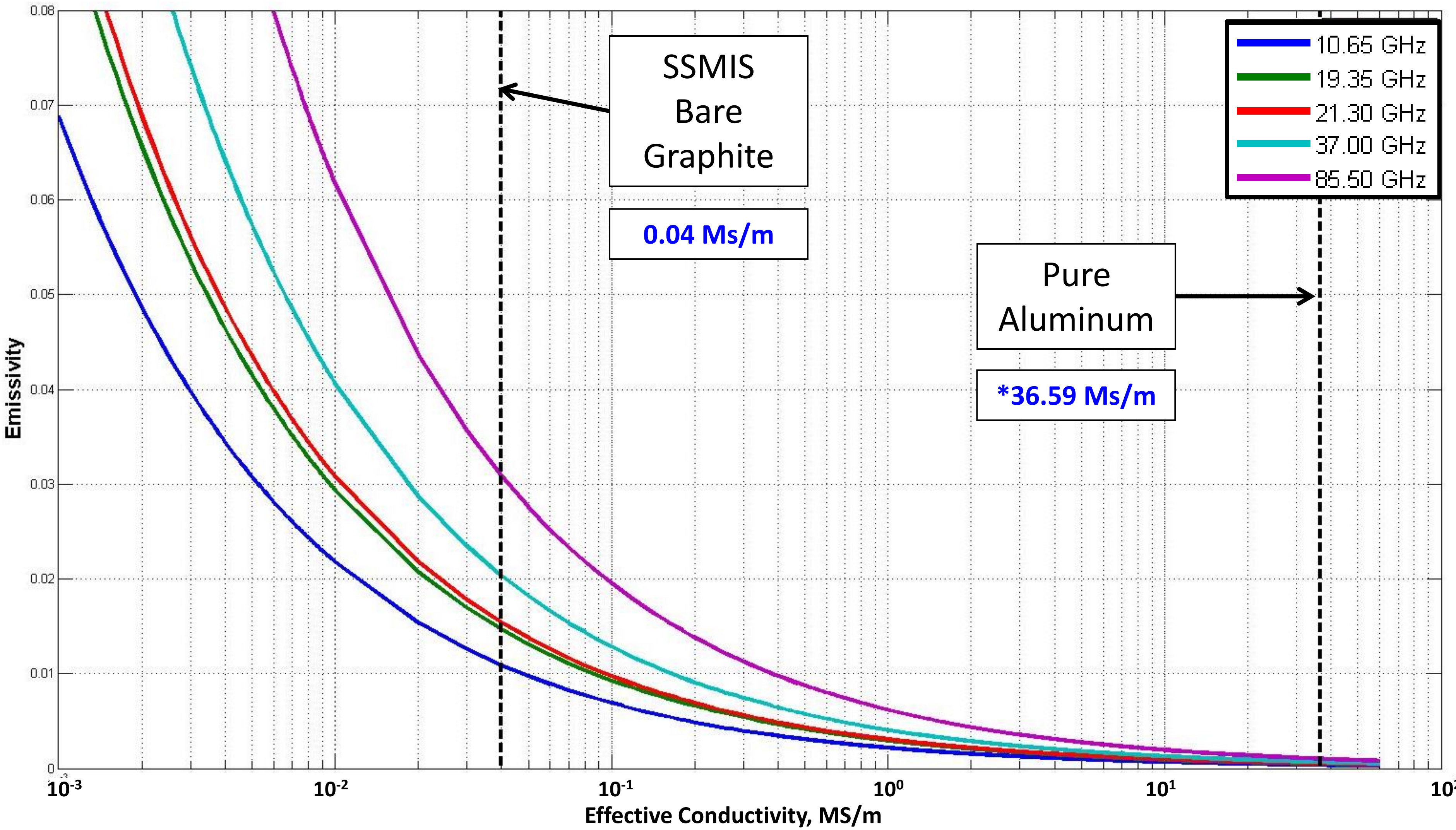


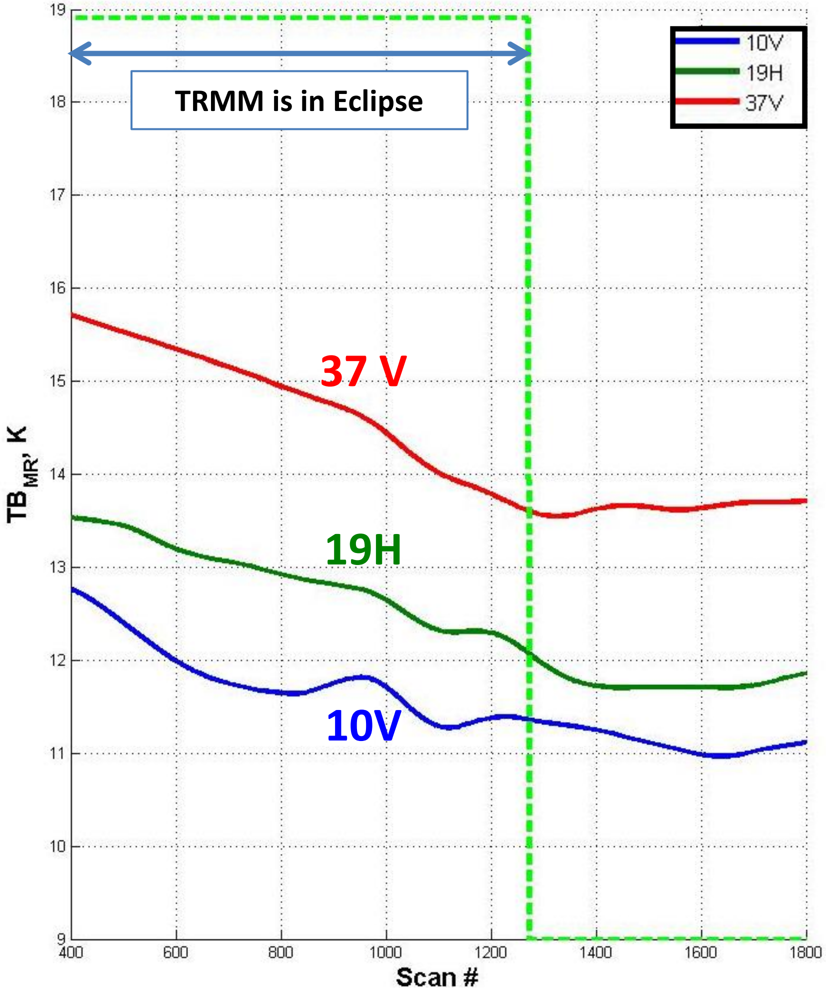
*Observed F-16 and F-17 Anomalies Detailed Analysis of the Root Causes, and the Path Forward

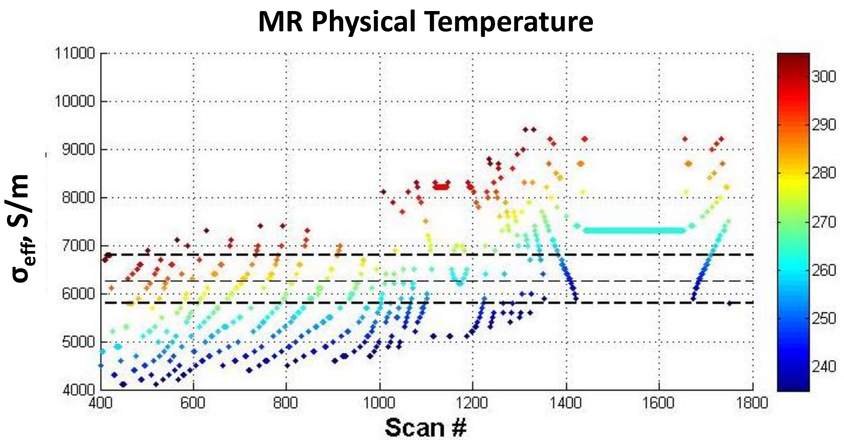
Constraints & Method

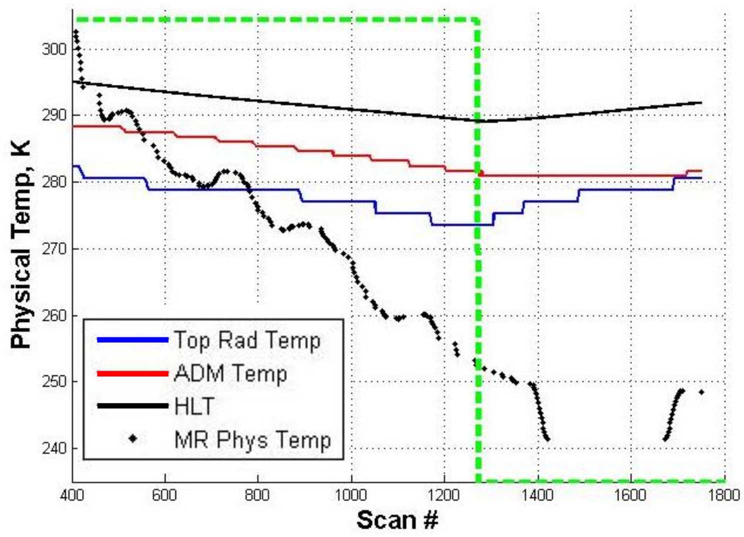
- Constraints
  - There are two unknowns: $T_{MR,Phys}$ & σ_{eff}
  - Using GMI MR temperature sensor as a proxy for TMI MR physical temperature limits:
    - Based on Solar Beta angle ±45° & Inertial hold maneuvers (240 – 300 K)
    - Temp Constraints: 235 - 305 K
  - Conductivity was bounded by 1000 to 36e6 S/m
- Method
  1. For each scan of a given channel
     a) Simulate $\boldsymbol{T'_{B,MR}}$ ($\boldsymbol{SimT'_{B,MR}}$) for all combinations of $T_{MR,Phys}$ & σ_{eff}
     b) Calculate the $|\boldsymbol{T'_{B,MR} - SimT'_{B,MR}}| = \boldsymbol{\Delta T_{B,MR}}$
  2. Average of $\boldsymbol{\Delta T_{B,MR}}$ for 10V, 19H, 37V channels , $\boldsymbol{< \Delta T_{B,MR} >}$
  3. Obtain the minimum $< \boldsymbol{\Delta T_{B,MR}} >$ with respect to scan

Determining Conductivity

Scan Bias Correction off







Determining Conductivity

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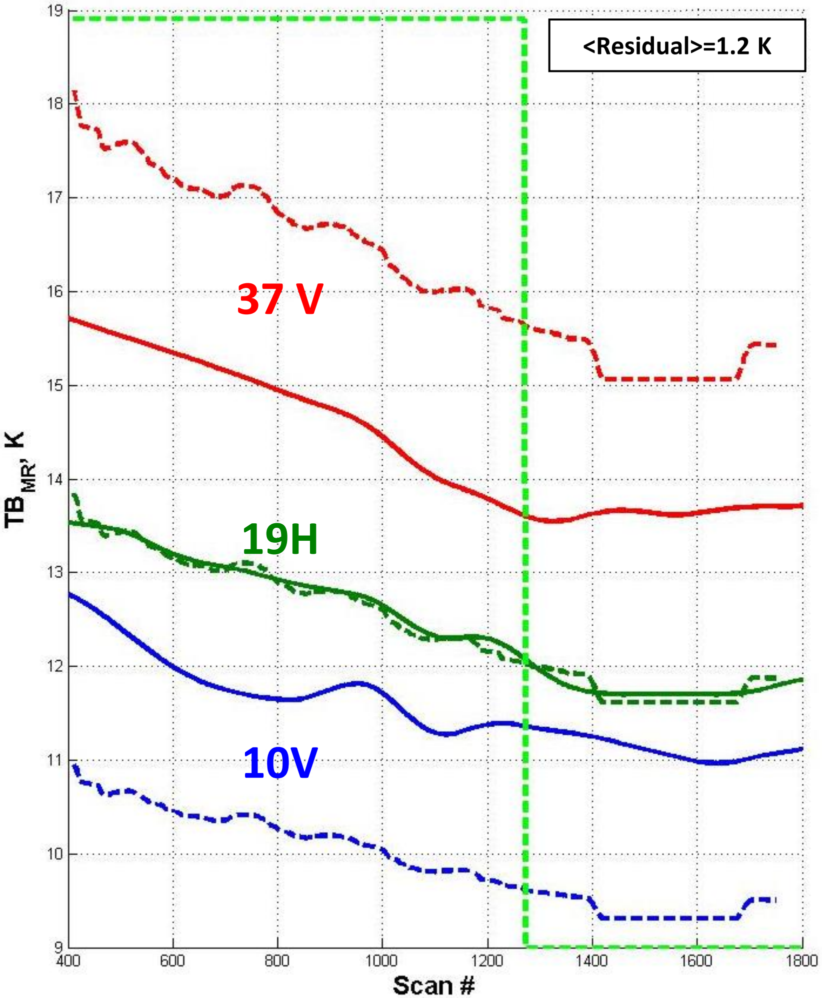
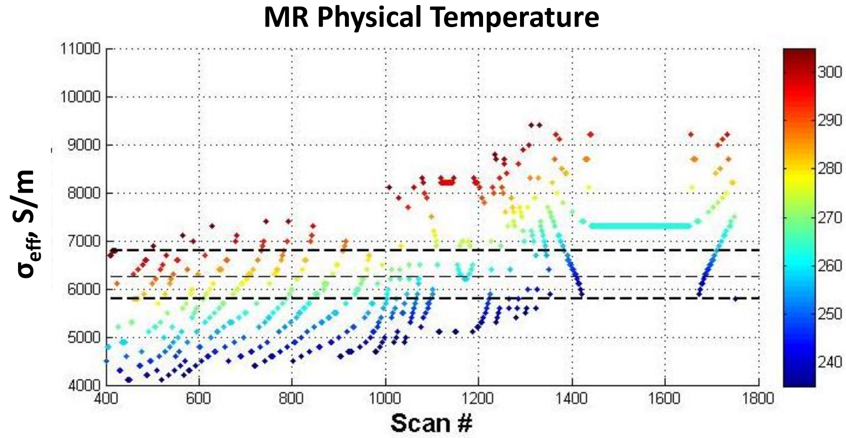
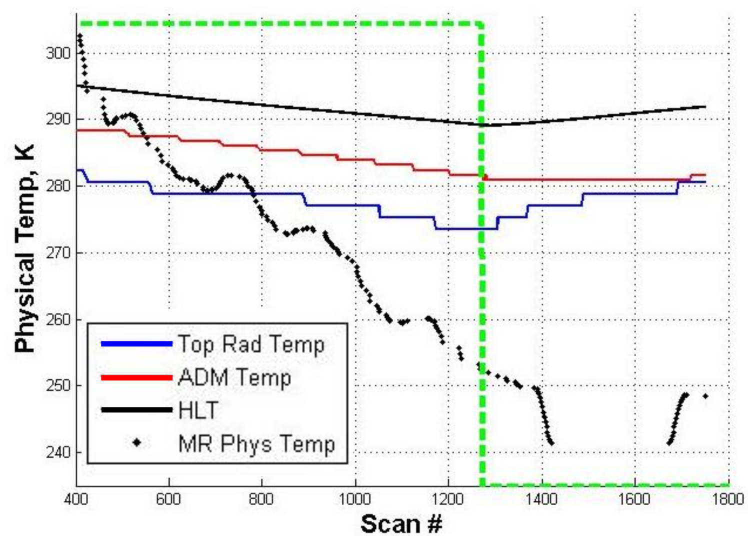
—— Lines: Is what I use determine σ_{eff}
------- Lines: Using σ_{eff} and $T_{MR,Phys}$ to recalculate TB,MR

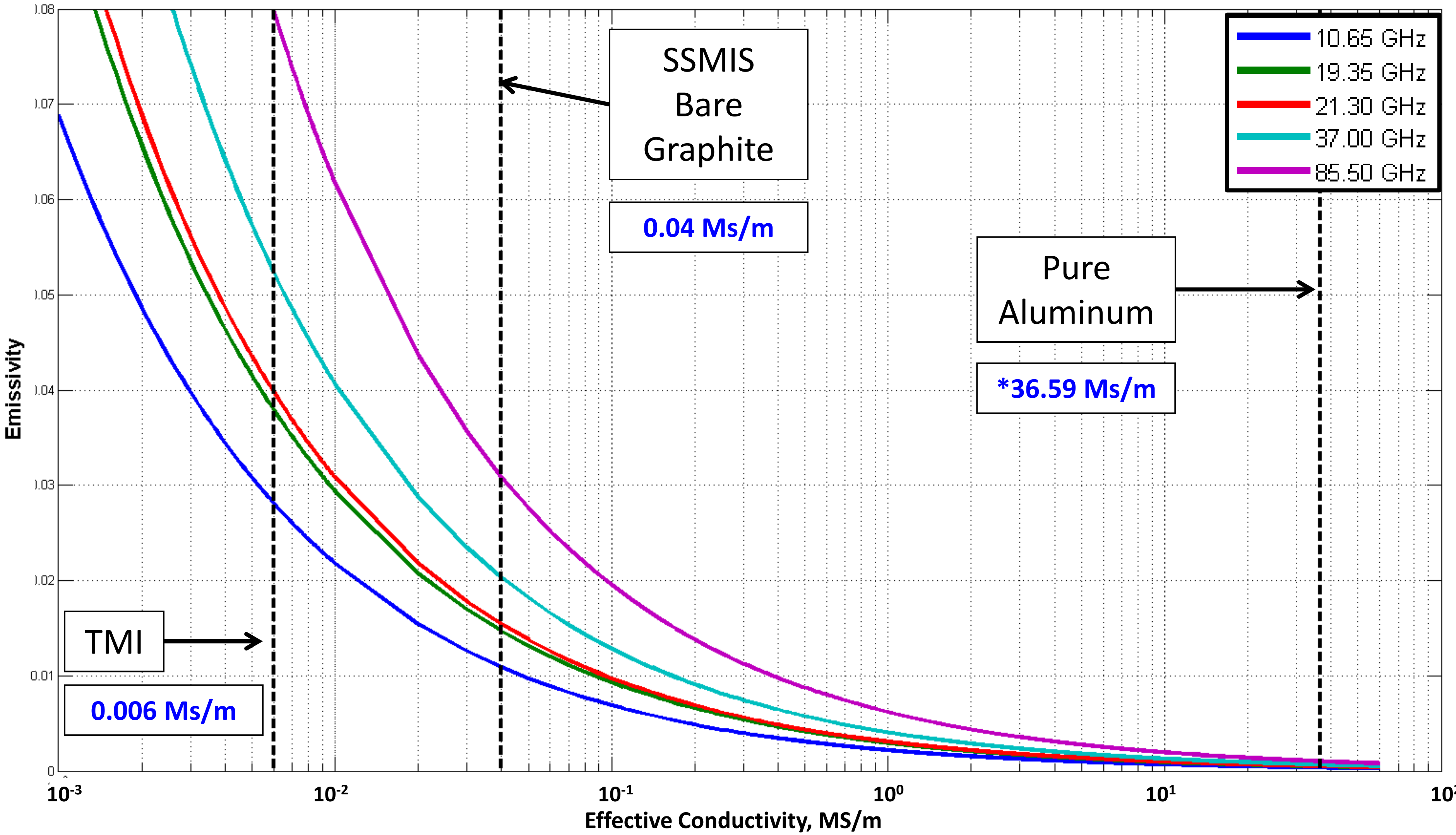
Scan Bias Correction off





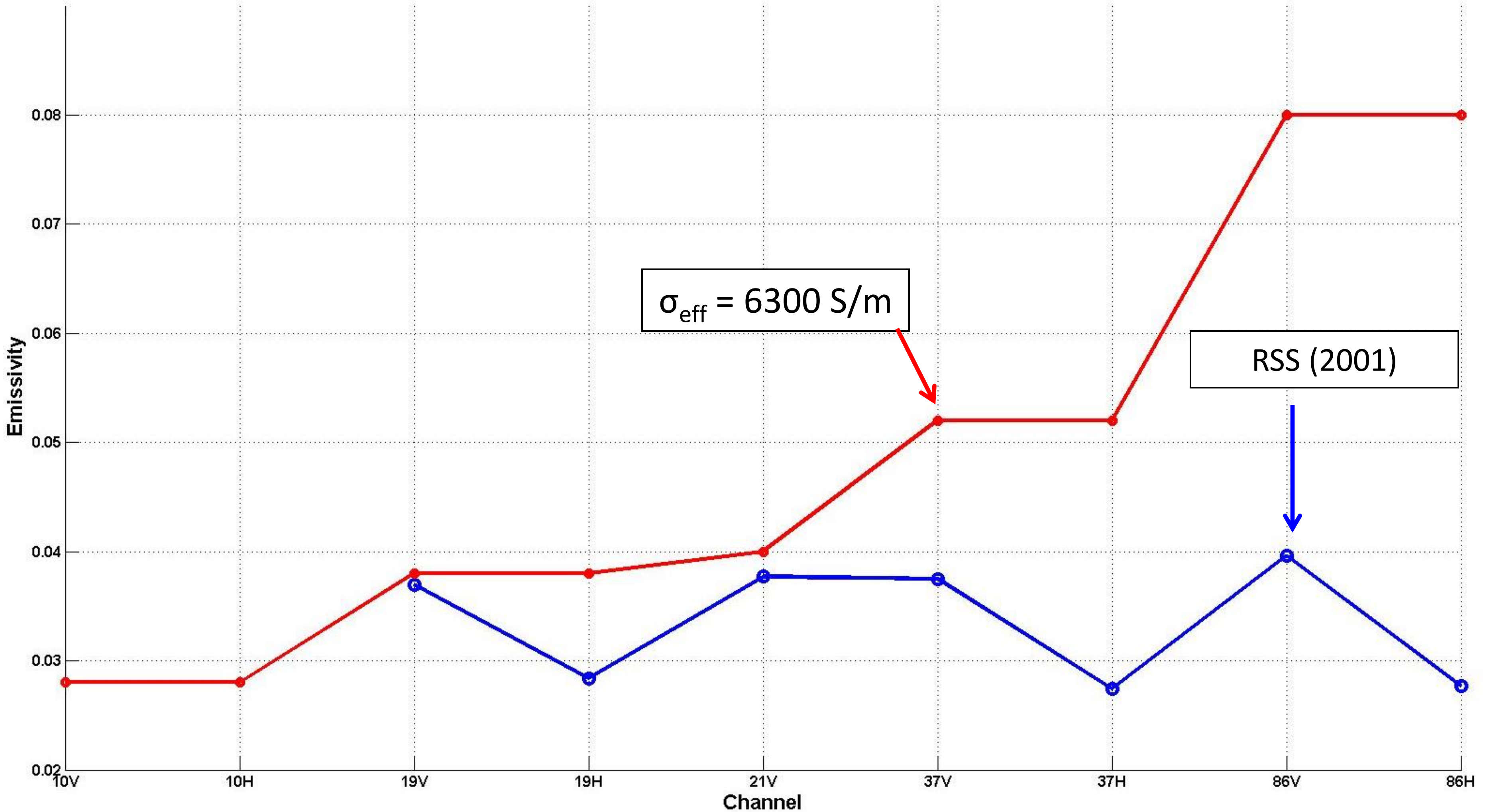


Emissivity Response to Frequency



*Observed F-16 and F-17 Anomalies Detailed Analysis of the Root Causes, and the Path Forward

Estimated TMI Emissivity Values



σ_{eff} = Based on DSCM 1-6

Estimated TMI Emissivity Values

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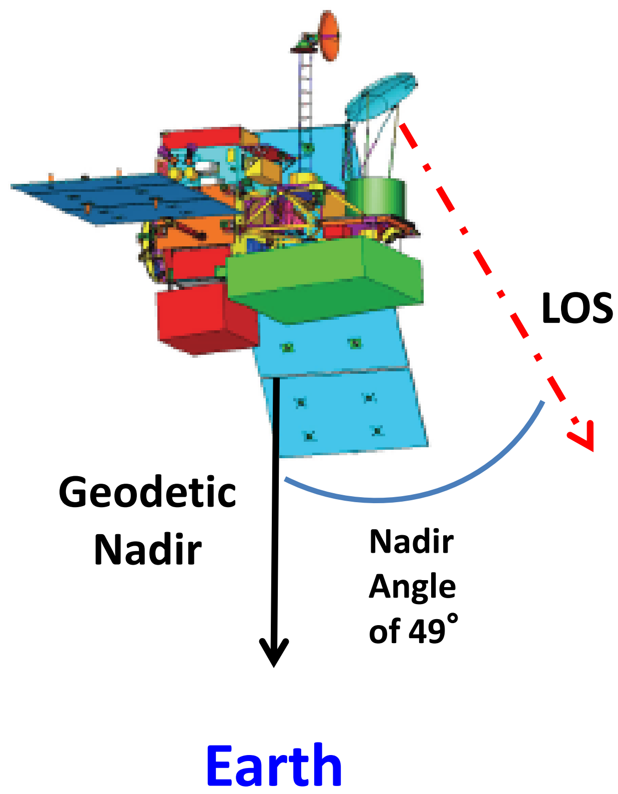
Channel	RSS (TGARS 2001)	CFRSL Viewing Space / Viewing Earth
10.65 V-pol	NA	0.028 / 0.031
10.65 H-pol	NA	0.028 / 0.025
19.35 V-pol	0.0370	0.038 / 0.042
19.35 H-pol	0.0284	0.038 / 0.034
21.30 V-pol	0.0377	0.040 / 0.044
37.00 V-pol	0.0375	0.052 / 0.058
37.00 H-pol	0.0274	0.052 / 0.048
85.50 V-pol	0.0396	0.080 / 0.088
85.50 H-pol	0.0277	0.080 / 0.072

Analysis

Second Stokes Analysis Using a Nadir Look

Nadir-Look

Normal Mode



Locked Pitch Angle at 49°

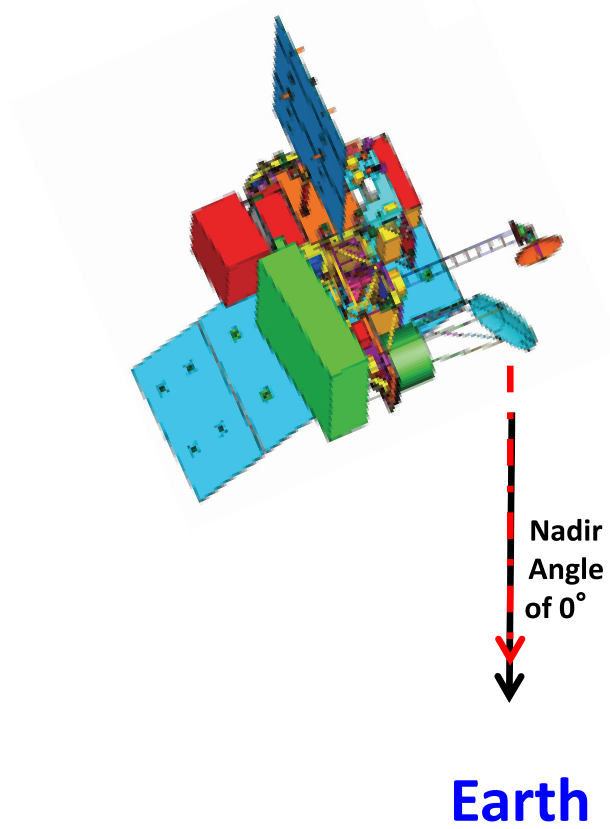


Illustration uses GPM spacecraft as example

2nd Stokes Analysis (SS)

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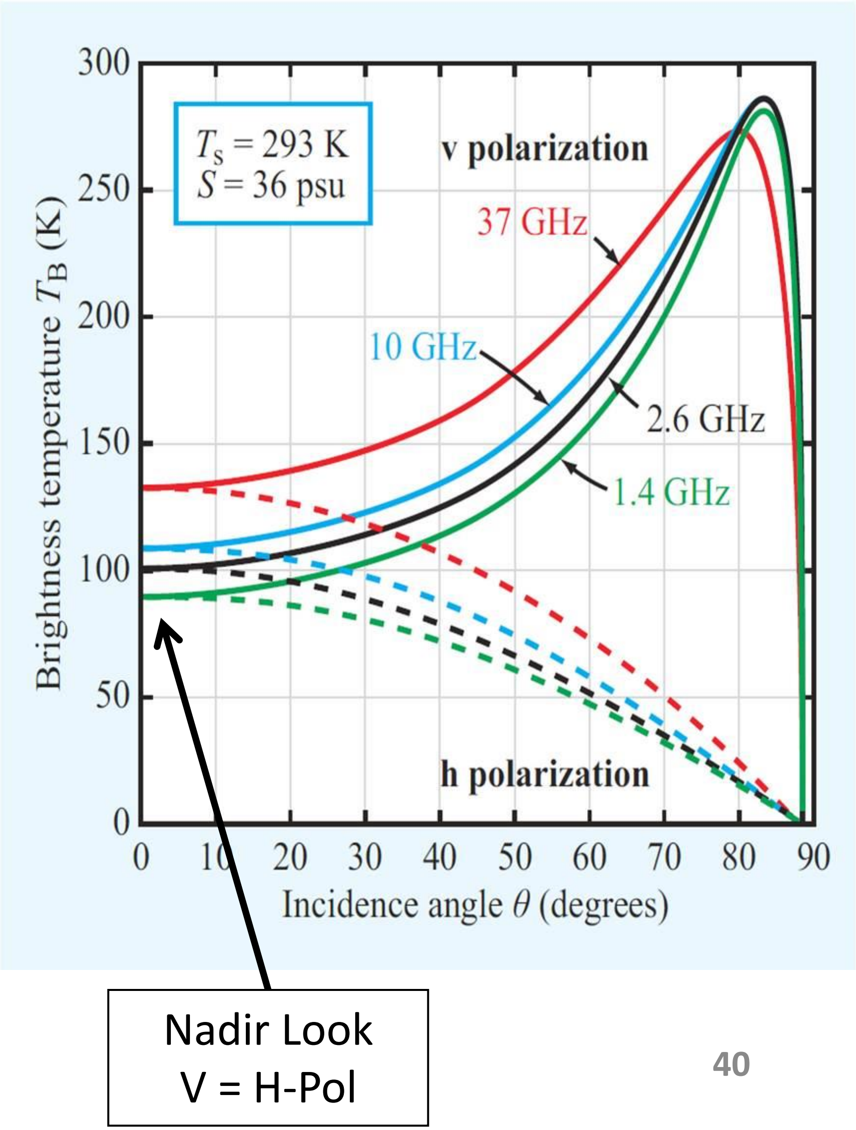
Image Source: Microwave Radar & Radiometric Remote Sensing (Ulaby)

- Stokes Parameters:

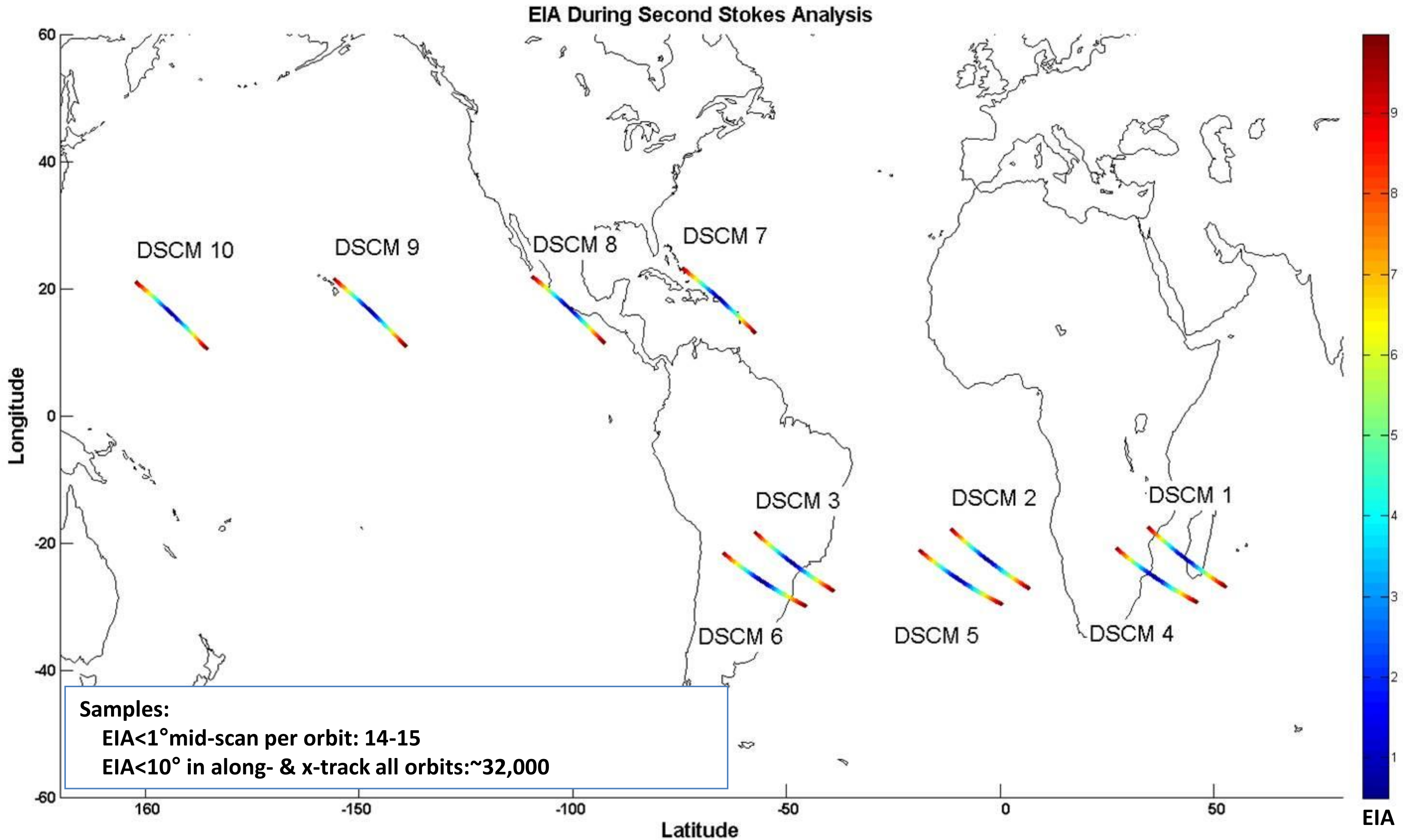
$$I = \frac{\langle |E_v|^2 \rangle + \langle |E_h|^2 \rangle}{\eta} = S_v + S_h, \quad U = \frac{2 \cdot \mathrm{Re}\langle E_v E_h^* \rangle}{\eta} = S_{+45} - S_{-45},$$

$$Q = \frac{\langle |E_v|^2 \rangle - \langle |E_h|^2 \rangle}{\eta} = S_v - S_h, \quad V = \frac{2 \cdot \mathrm{Im}\langle E_v E_h^* \rangle}{\eta} = S_{lc} - S_{rc},$$

- During the "nadir" look
  - The polarization of the same frequency should be equal
  - This should be true over a land and ocean (assuming low oceans wind speeds)
  - Cross pol should be negligible
  - Hence, if Q!=0, there are calibration issues
  - Insight into the relative calibration of channels at "warmer" TBs compared to cold space



Geolocation of EIA for Mid-scan Position

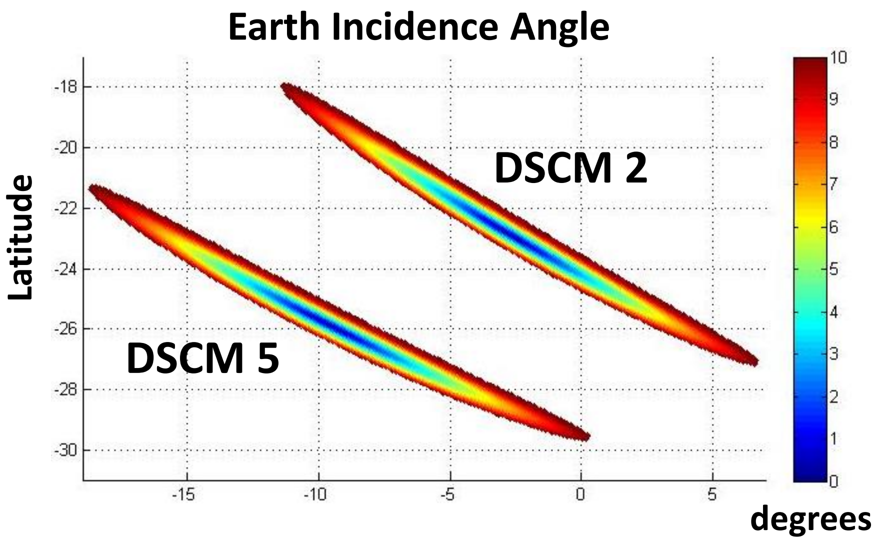


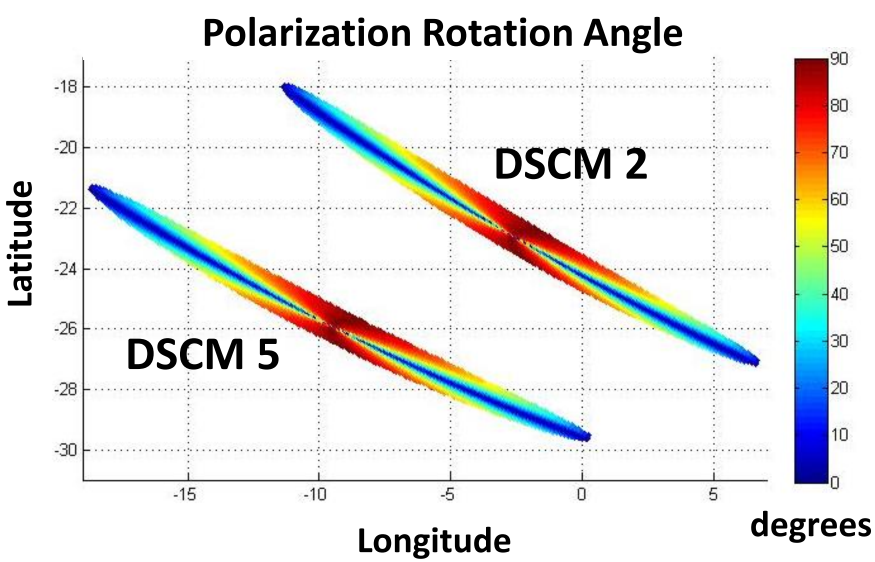
Samples:

EIA<1°mid-scan per orbit: 14-15

EIA<10° in along- & x-track all orbits:~32,000

EIA & Polarization Rotation Effects





- EIA & PR dependence must be removed
  - Using RTM code provided by CSU
- The corrected Q (Q_c) with EIA & PR effects removed is:

$$Q_C = Q_{Obs} - Q_{Sim,PR}$$

- Q_{obs} is the observed Q with EIA & PR effects
- $Q_{sim,PR}$ simulated Q with PR effects

Correcting for PR & EIA Effects: 11 GHz

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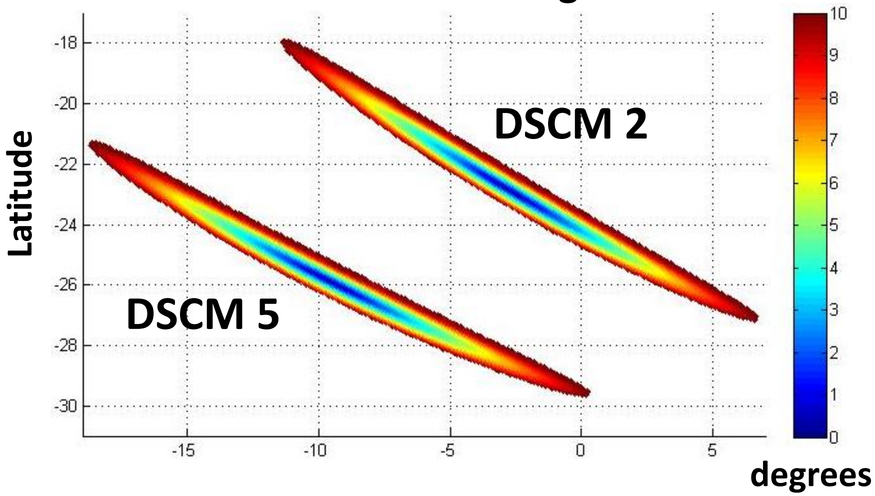
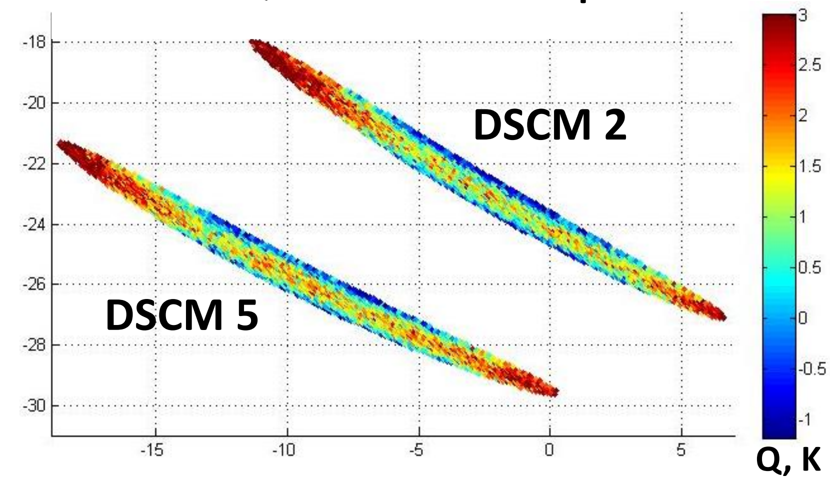
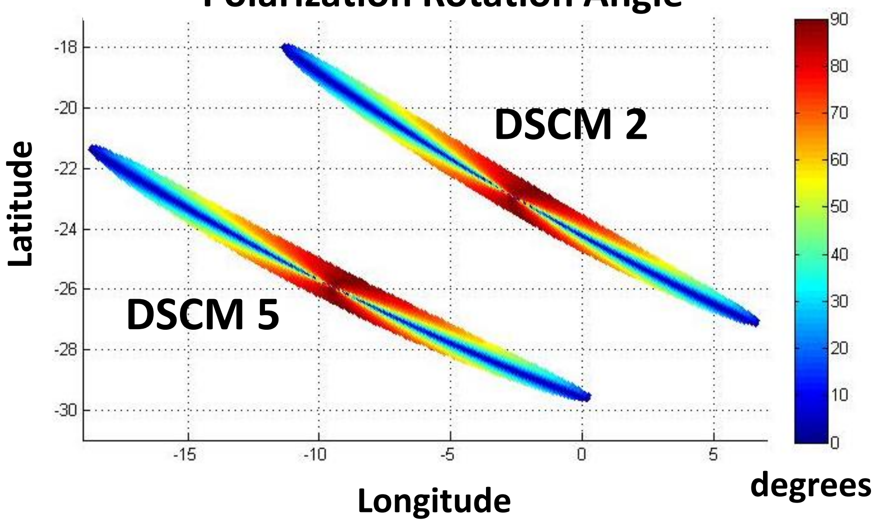
Earth Incidence Angle



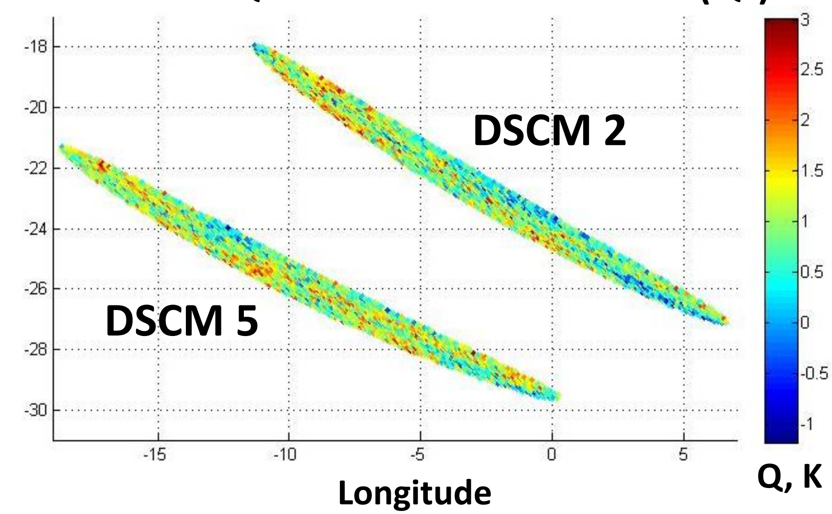
Observed Q with PR & EIA Dependence



Polarization Rotation Angle



Observed Q with PR & EIA Removed (Qc)



Before & After Correction: All Freqs

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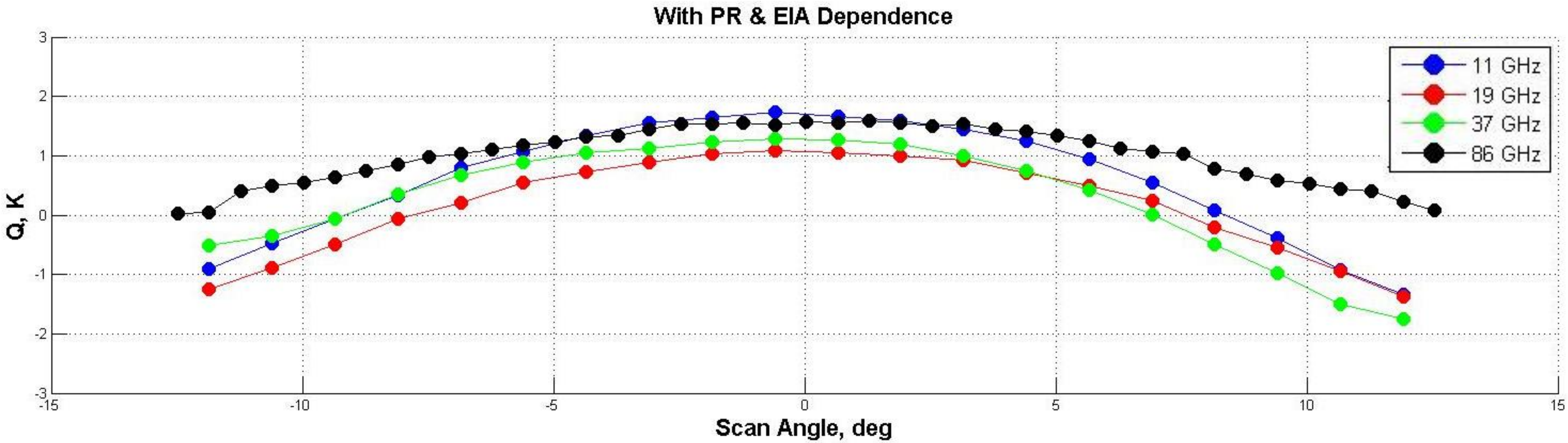
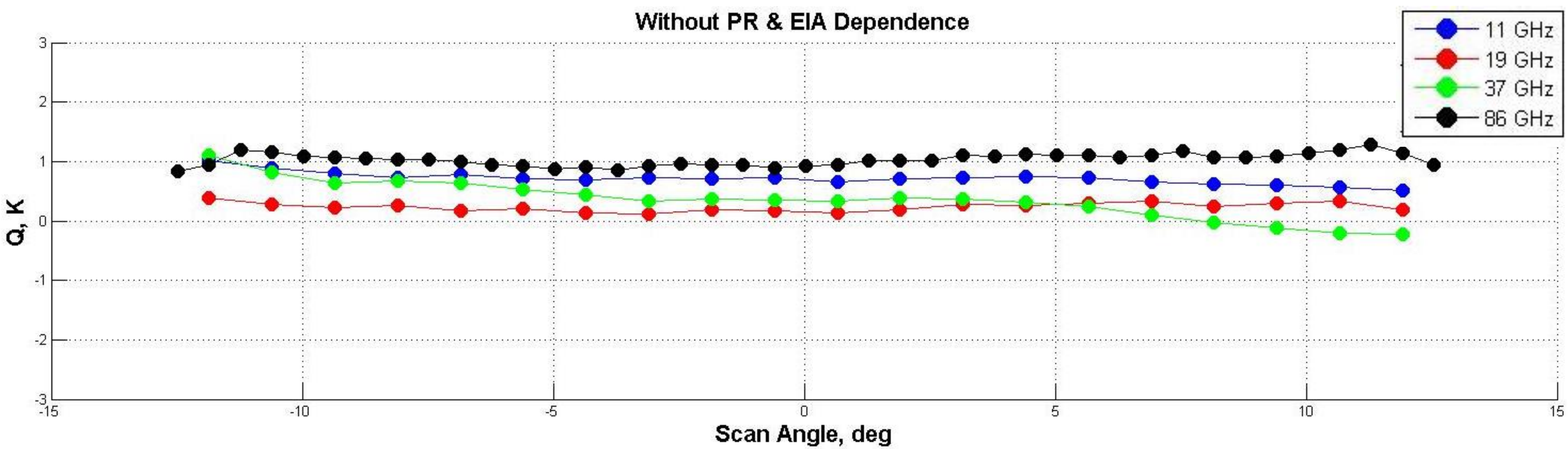
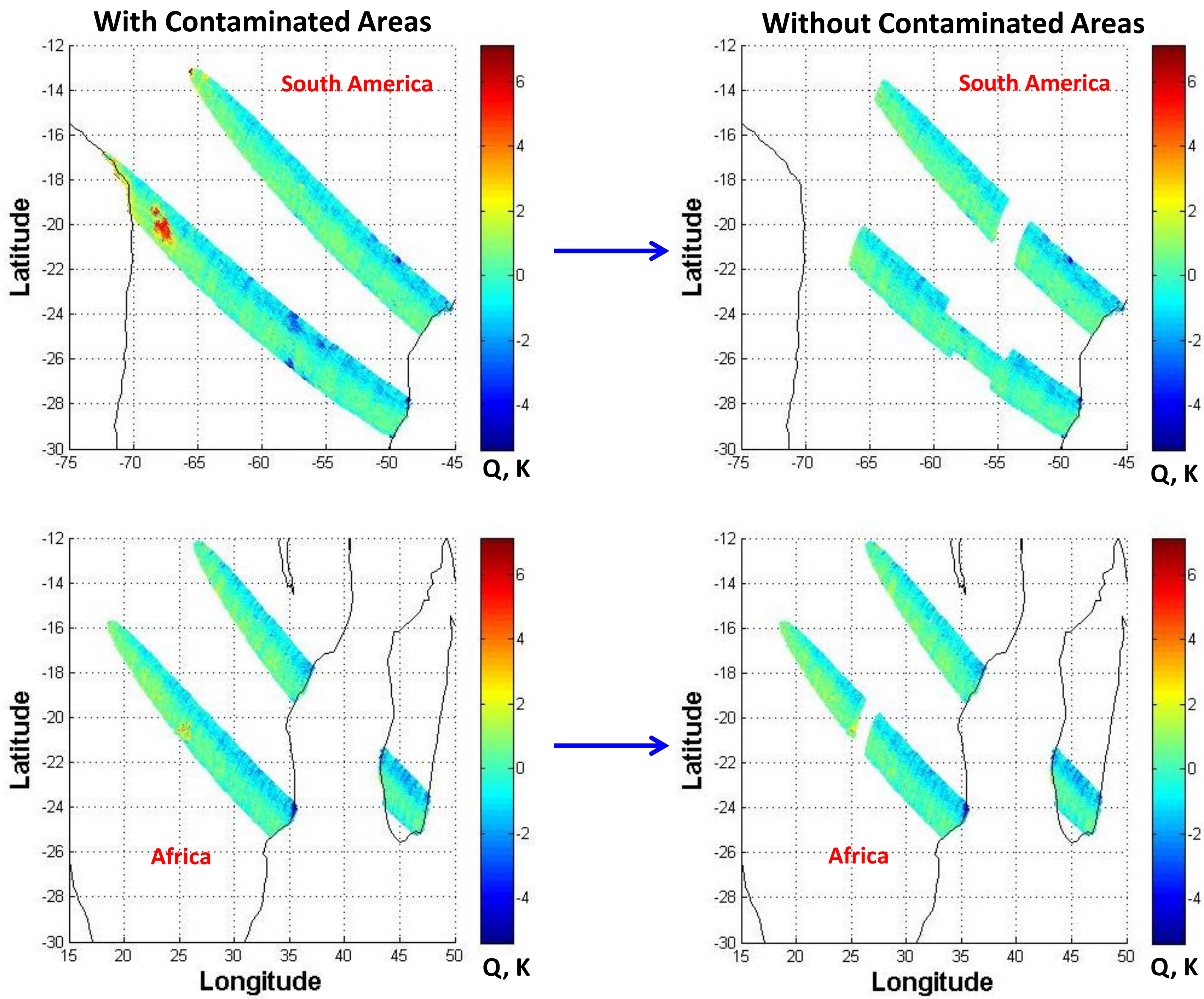
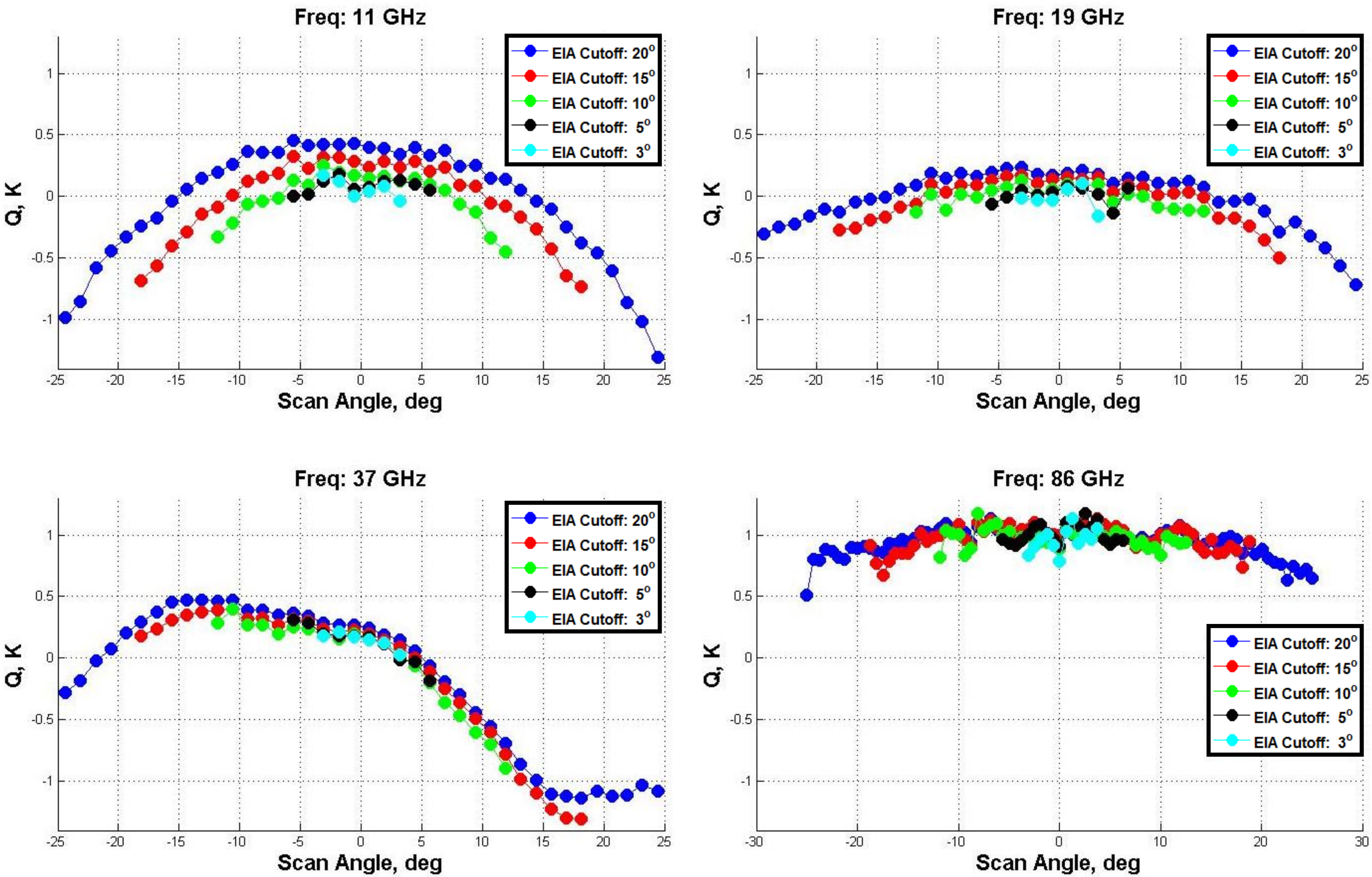




Q Over Land for 37 GHz (EIA Cutoff:20°)



Determining the Proper EIA Cutoff



Comparing Land & Ocean Q Values

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Frequency	$\langle Q \rangle / \sigma$		$\langle Q_{Ocean} \rangle - \langle Q_{Land} \rangle$
	Ocean (EIA cutoff: 10°)	**Land** (EIA cutoff: 3°)	
10.65 GHz	0.78 / 0.67	0.06 / 0.83	0.72
19.35 GHz	0.27 / 0.82	-0.00 / 0.74	0.27
37.00 GHz	0.57 / 0.93	0.15 / 0.52	0.42
85.50 GHz	1.08 / 1.20	0.96 / 1.21	0.12

Speculation if differences are erroneous:

- Correction over ocean needs work
- Correction over land is required
- Non-linearity of TMI Receivers

Speculation if differences are correct:

- 10 GHz: Has Boresight misalignment
- 37 GHz: Along-scan Bias is present

Work & Timeline

Analysis	Performed Before	New	Notes
Beam Width	✓		JAXA used for AMSR-E
Boresight Pointing		✓	Using Earth's Horizon
Along-scan Bias	✓		RSS did not use full DSV
TMI MR Emissivity	✓		RSS did not use full DSV
SS Analysis		✓	

- This timeline dissertation (Based on Weekly Reports):
  - **Part Time:** 03-2010 to 05-27-2011 (just over 1 year)
    - Developing Matlab code to read binary 1A11 & geolocated LOS during inertial hold
    - Import ephemeris & attitude data into STK for visualization & confirmation
    - Started Reconstruction of T_A for 10 V-pol
  - **Other Projects:** June 2011 to March 2013 (1 year 9 months)
  - **Full Time:** 03-29-2013 to Present (~ 2 years)

Conclusion

CFRSL

- Develop & document methods for post-launch calibration of spaceborne microwave radiometers
  - Use pre-existing & new Calibration Attitude Maneuvers
- Used TRMM Deep Space Calibration maneuvers for developing this plan using Jan & Sept 1998 and July 2014
- All objectives for bullets-1 & -2 have been successfully achieved
- Calibrate TRMM Microwave Imager (TMI) for the upcoming Archived T_B data product
  - Has mostly been completed with remaining work to be completed as post-doc research during the summer 2015

Future Work – To Be Included in the Dissertation

CFRSL

- Beam Width Analysis:
  - Use range of scan positions for better determining TMI beam width
    - reduce the variance as well as more sample points for the 10.65 GHz channels to improve the mean (refer to back-up for examples)
- Beam Boresight:
  - Obtain boresight differences between X-band feed to multi-frequency feed channels
  - Use STK or TMI geolocation code to determine match the nadir angles for the convex & concave cases

Future Work – Post Dissertation

CFRSL

- Plans to write two Journal Papers:
  - TMI Calibration:
    Authors: CFRSL, Wyle Systems
  - GMI Calibration:
    Authors: CFRSL, Wyle Systems, Ball Aerospace, & RSS
- Use Feb & Mar 2015 Maneuvers:
  - March 2015 maneuvers, Yaw 90°, to better estimate this angle in the along-scan direction
- For Journal Papers
  - Investigate ERA-I for spillover
- Use multi-freq horn primary pattern from Boeing

What this Research Has Influenced

- GPM Has Used This Nadir-Look Maneuver
  - 2 Orbits in December 2014
  - Locked-pitch (LOS stays aligned with Nadir) over ocean & land (Amazon)
- Detection of RFI in TMI's Cold Sky View
  - Analysis (week of DSCM Set 3) on T_A reconstruction revealed that there is RFI from geostationary satellites in the CSR view
- TRMM 90° Yaw Inertial-Hold - To:
  - provide a different DSV compared to Yaw 0° /180° maneuvers
    - Along Scan bias & back lobe location
  - determine azimuthal Cold Sky Mirror boresight

Recommendations

- Soil Moisture Active Passive (SMAP)
  - L-Band Radar/Radiometer
  - Internally calibrated
  - Feed horn illuminates a 6 m parabolic mesh reflector
  - Reflector supported by a single boom
  - Not a hard surface reflector so compared to simulation or on ground testing the
    - beam boresight & beam width can change
    - Back lobes can change which is of importance because galactic background at L-Band is not homogenous

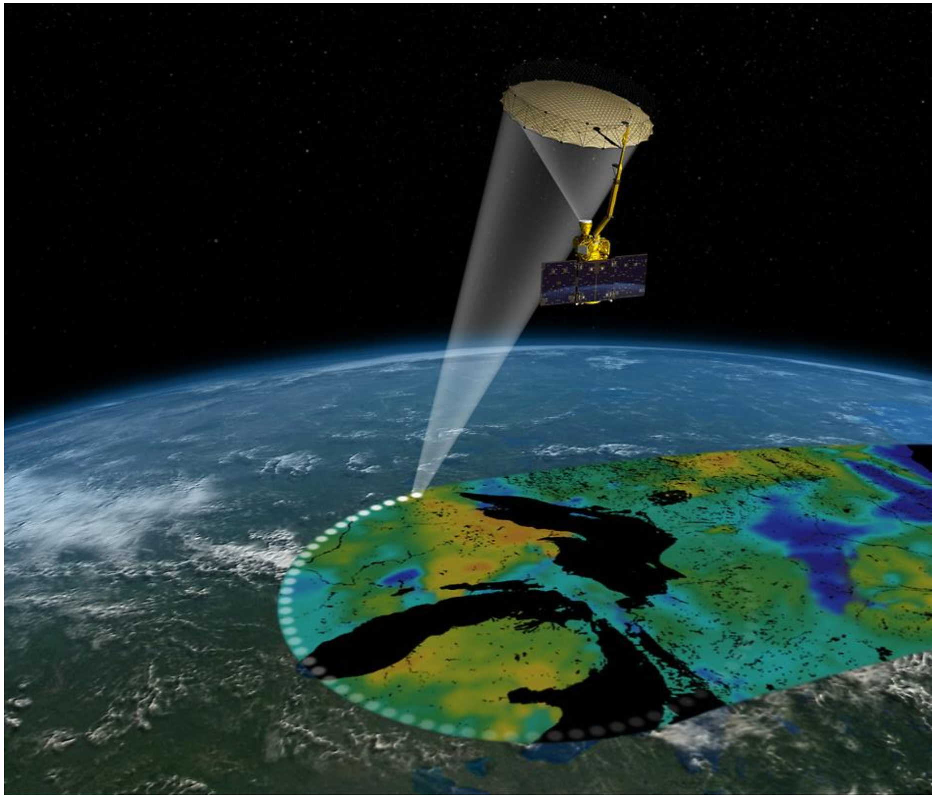

Image Credit: NASA/JPL-Caltech
http://www.nasa.gov/jpl/smap/pia19133/

Recommendations Cont'd

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- Synthetic Aperture Radiometers:
  - Soil Moisture Ocean Salinity (SMOS) or Hurricane Imaging Radiometer (HIRAD)
  - Uses an arrangement of feeds or stick/patch antennas to increase beam resolution
  - IFOVs are obtained by using aperture synthesis
  - Benefit from all analysis mentioned within this dissertation
- Compact Ocean Vector Wind Radiometer (COVWR)
  - Low cost, low mass, low-power internally calibrated radiometer
  - Conical scanner but feed does not rotate with reflector
  - Fully-polarimetric as scan position changes
  - Big advantage would be SS & DSV with spillover & Back lobe illuminating the Earth

Conference Publications

CFRSL

[1] ***S. Farrar***, *L. Jones, T. Kasparis*, “Comparisons of Ocean Precipitation Measurements between SeaWinds and TRMM 3B42 Data Product”, paper presented at IEEE International Symposium on Antennas & Propagation and USNC/URSI National Radio Science Meeting, June 1-5, 2009, Charleston, S.C.

[2] ***S. Farrar***, *L. Jones, S. Masuelli, J. Gallo,* “Microwave Radiometer (MWR) Oceanic Integrated Rain Rate Algorithm for Aquarius/SAC-D” , poster presented at the 11th Specialist Meeting on Microwave Radiometery and Remote Sensing of the Environment, March 1-4, 2010, Washington, D.C.

[3] *R. Amarin, S.El-Nimri, S.Biswas,* ***S. Farrar***, *J. Johnson, L. Jones*, “Enhancing Oceanic Retrievals using Microwave Radiometery” , presented at the 2010 IGARSS, July 25-30, 2010, Honolulu, HI

[4] ***S. Farrar***, *L. Jones, “*Preliminary Analysis of the Aquarius/SAC-D Microwave Radiometer (MWR) Antenna Temperature: Possible Antenna Pattern Issue” , presented at the 2012 IEEE SoutheastCon, Mar 15-18, 2012, Orlando, FL

[5] ***S. Farrar***, *M. Labanda, M. Jacob, S. Masuelli, S. Biswas, H. Raimondo, L. Jones,* “An Empirical Correction for the MWR Brightness Temperature” , IGARSS 2012, July 22-27, 2012, Munich, Germany

[6] *T. Miller, M. James, J. Roberts, S. Biswas, E. Uhlhorn, R. Atlas, P. Black, L. Jones, J. Johnson,* ***S. Farrar***, *S. Sahawneh, C.S. Ruf, M. Morris*, “Observations of C-Band Brightness Temperature from the Hurricane Imaging Radiometer (HIRAD) on-board the NASA WB-57 during GRIP in Hurricanes Earl And Karl (2010),” *Fall Meeting, American Geophysical Union*, San Francisco, CA, 3-7 Dec., 2012

[7] *Timothy L. Miller, M. W. James, J. B. Roberts, S. Biswas, D. Cecil, W. L. Jones, J. Johnson,* ***S. Farrar***, *C. S. Ruf, E. W. Uhlhorn, R. Atlas, and Peter G. Black*, “Observations of C-band Brightness Temperatures and Ocean Surface Wind Speed and rain Rate from the Hurricane Imaging Radiometer (HIRAD) during GRIP and HS3,” AMS 17th Conf on Integ. Observing and Assimilation Sys, Austin, TX, 6-10 Jan, 2013.

Conference Publications

CFRSL

[8] *S. Sahawneh, **S. Farrar**, J. Johnson, L. Jones*, "Hurricane Wind Speed and Rain Rate Measurements using the Airborne Hurricane Imaging Radiometer (HIRAD)" , presented at the 2013 IEEE SoutheastCon, Apr 4-7, 2013

[9] *T. Miller, M. James, J. Roberts, S. Biswas, D. Cecil, W. Jones, J. Johnson, **S. Farrar**, et al,* "The Hurricane Imaging Radiometer: Present and Future," , IGARSS 2013, July 21-26, 2013, Melbourne, Australia

[10] ***S. Farrar**, L. Jones,* "Estimation of TRMM Microwave Imager Antenna Temperature During Deep Space Calibration Maneuvers", 13th Specialist Meeting on Microwave Radiometery and Remote Sensing of the Environment, March 24-27, 2014, Pasadena, CA.

[11] ***S. Farrar**, L. Jones,* "GPM Microwave Imager On-Orbit Radiometric Calibration Using a Satellite Deep Space Calibration Maneuver" , IGARSS 2014, July 13-18, 2014, Quebec, Canada

[12] *M. Morris, C. Ruf, S. Biswas, **S. Farrar***, "A Coupled-Pixel Retrieval Algorithm for High Resolution Imagers" , 95th AMS Annual Meeting, Phoenix, AZ, Jan 4-8, 2015

Journal Publications

CFRSL

[1] *S. Biswas,* ***S. Farrar****, K. Gopalan, A. Santos-Garcia, L. Jones, S. Bilanow,* "Inter-Calibration of Microwave Radiometer Brightness Temperatures for the Global Precipitation Measurement Mission", IEEE Trans. GeoSci. & Rem Sens, Vol. 51, No. 3, March 2013

[2] *M. Labanda, M. Jacobs,* ***S. Farrar****, L. Jones,* "MWR Smear Effect: A Counts-level Empirical Correction and Possible Causes", JSTARS - Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 8. **Under Review**

NASA Project Presentation - XCAL

Orlando, FL – June 2010

- [1] ***S. Farrar***, *S. Biswas, W.L. Jones*, "TMI With Respect to WindSat Over the Amazon" , XCAL Science Team Meeting, June 29-30, 2010 Orlando, FL

Ashville, NC – October 2010

- [2] ***S. Farrar****, W.L. Jones, S. Bilanow, K. Gopalan, C. Lyu, J. Shiue,* "TMI Deep Space Calibration (DSC) Re-Analysis" , XCAL Science Team Meeting 21-22 October 2010 Ashville, NC
- [3] ***S. Farrar****, S. Biswas, L. Jones, K. Gopalan,* "WindSat / AMSR-E Biases" , XCAL Science Team Meeting October 21-22, 2010, Ashville, NC

College Park, MD – March 2010

- [4] ***S. Farrar****, L. Jones, S. Bilanow, K. Gopalan,* "AMSR-E Revisited" , XCAL Science Team Meeting March 1-2, 2011 College Park , MD
- [5] *S. Bilanow, K. Gopalan,* ***S. Farrar****, W.L. Jones,* "Notes on Earth incidence Angle (EIA) Uncertainty Contribution to Tb Uncertainty" , XCAL Science Team Meeting March 1-2, 2011 College Park, MD
- [6] ***S. Farrar****, L. Jones, S. Bilanow, K. Gopalan,* "TMI Deep Space Calibration (DSC) Gain and Offset Relationship Update Status" , XCAL Science Team Meeting March 1-2, 2011 College Park , MD
- [7] ***S. Farrar****, L. Jones, S. Bilanow, K. Gopalan,* "Uncertainty Estimate for UCF XCAL Biases" , XCAL Science Team Meeting March 1-2, 2011 College Park , MD

Fort Collins, CO – July 2011

- [8] *S. Bilanow, K. Gopalan,* ***S. Farrar****, W.L. Jones,* "Notes on GMI Alignment" , XCAL Science Team Meeting July 13-14, 2011 Fort Collins, CO
- [9] ***Spencer Farrar****,* "TMI TB Striping Analysis" , XCAL Science Team Meeting July 13-14, 2011 Fort Collins, CO
- [10] ***S. Farrar****,* "TMI Gyro-Hold Status Update Using STK", XCAL Science Team Meeting July 13-14, 2011 Fort Collins, CO

Denver, CO – November 2011

- [11] ***S. Farrar****, S. Aslebagh, W.L. Jones, S. Bilanow,* "The Effects of TMI 1B11 V7 Solar Beta/Time Varying Bias Correction on 2A12 Rain Rates" , XCAL Science Team Meeting November 5-6, 2011 Denver, CO
- [12] ***S. Farrar****, A. Santos-Garcia, W.L. Jones, S. Bilanow,* "TMI/SSMI Biases (F13, F14, & F15)" , XCAL Science Team Meeting November 5-6, 2011 Denver, CO

Ann Arbor, MI – July 2012

- [13] *W.L. Jones, A. Santos-Garcia, S. Aslebagh,* ***S. Farrar****, Y. Hejazin*, "Microwave Radiometer (MWR) on Aquarius X-Cal Update" , XCAL Science Team Meeting July 11-12, 2012 Ann Arbor MI
- [14] ***S. Farrar****, A. Santos-Garcia, W.L. Jones*, "Further Analysis on TMI/SSMI Biases (F13 through F15)" , XCAL Science Team Meeting July 11-12, 2012 Ann Arbor MI
- [15] ***S. Farrar****, W.L. Jones*, "SSMIS-TMI XCAL Cold End Analysis (F16 through F18)", XCAL Science Team Meeting July 11-12, 2012 Ann Arbor MI

NASA Project Presentation - XCAL Cont'd

Orlando, FL – February 2013

- [16] ***S. Farrar**, W.L. Jones*, "AMSR2-TMI XCAL Cold End Analysis", XCAL Science Team Meeting, February 21-22, 2013 Orlando, FL
- [17] ***S. Farrar**, W.L. Jones*, "Steps Towards Conventions Within XCAL", XCAL Science Team Meeting, February 21-22, 2013 Orlando, FL

Toulouse, France – May 2013

- [18] *W.L. Jones, H. Ebrahimi, **S. Farrar***, "TMI to MADRAS X-CAL Colde End Analysis", XCAL Science Team Meeting, May 23-24, 2013 Toulouse, France
- [19] ***S. Farrar**, A. Santos-Garcia, W.L. Jones*, "Further Analysis on TMI/SSMI Biases (F13 through F15)", XCAL Science Team Meeting, May 23-24, 2013 February 2013 Toulouse, France

Fort Collins, CO – August 2014

- [20] ***S. Farrar**, W.L. Jones*, "TMI-AMSR2 XCAL Cold & Warm End Analysis", XCAL Science Team Meeting, August 22-23, 2014 Fort Collins, CO
- [21] ***S. Farrar**, M. Salemin, W.L. Jones*, "SSMI-TMI Cold & Warm End Analysis (F13 through F15)", XCAL Science Team Meeting, August 22-23, 2014 Fort Collins, CO
- [22] ***S. Farrar**, R. Chen, W.L. Jones*, "SSMIS-TMI Cold & Warm End Analysis (F16 through F18)", XCAL Science Team Meeting, August 22-23, 2014 Fort Collins, CO

College Park, MD – July 2014

- [23] ***S. Farrar**, H. Ebrahimi, W.L. Jones*, "GMI Anomalies", XCAL Science Team Meeting, July 10-11, 2014 College Park, MD

Orlando, FL – February 2015

- [24] ***S. Farrar**, W.L. Jones*, "TMI Cold Sky Anomaly", XCAL Science Team Meeting, February 28-29, 2015 Orlando, FL
- [25] ***S. Farrar**, W.L. Jones*, "GMI Second Stokes Analysis Using a Nadir-Look Maneuver", XCAL Science Team Meeting, February 28-29, 2015 Orlando, FL

Other NASA Project Presentations

CFRSL

[1] *L. Jones, K. Ahmad ,* ***S. Farrar****, T. Kasparis*, "Ocean Precipitation Measurements using SeaWinds" , poster presented at the NASA Ocean Vector Winds Science Team Meeting, Nov 19-21, 2008, Seattle, WA

[2] *L. Jones, S. AlSweiss,* ***S. Farrar****, S. Masuelli, and H. Raimondo*, "Microwave Radiometer (MWR) Contributions to Aquarius Science: Ocean Vector Winds & Ocean Precipitation Retrievals", poster presented at the 4th AQUARIUS/SAC-D Int. Science Workshop, Dec 3-6, 2008, Argentina

[3] ***S. Farrar****, L. Jones, R. Menzerotolo, S. Masuelli, M.M. Jacob, C. Tauror, H. Raimando,* "Microwave Radiometer (MWR) Oceanic Integrated Rain Rate Algorithm for Aquarius/SAC-D" , poster presented at the 2010 Aquarius/SAC-D Science Team Meeting, July 19-21, 2010, Seattle, WA

[4] *L. Jones, S. Bilanow,* ***S. Farrar****, S. Aslebagh,* "The Effects of TMI 1B11 V7 Solar Beta/Time Varying Bias Correction on 2A12 Rain Rates", poster presented at the 2011 PMM Science Team Meeting, Nov 7-11, 2011, Denver, CO

[5] *L. Jones and* ***S. Farrar***, "MWR Tb Anomaly: Antenna Pattern Effects", AQ Cal/Val meeting, Nov. 15-17, 2011, Pasadena, CA

[6] ***S. Farrar*** *and L. Jones, M. Labanda, March Jacobs and Sergio Masuelli*, "MWR Tb Anomaly: Smear Effect", Aquarius Cal/Val meeting, March 27-28, 2012, Santa Rosa, CA.

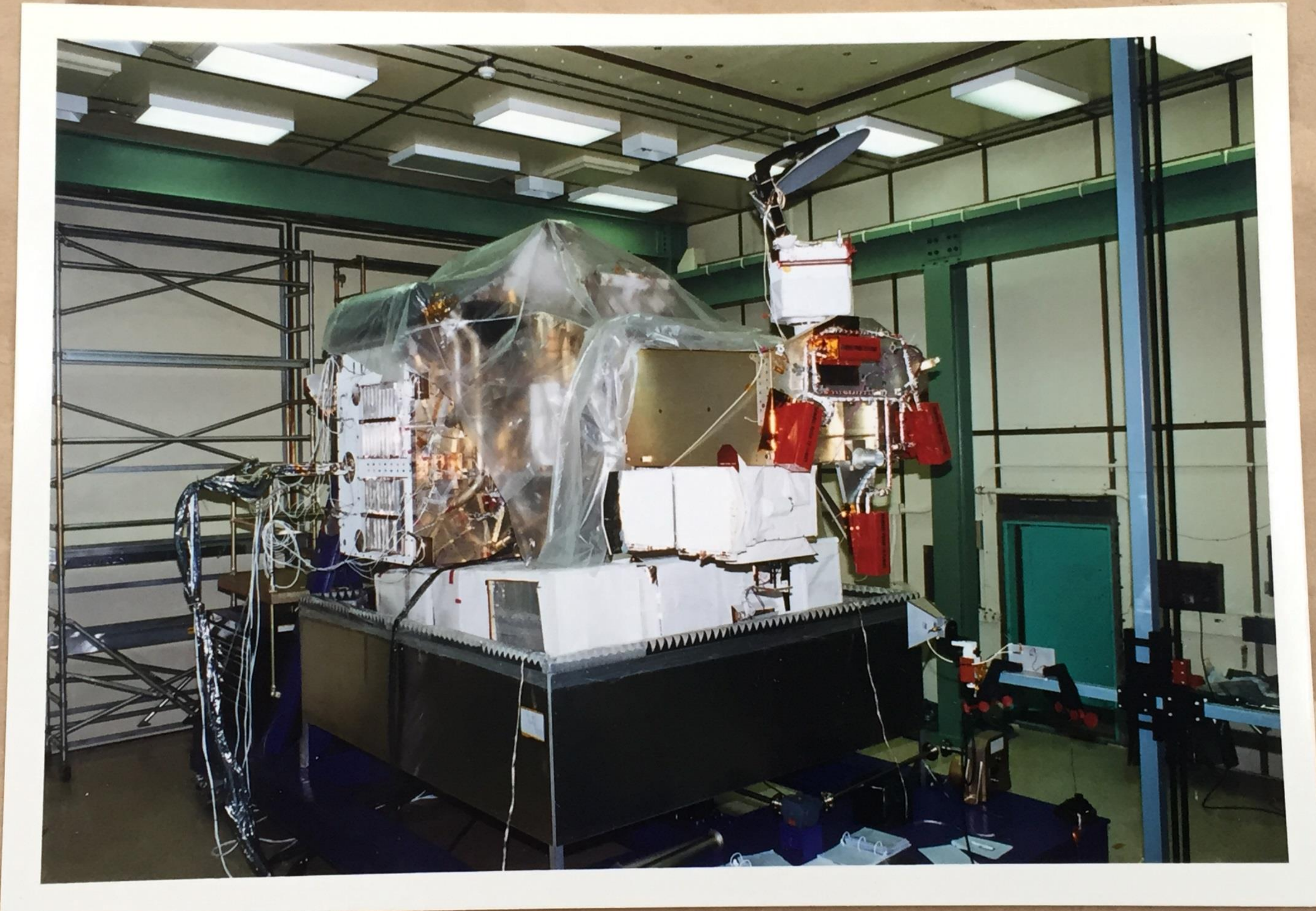
[7] *M. Labanda, M. Jacob, S. Masuelli,* ***S. Farrar****, H. Raimondo, W.L. Jones*, "MWR Smear Effect: Analysis and Its Possible Correction" , 7th Aquarius/SAC-D Science Meeting Preliminary Agenda 11-13 April 2012 Buenos Aires, Argentina

[8] *L. Jones, S. Datta,* ***S. Farrar****, A. Santos-Garcia, and H. Ebahimi*, "Inter-Satellite Microwave Radiometric Calibration for the GPM Constellation," NASA PMM Internat. Science Team meeting, Annapolis, MD, March 20, 2013

Acknowledgements

CFRSL

- Yimin Ji (PPS)
  - Providing 1A11 & Base files and related material
- James Shiue (SGT Inc)
  - Providing insight of the instrument from our discussions & obtaining documents & data of TMI
- Steve Bilanow (PPS)
  - Helping resolve geolocation errors, questions, understanding of the inertial-hold, and help with reading the 1A11 data product
- Second Stokes Analysis
  - Rachael Kroodsma (PPS) for providing converted RSS Surface Emissivity Matlab Code
  - Wes Berg (CSU) for providing Fortran Code that contains XCAL atmospheric & RSS' new surface emissivity model to account for wind direction
- Shannon Brown (JPL)
  - Providing insight on his effective conductivity work with reflectors
- RSS for providing their Surface Emissivity Model (Fortran) to the XCAL group
- Tom Wilheit
  - For being an influential proponent for CAMS for the TMI & GMI instruments



Courtesy of Steve Bilanow (PPS)

Thank You!

Back Up Slides

Backup Slides Setup

CFRSL

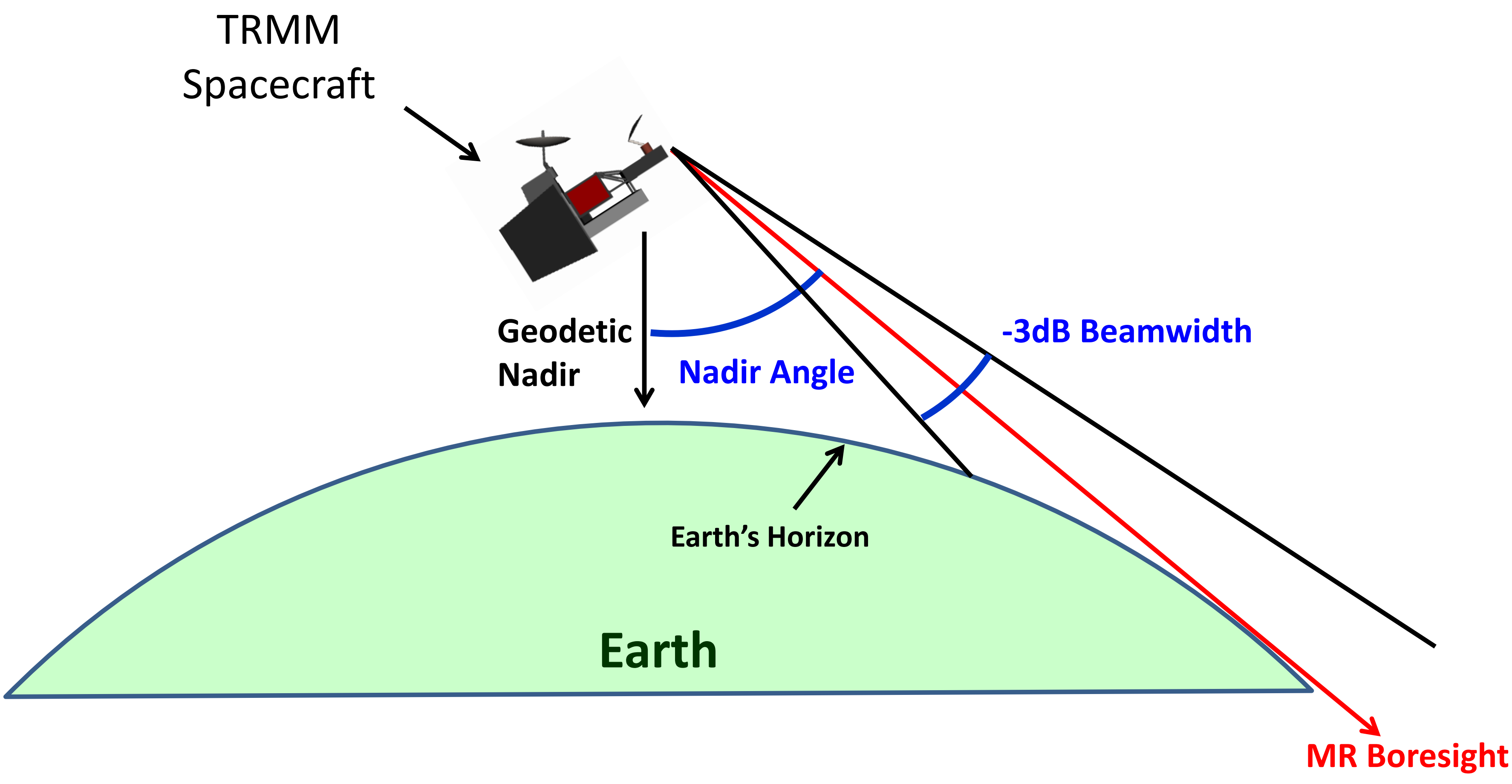
- Analyzes that Were Removed Due to Time Constraints
  - TMI Main Beam Width (Link)
  - TMI Main Beam Boresight (Link)
  - Along-scan Bias (Link)
- Actual Backups
  - Intro (Link)
  - Beam Width (Link)
  - Beam Pointing (Link)
  - Along-scan Bias (Link)
  - Second Stokes (Link)
  - Emissivity (Link)
  - Backups From Proposal (Link)

Analyses that Were Removed Due to Time Constraints

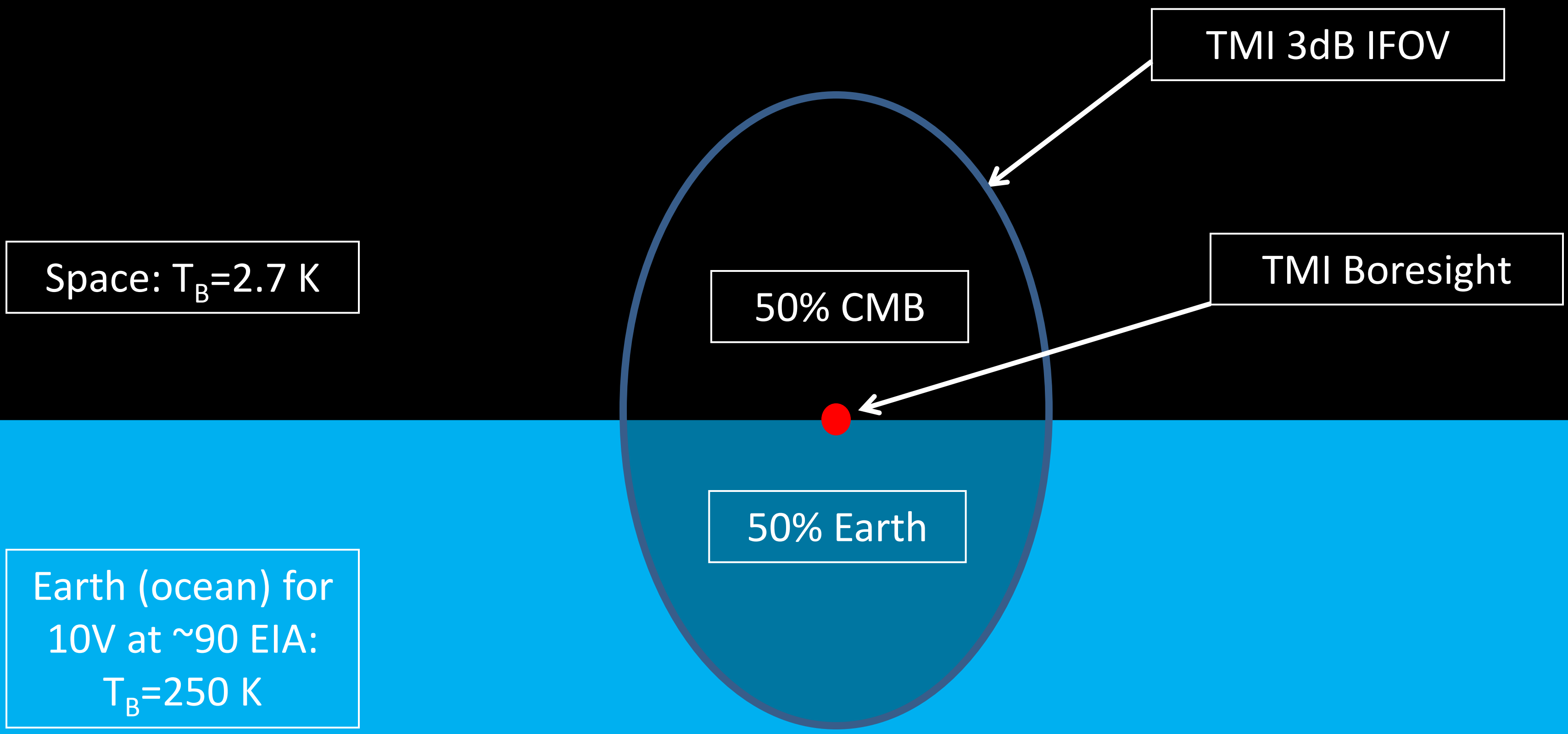
Analysis

TMI Main Reflector Beamwidth

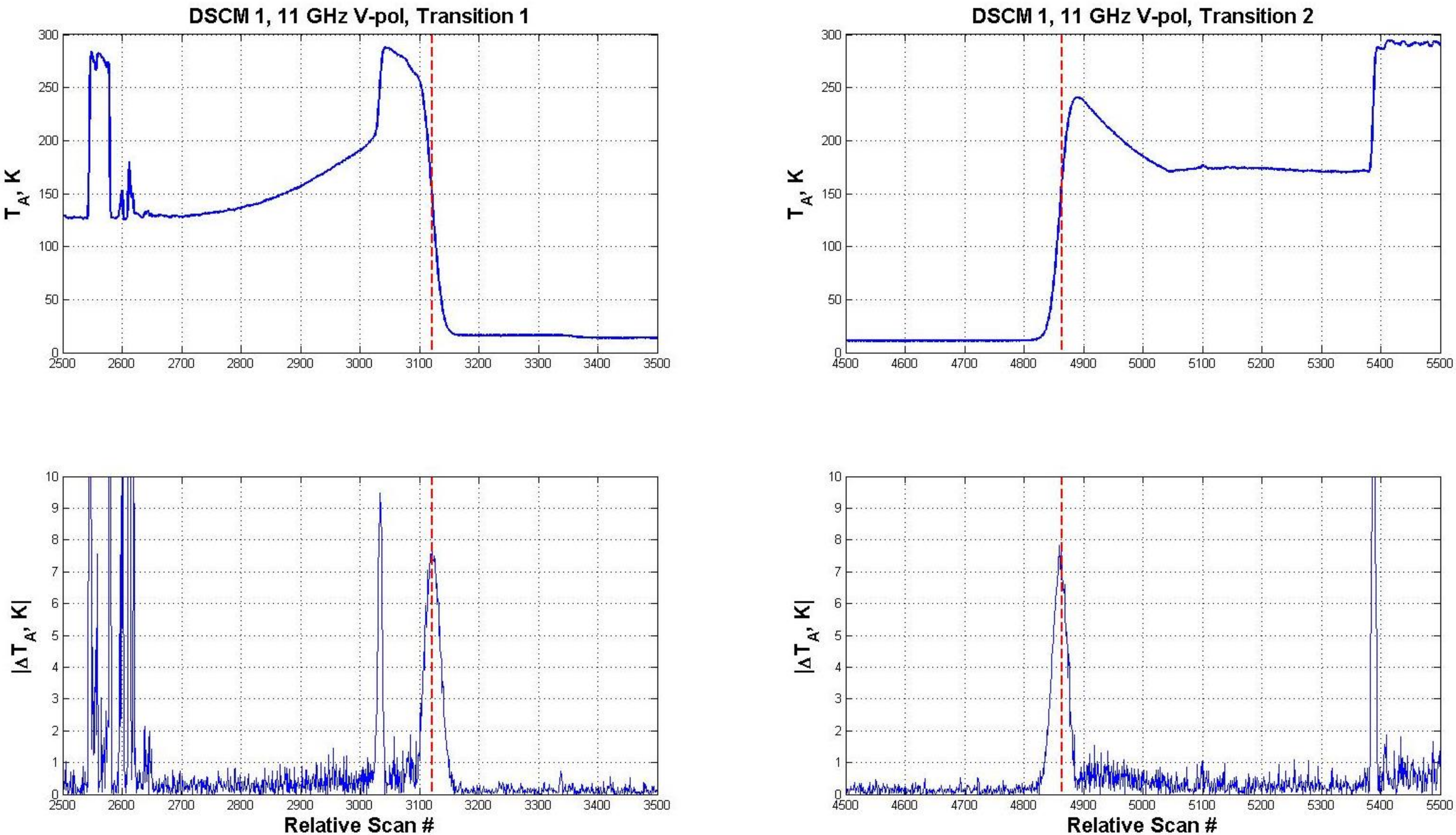
Illustration of Nadir Angle



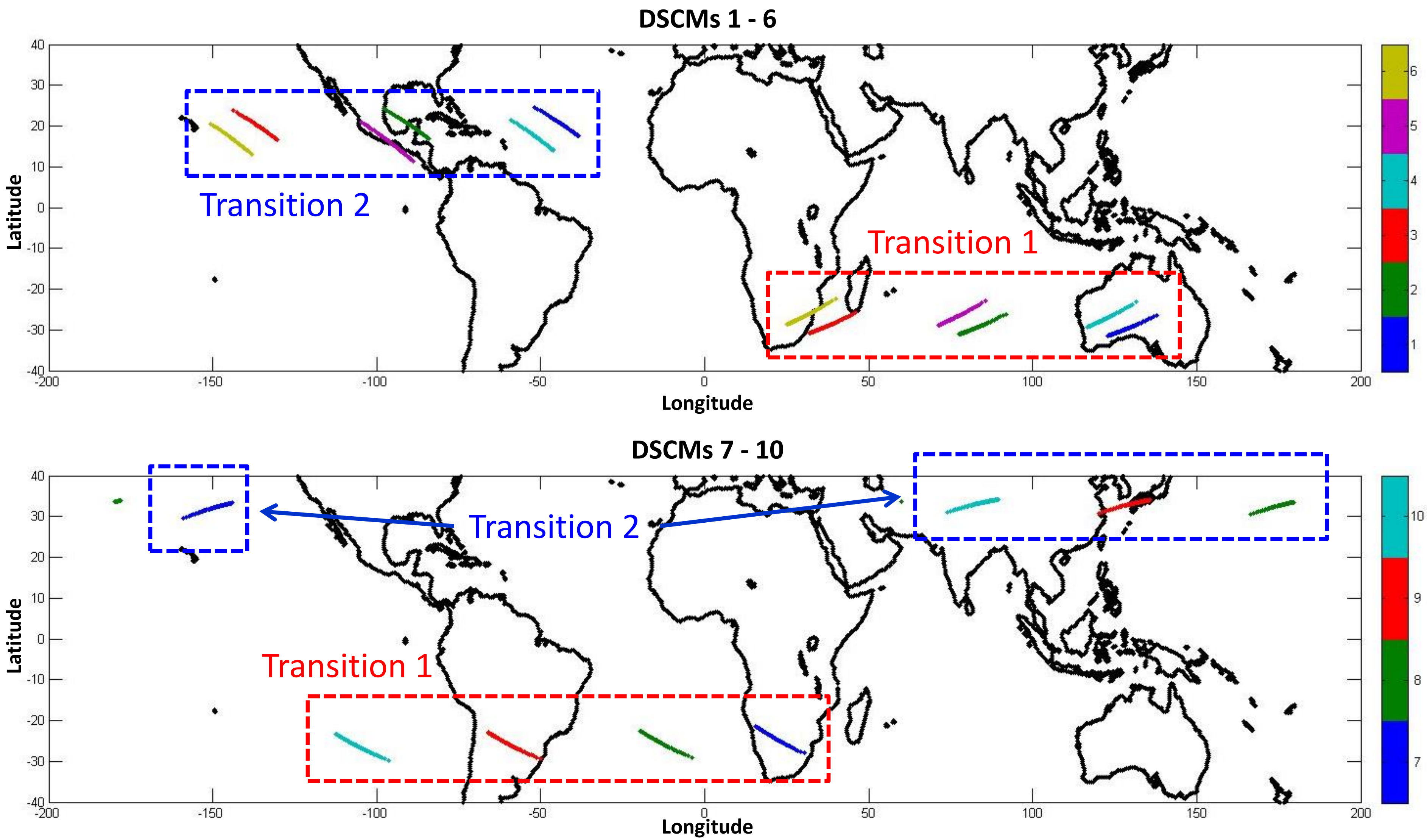
TMI's IFOV While Leaving Earth



Example of $|\Delta T_A|$

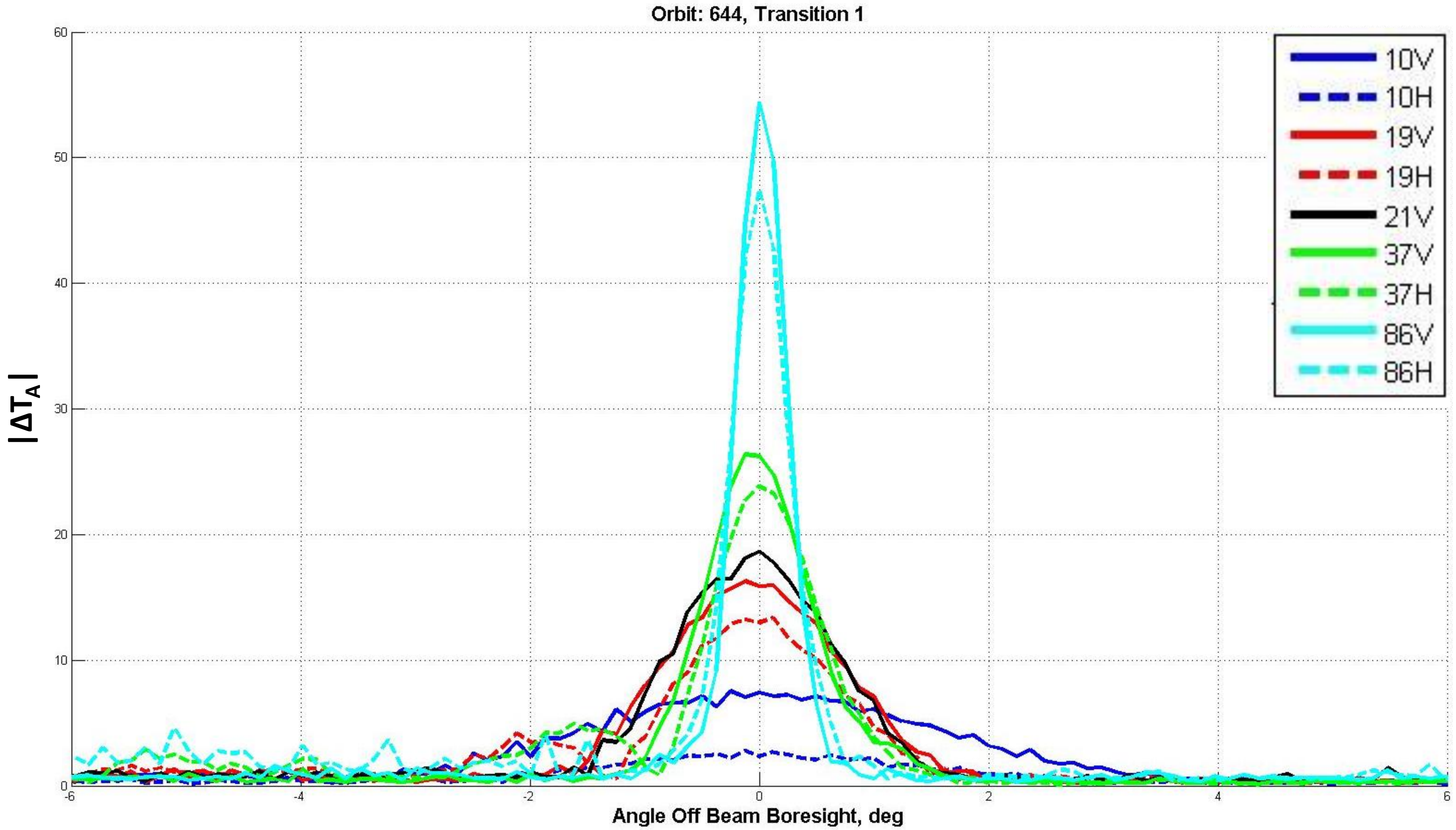


DSV Transitions Geolocated



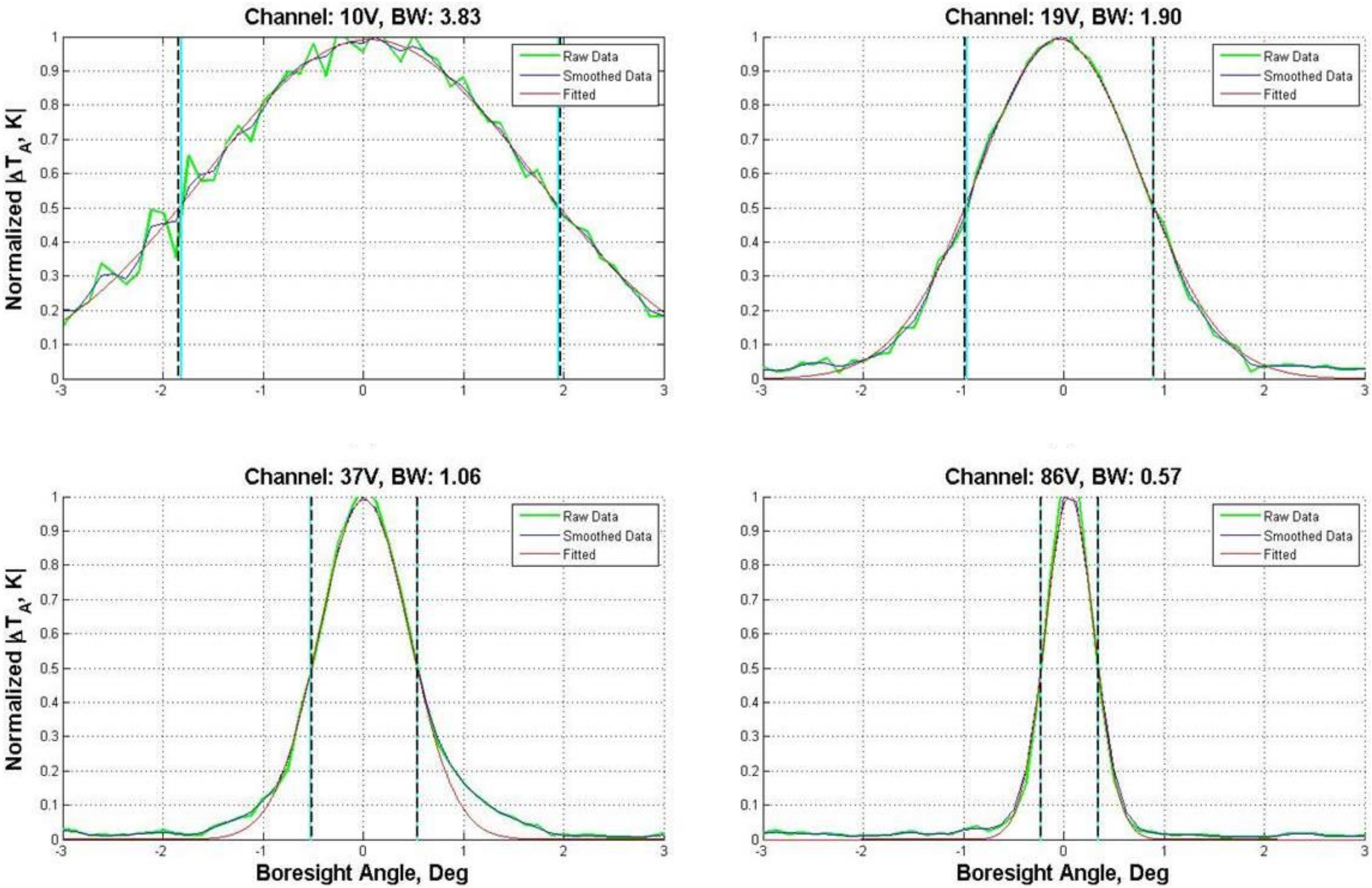
Note: Only half of transition is shown since other have views space

Amplitude of ΔT_A



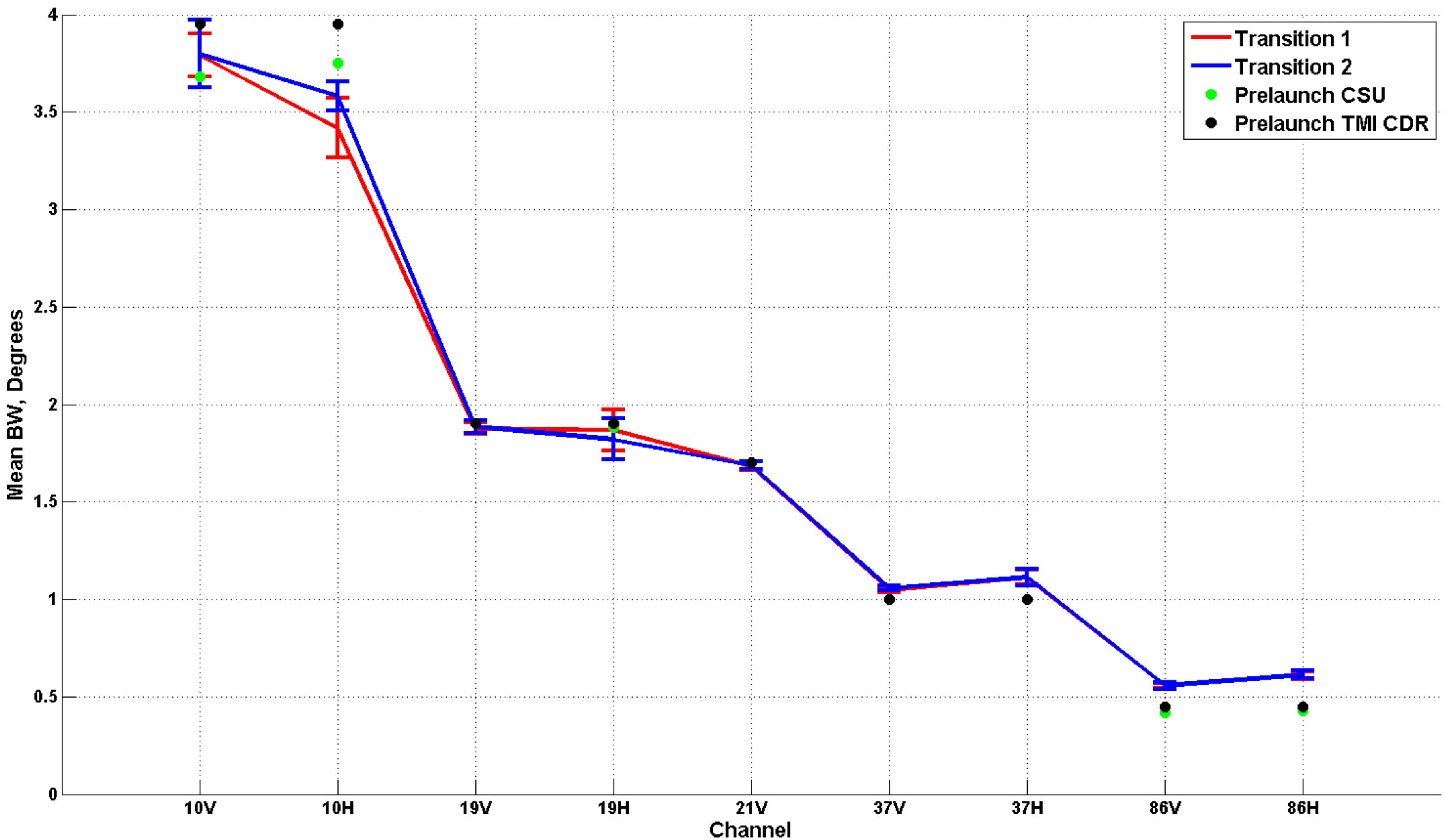
Beamwidths

DSCM-4, Transition 1



(c) (d)

Beamwidth For All Channels



CSU values are from “The Tropical Rainfall Measuring Mission (TRMM) Sensor Package” (1998)

Conclusion & Future Work

CFRSL

- This analysis uses the edge of the earth, a sharp transition in TB (Ex: ~Δ240 K @ 10V-pol) for calculating TMI BW in the elevation plane
- H-Pol channels have the largest variation
- Disagreement between mean BW are largest for 10.65 GHz channels for Transition 1 to CSU & CDR beam widths
  - 10V: CSU (Δ=0.12°), CDR (Δ=0.15°)
  - 10H: CSU (Δ=0.35°), CDR (Δ=0.60°)
- Future Work To Be included in the Dissertation
  - Include multiple scan positions so to reduce the variance as well as more sample points for the 10.65 GHz channels to improve the mean (refer to back-up for examples)

Analysis

TMI Main Beam Boresight

Main Reflector Boresight

CFRSL

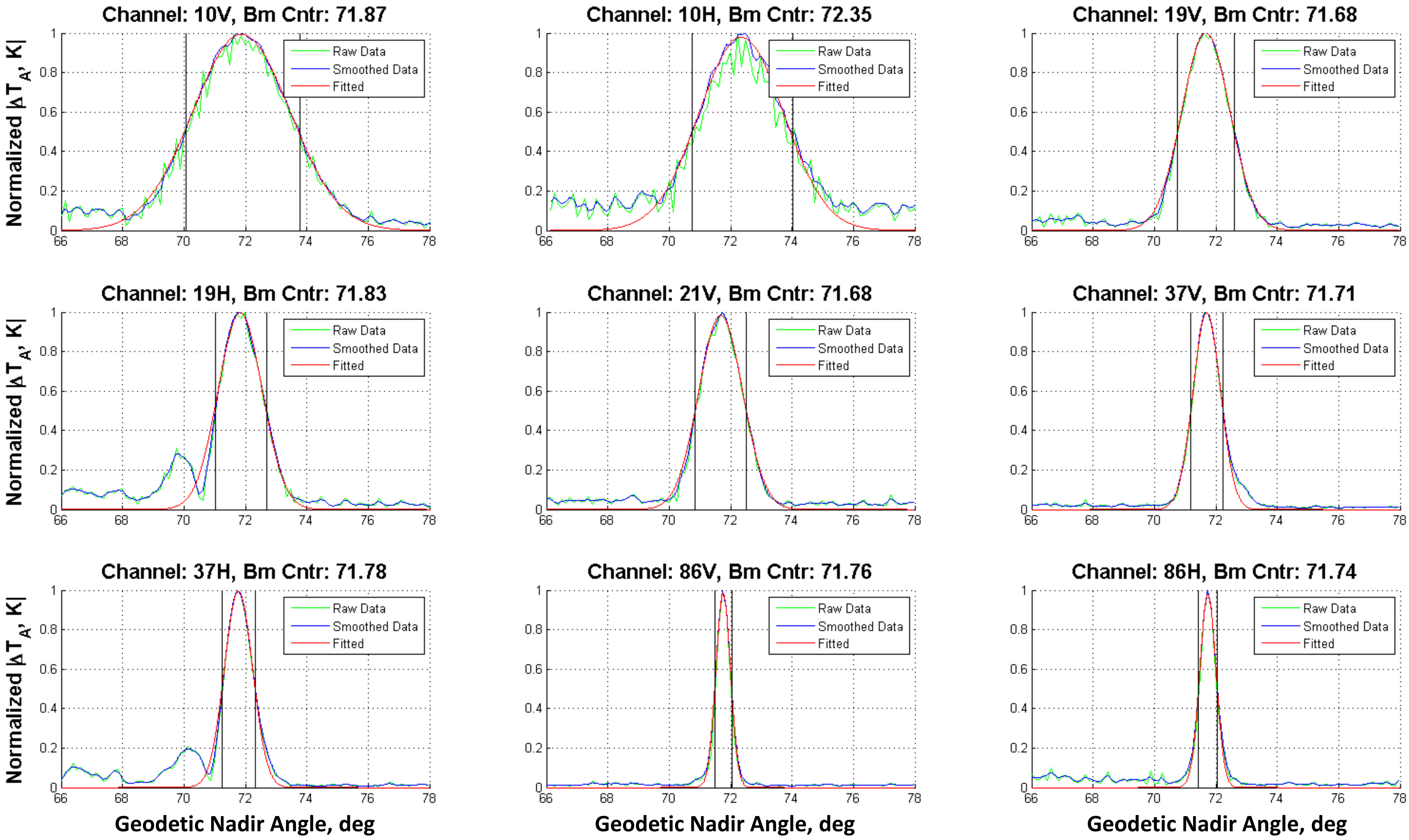
- Method:
  - Follows similar method as Beamwidth analysis except:
    - interested in when the boresight (peak of the secondary radiation pattern) passes the Earth's horizon
    - angle between boresight & geodetic nadir (nadir angle) is used for comparisons
- It is understood that TMI's MR boresight for 11 GHz channels are misaligned compared to the multi-frequency feed
  - But by how much is in question?

Channels	Offsets from Shiue Memo (deg)		Offsets from TMI Subsystem Test Doc (deg)	
	Along-Track	X-Track	Along-Track	X-Track
10.65 V	0.555	-0.185	0.487	0.09
10.65 H	0.185	0.555	0.568	0.134

TMI Subsystem Test Doc: Nov 07, 1994
Shiue Memo: 12-11-1997

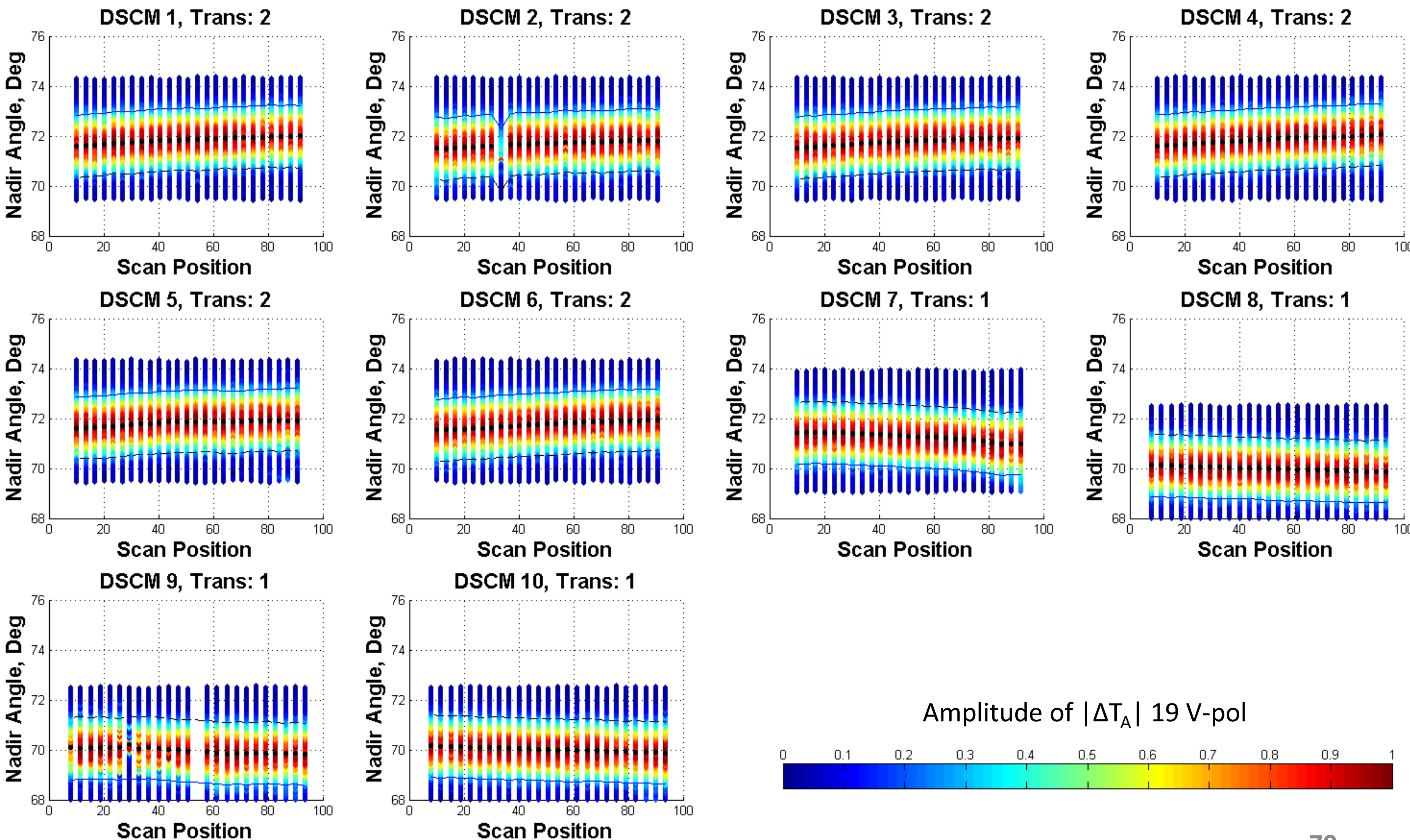
Table for all Channels: Link

Boresights w.r.t. Nadir Angle

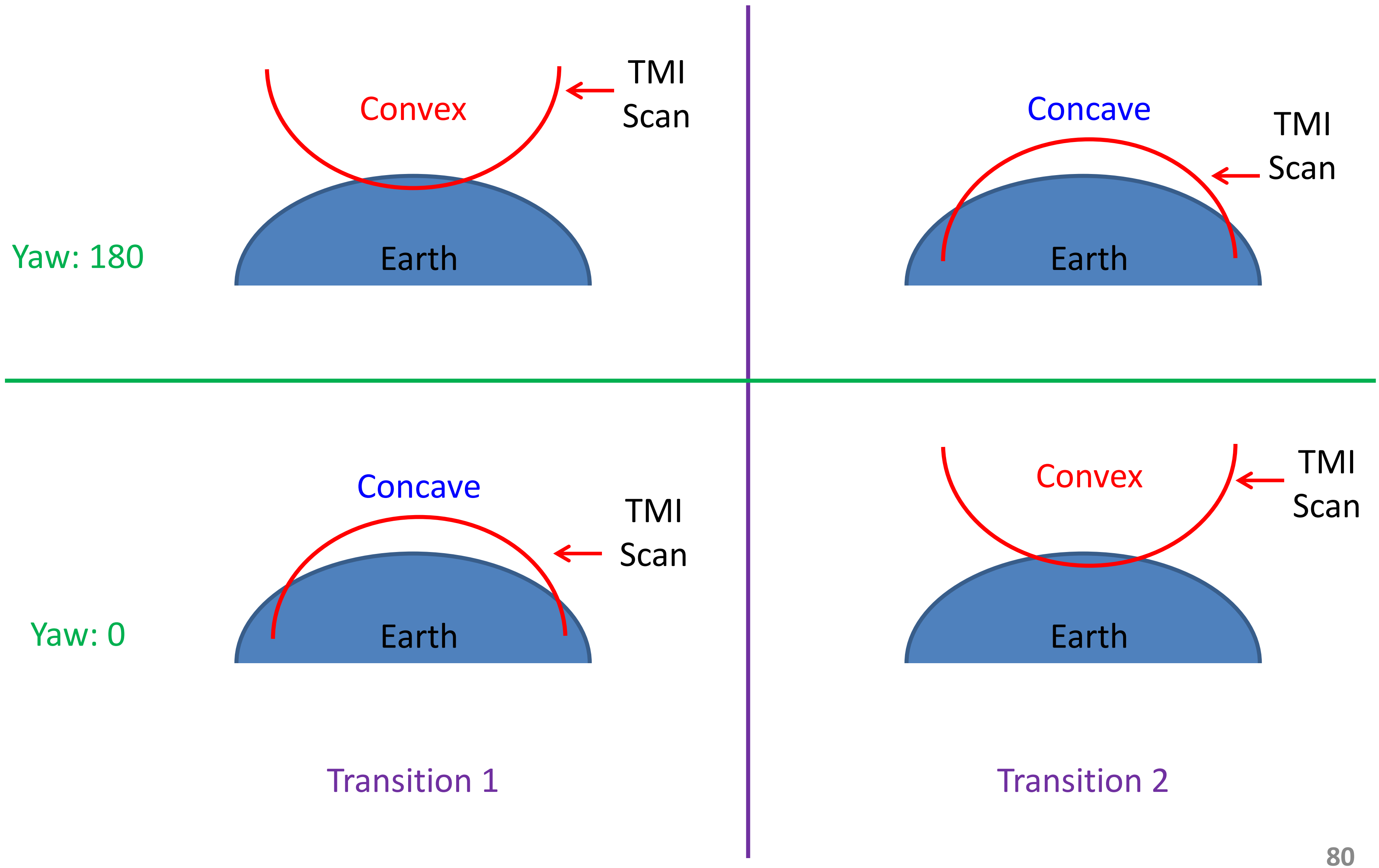


Nadir Dependence on Scan Position
19 V-pol

CFRSL

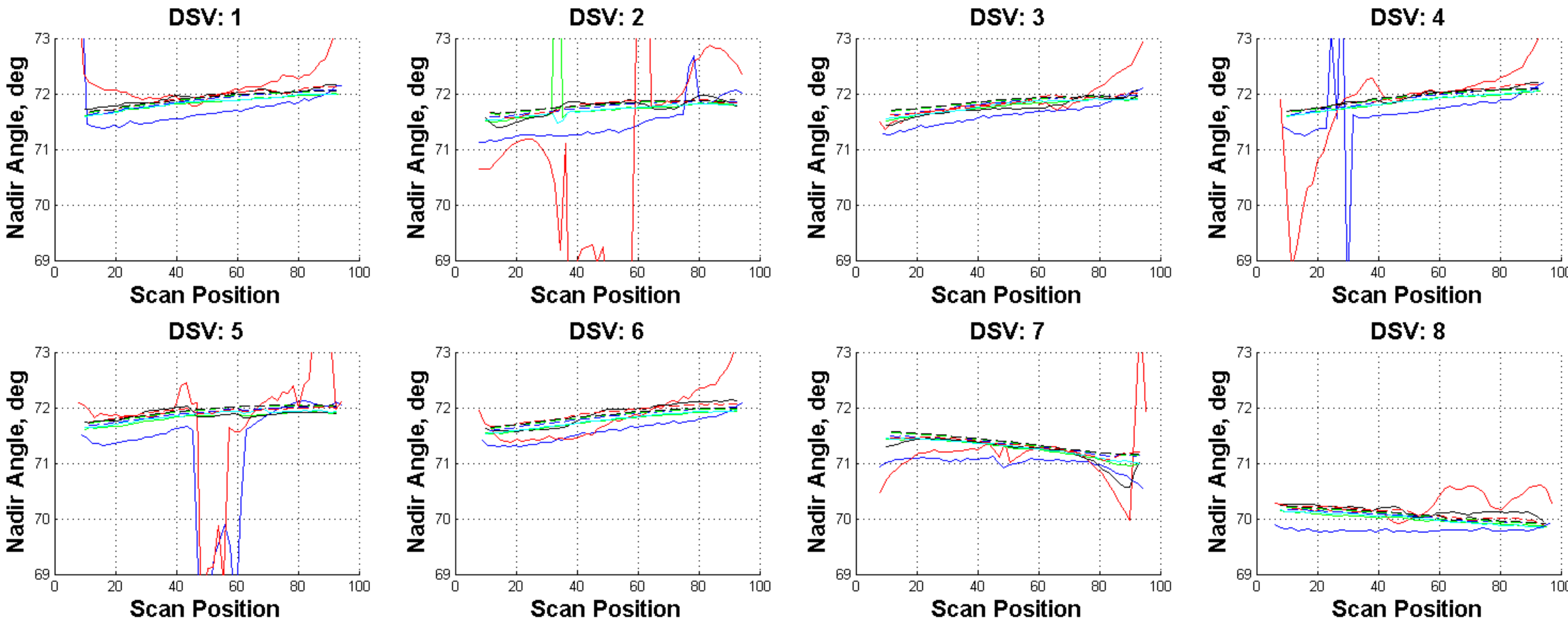


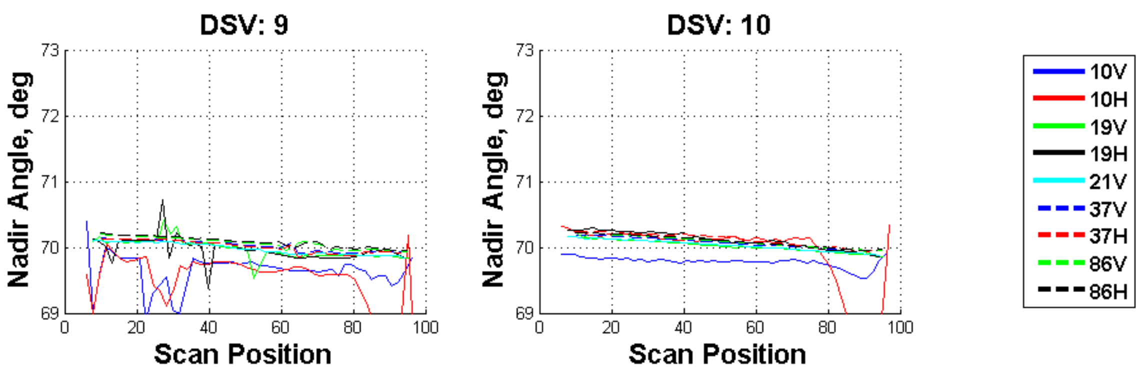
TMI Scan: Concave & Convex Transitions



Concave Transitions

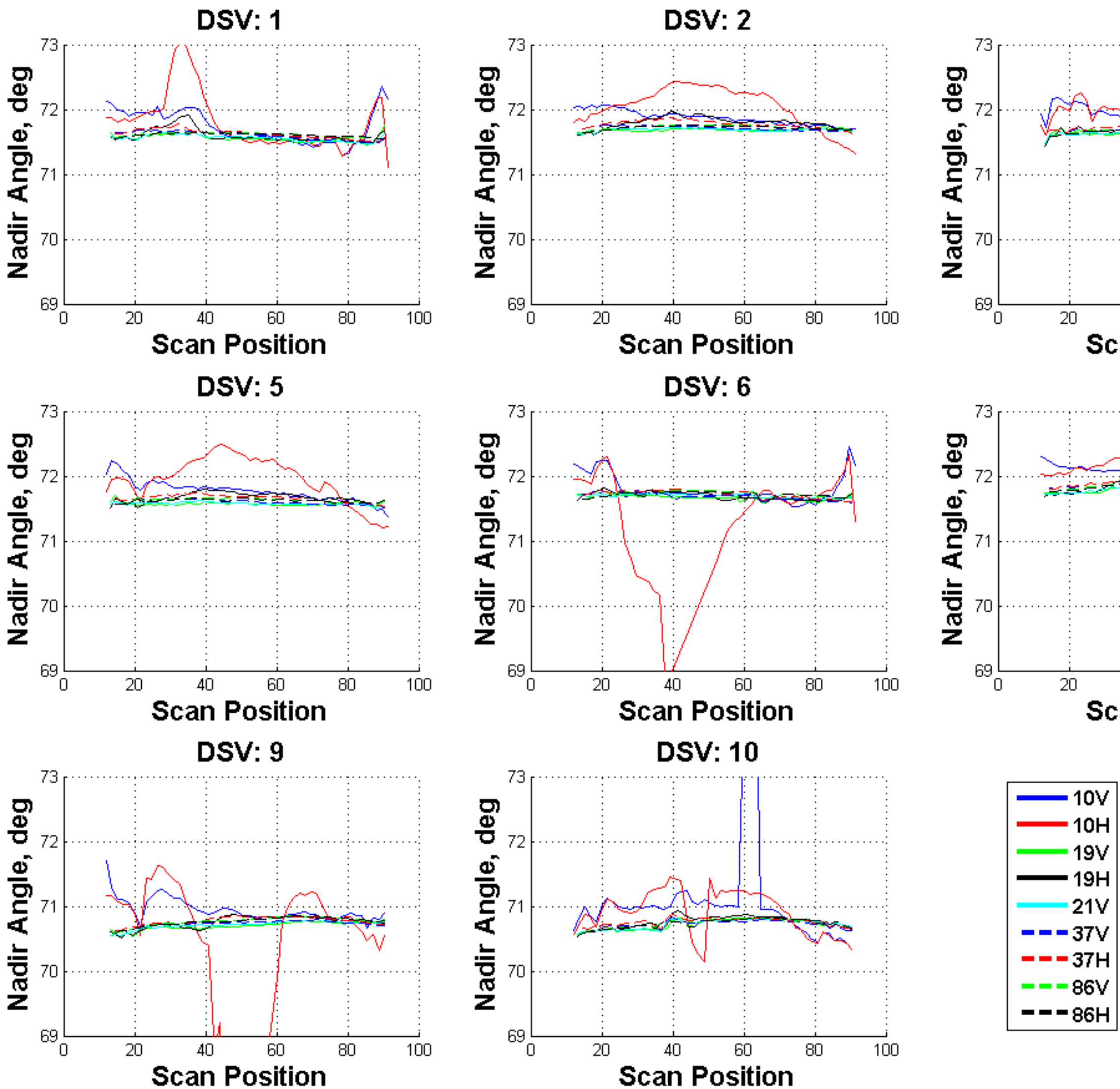
CFRSL





Difference between 10V & multi-freq channels ~0.3°

Convex Transitions



Difference in nadir angle is much different for convex case

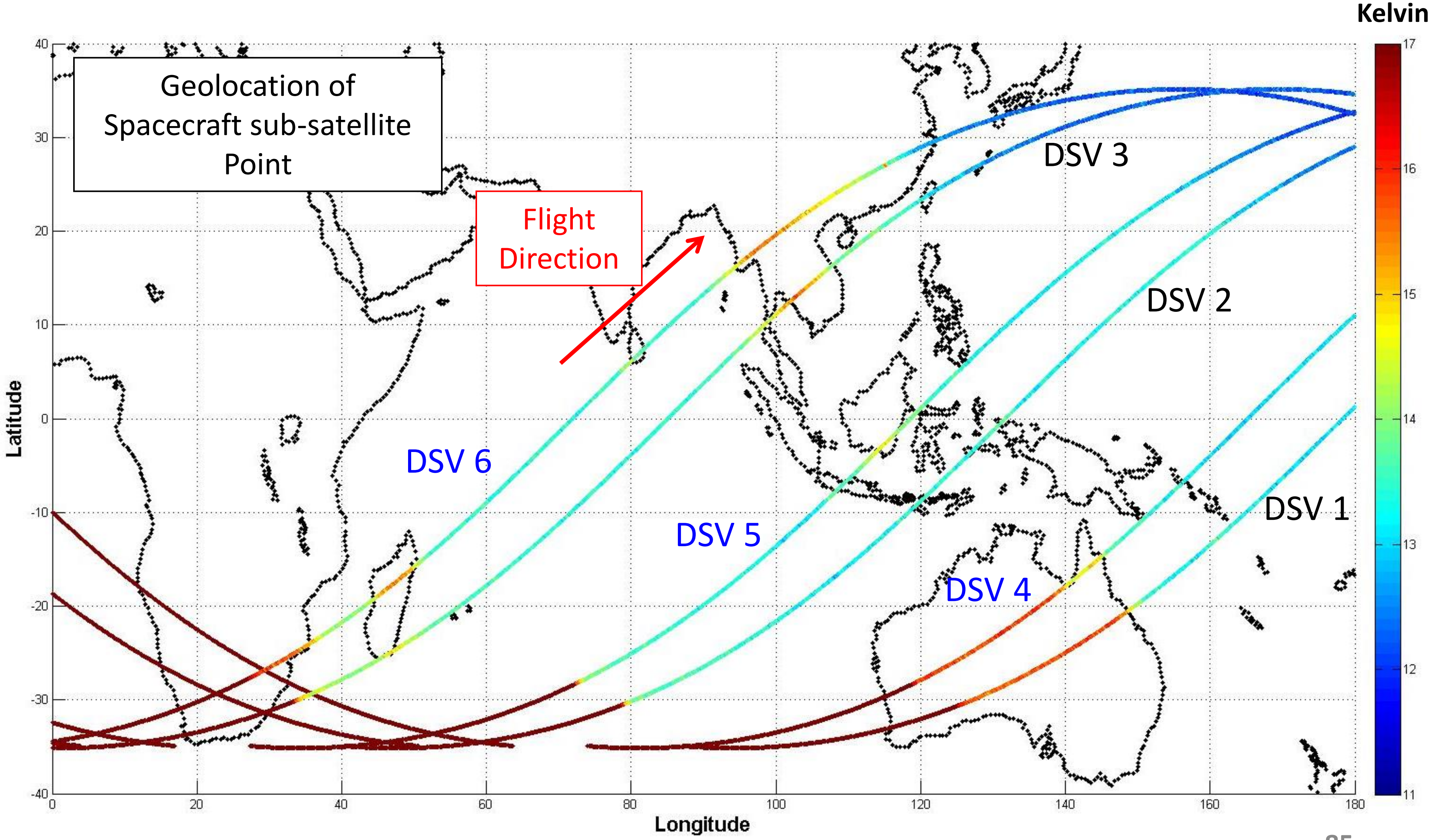
Conclusion & Future Work

- There are differences in the Nadir Angles for 10 V- & H-pol
  - Largest in 10 V for Concave but disappears for the convex case
  - There should be an offset in the along-scan direction which justifies why we don’t see a difference in angle for convex cases
- Future Work To Be included in the Dissertation
  - Use STK or TMI geolocation code to determine match the nadir angles for the convex & concave cases
- Future Work: Post Dissertation
  - Use March 2015 maneuvers, Yaw 90°, to better estimate this angle in the along-scan direction

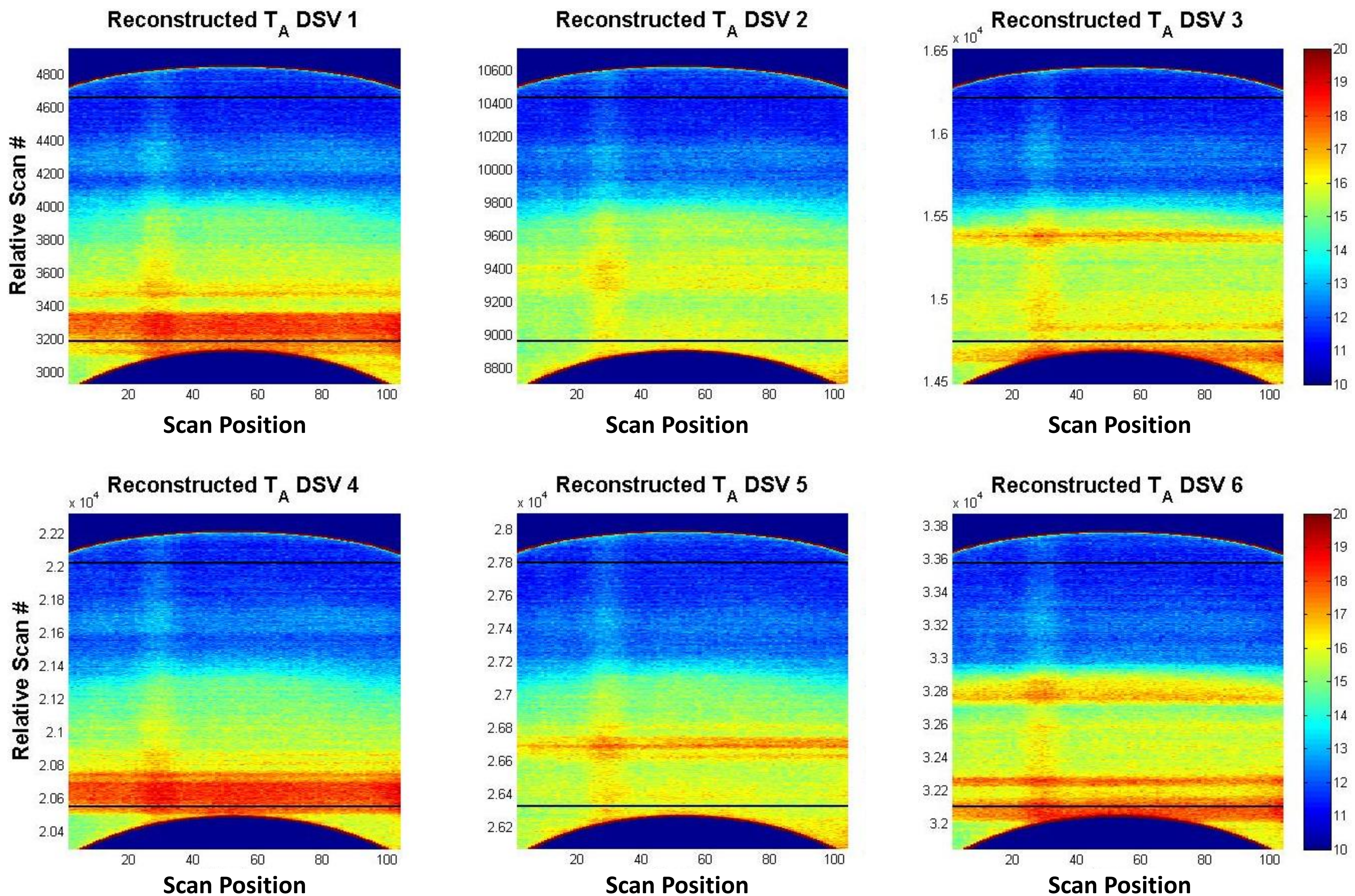
Analysis

Along-scan Bias

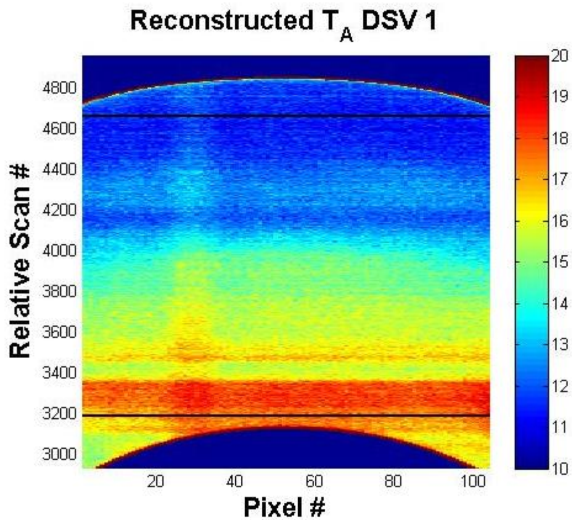
T_A (19 V-pol) Earth Contamination (Spillover) for DSV 1-6

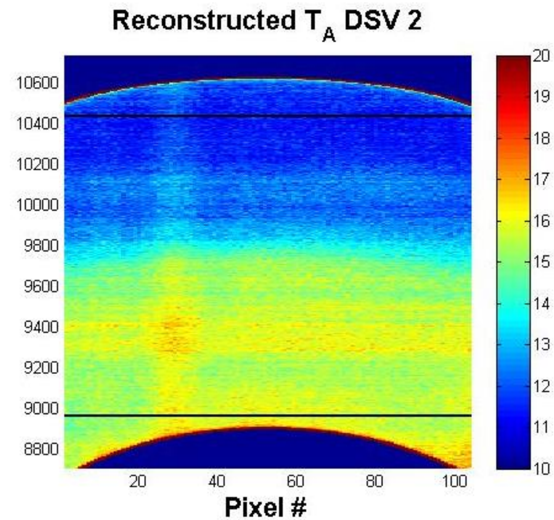


Deep Space Views for 19 V-Pol TA

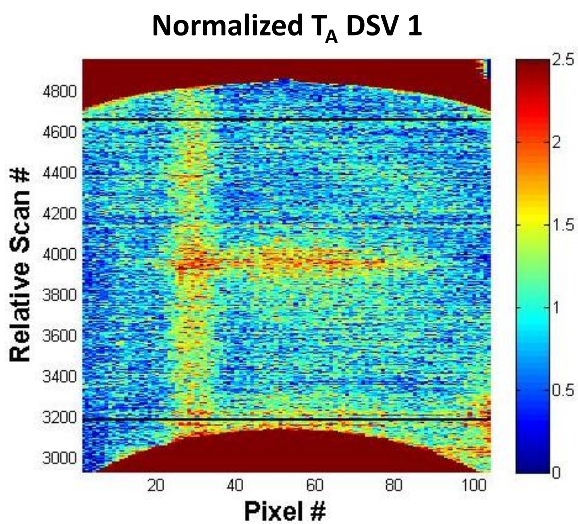


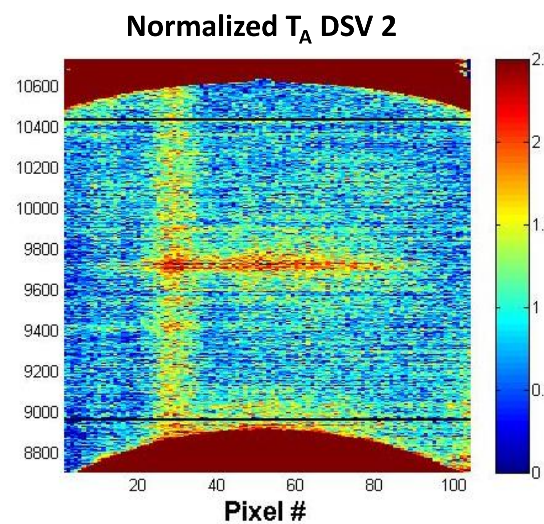
Deep Space Views for 19 V-Pol



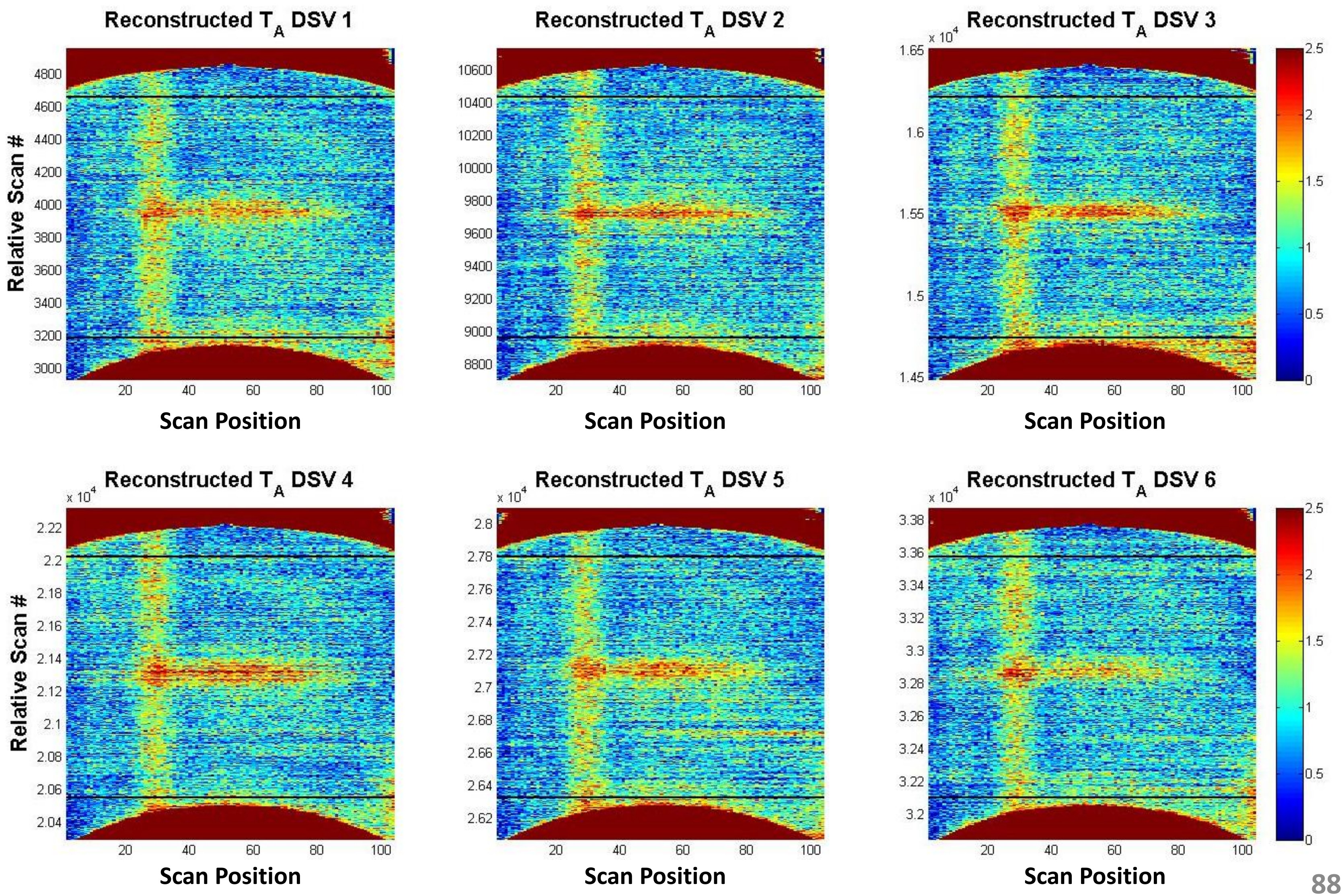


Subtracting out the minimum value within each scan



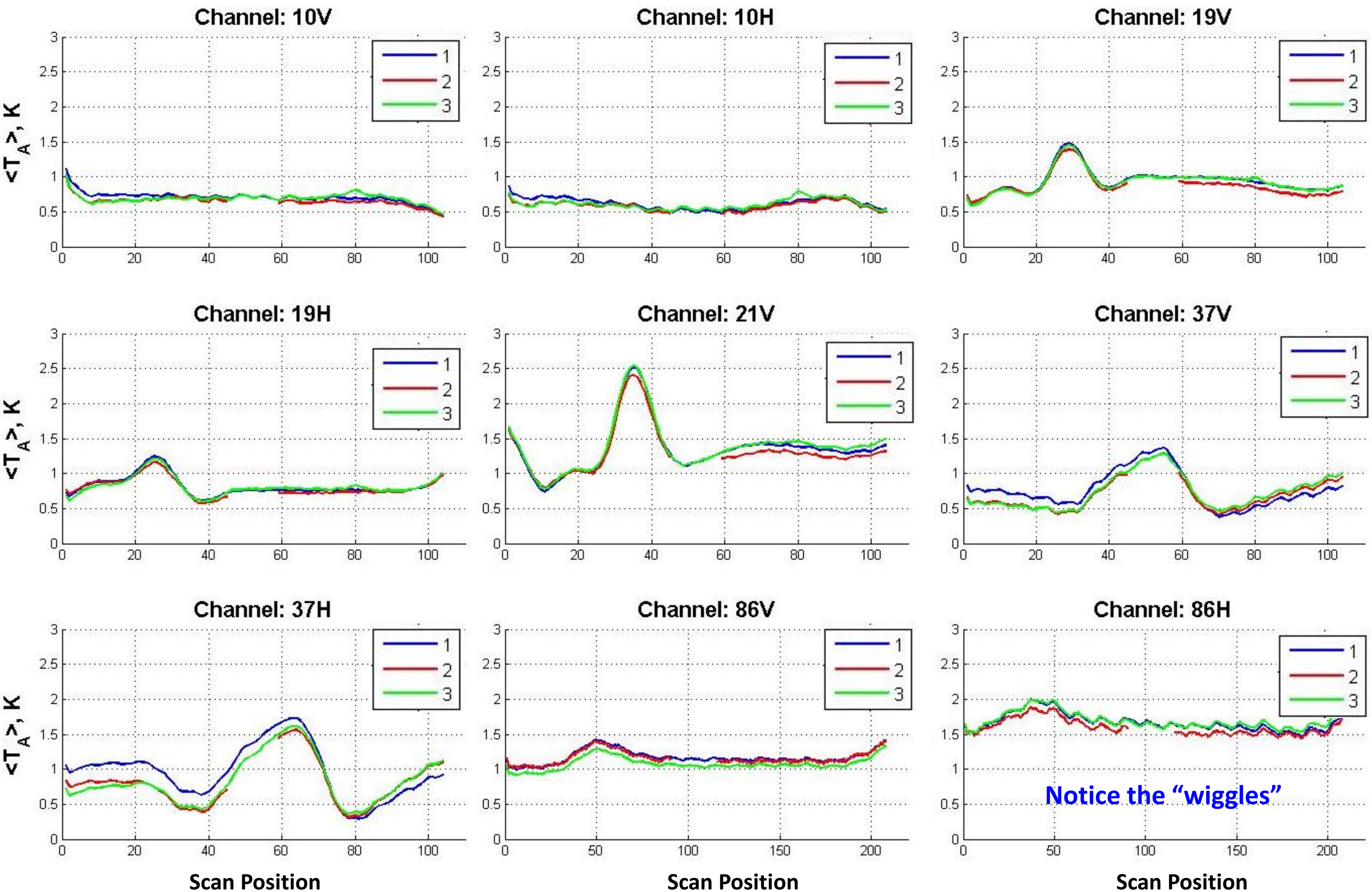


Deep Space Views for 19 V-Pol

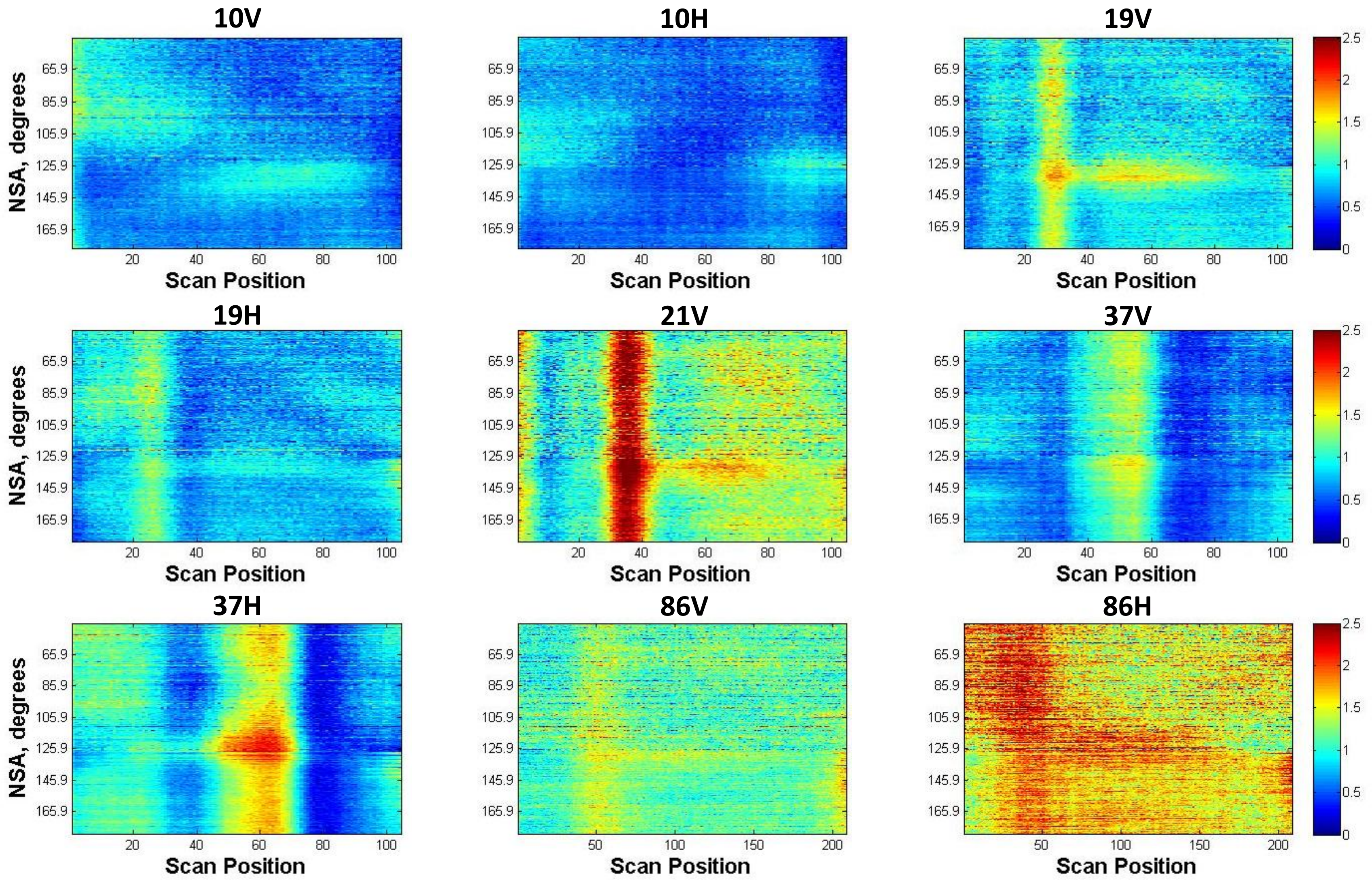


DSCM Sets

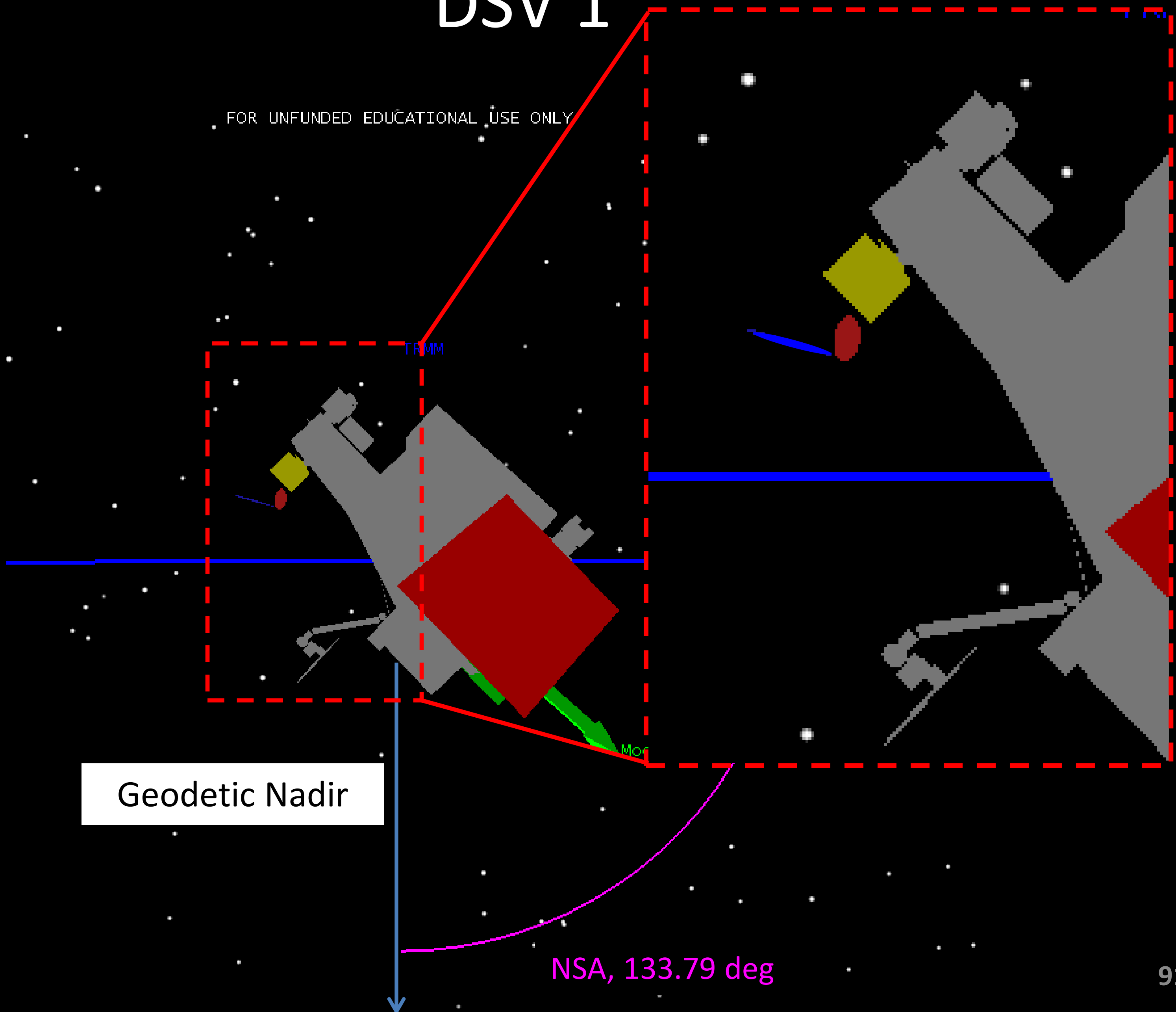
Limited Range Data



DSCM Set 1 – Averaged w.r.t. NSA



DSV 1


FOR UNFUNDED EDUCATIONAL USE ONLY
TRMM
Geodetic Nadir
NSA, 133.79 deg

Conclusion & Future Work

- Along-scan analysis is in good agreement with RSS' (2001) analysis but this depends on channel
- Back-lobe / Spillover is present in this analysis and is obvious at an NSA angle of ~133°
  - Depending on channels can be up to 1.0 K for a given scan position
- Future Work: Post Dissertation
  - Include Year 2015 maneuvers into this analysis

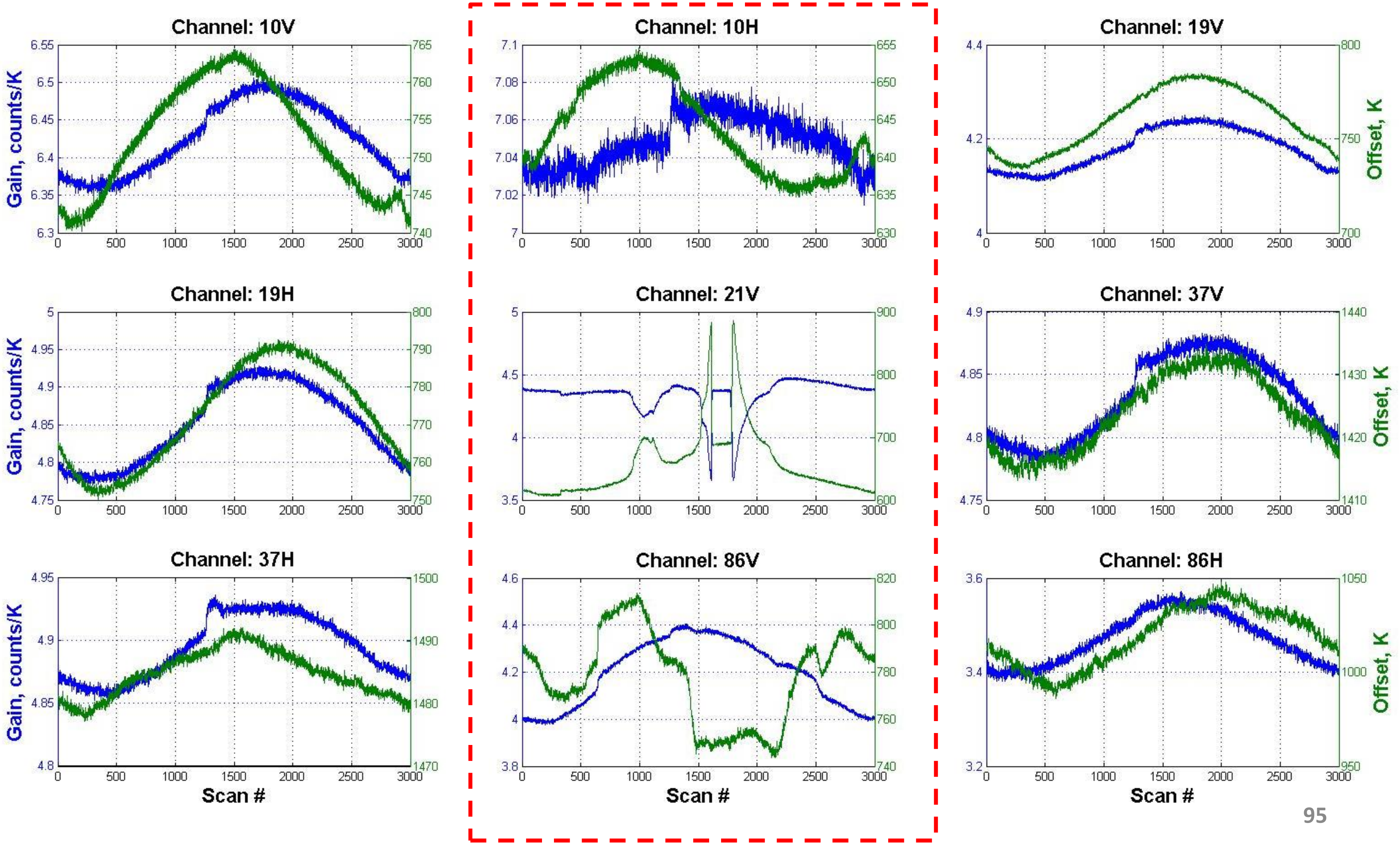
Extra Slides

Back Up

Intro

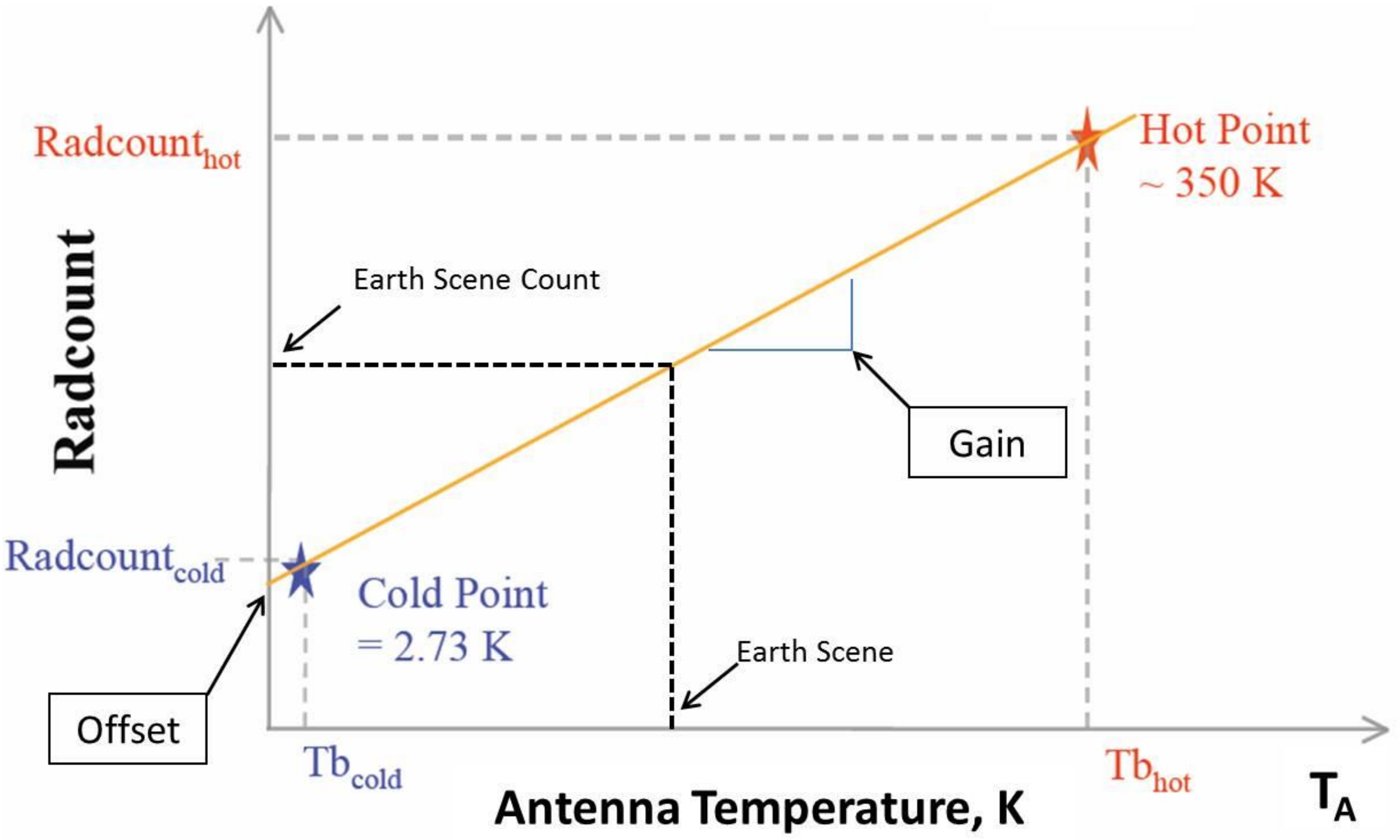
Gain & Offset for All TMI Channels

TMI Orbit 601

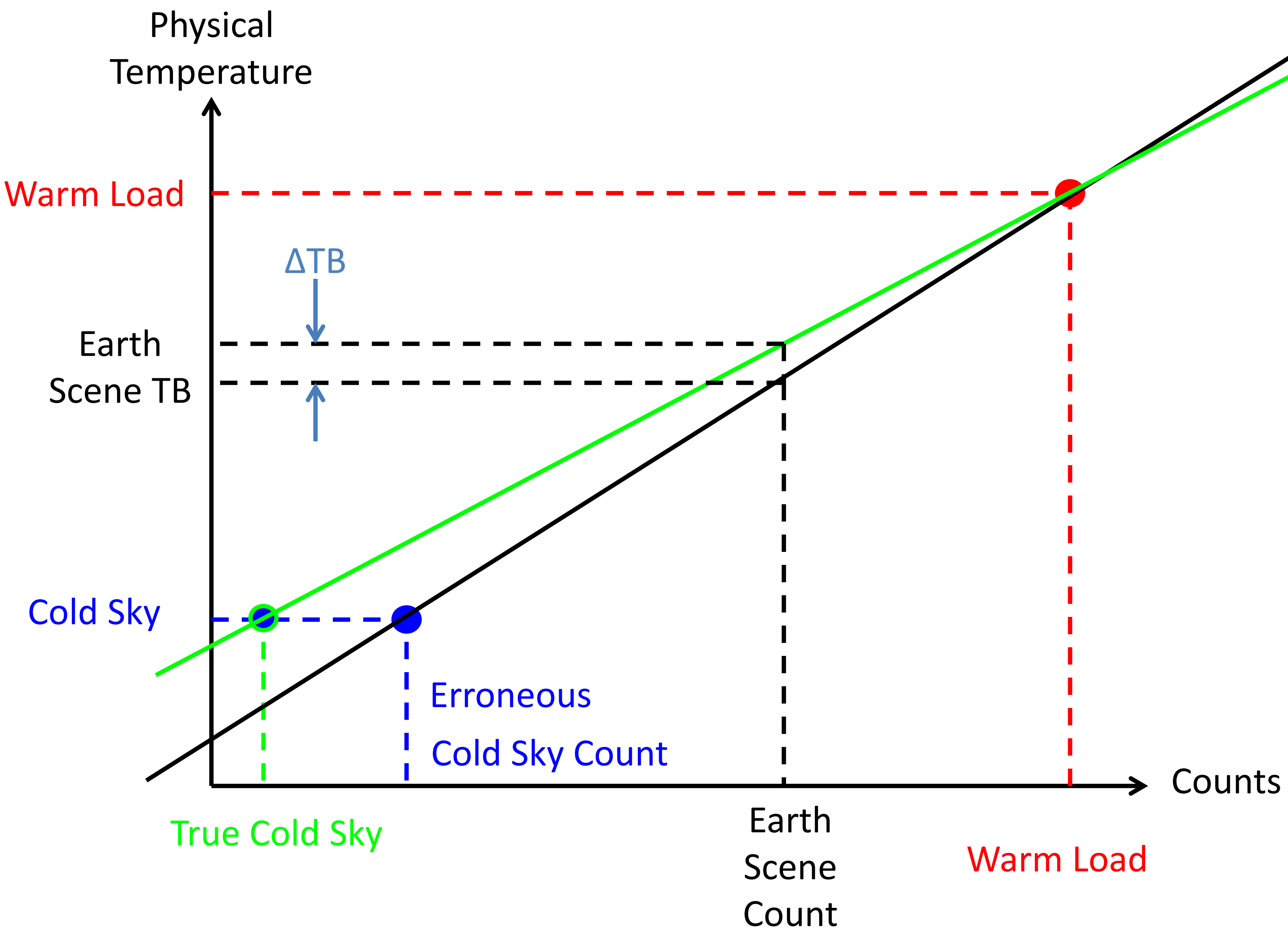


Two Point Calibration

CFRSL

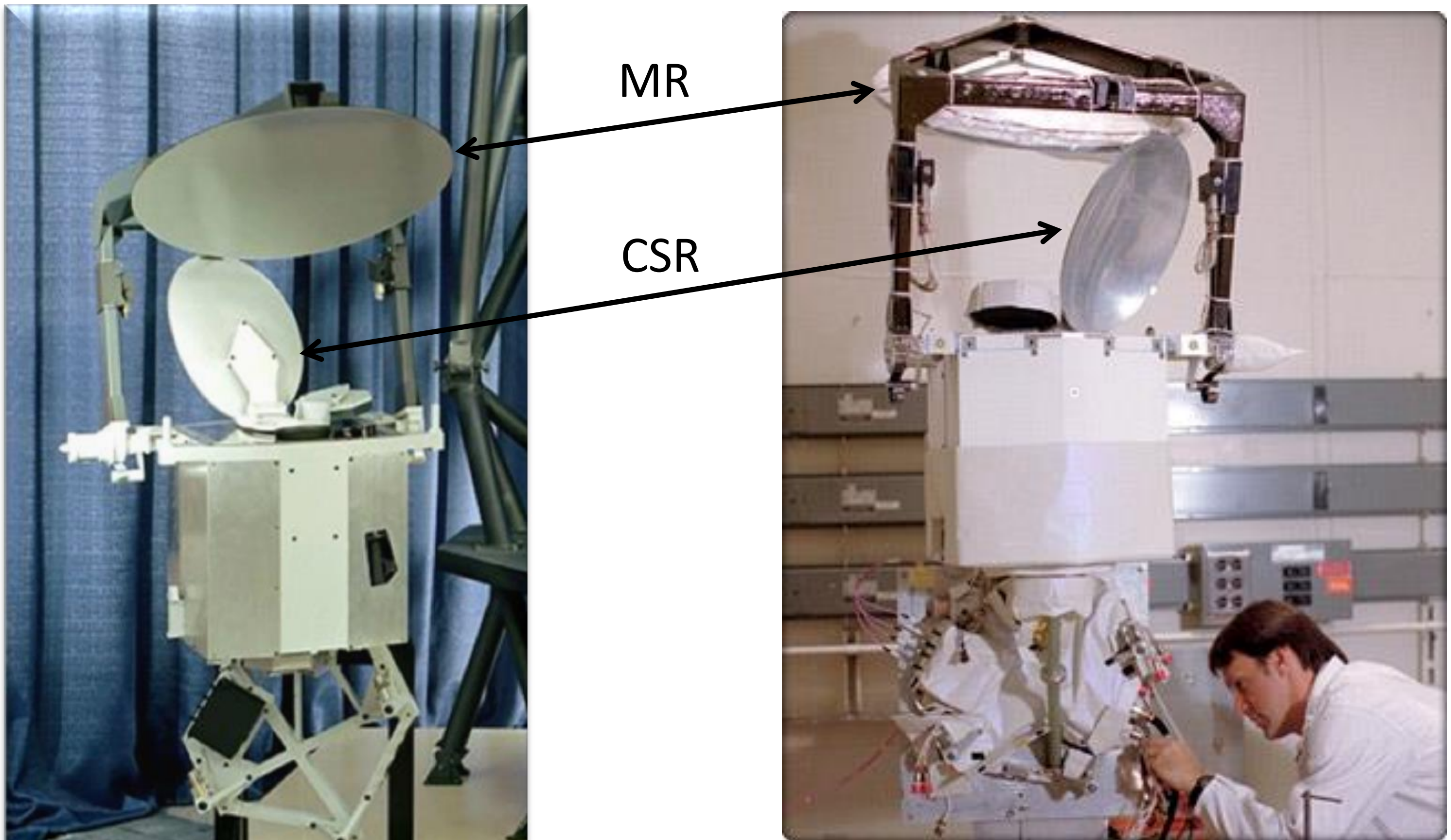


Transfer Function (Two-Point Calibration)



TRMM Microwave Imager (TMI)

Facing Main Reflector (MR) | **Facing Cold Sky Reflector (CSR)**

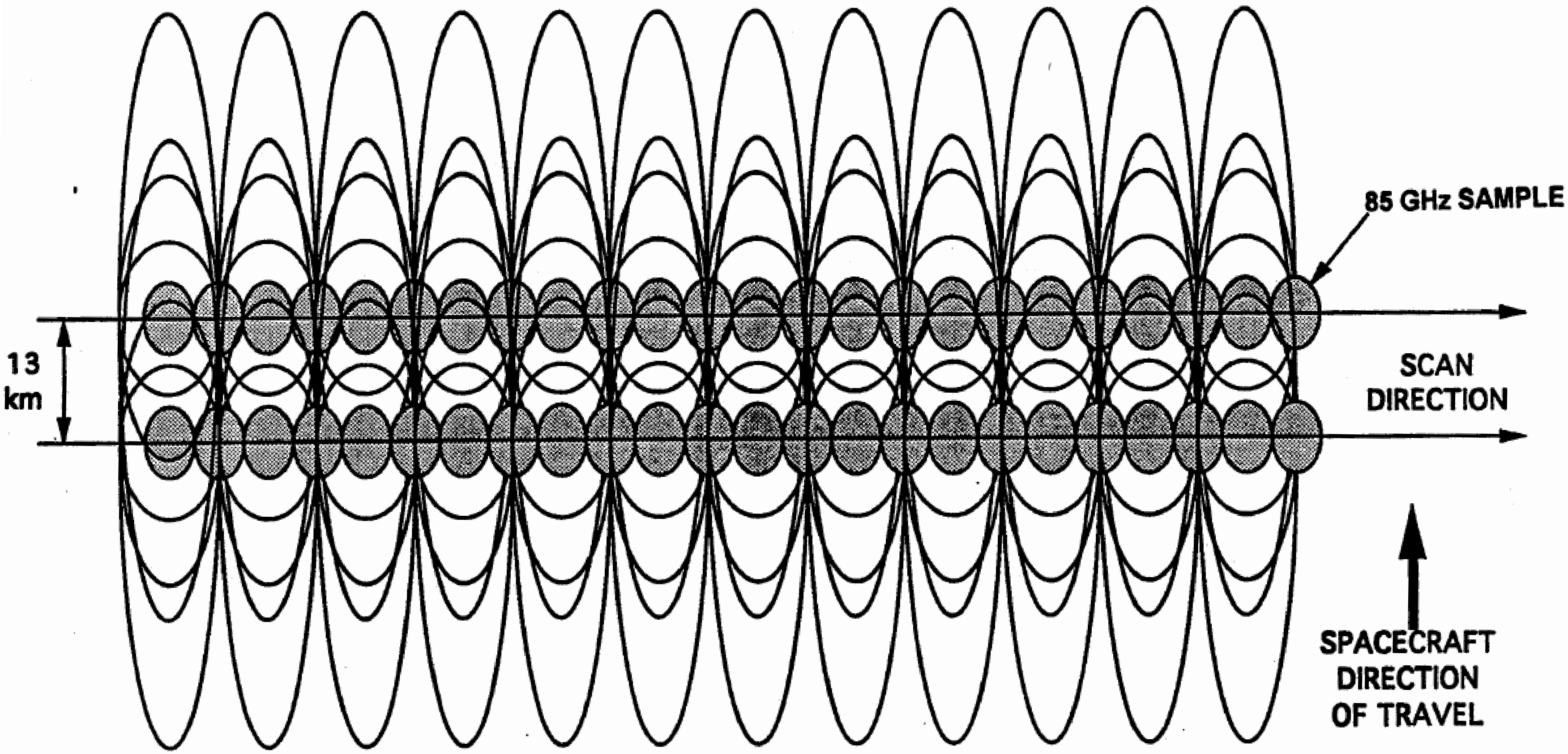


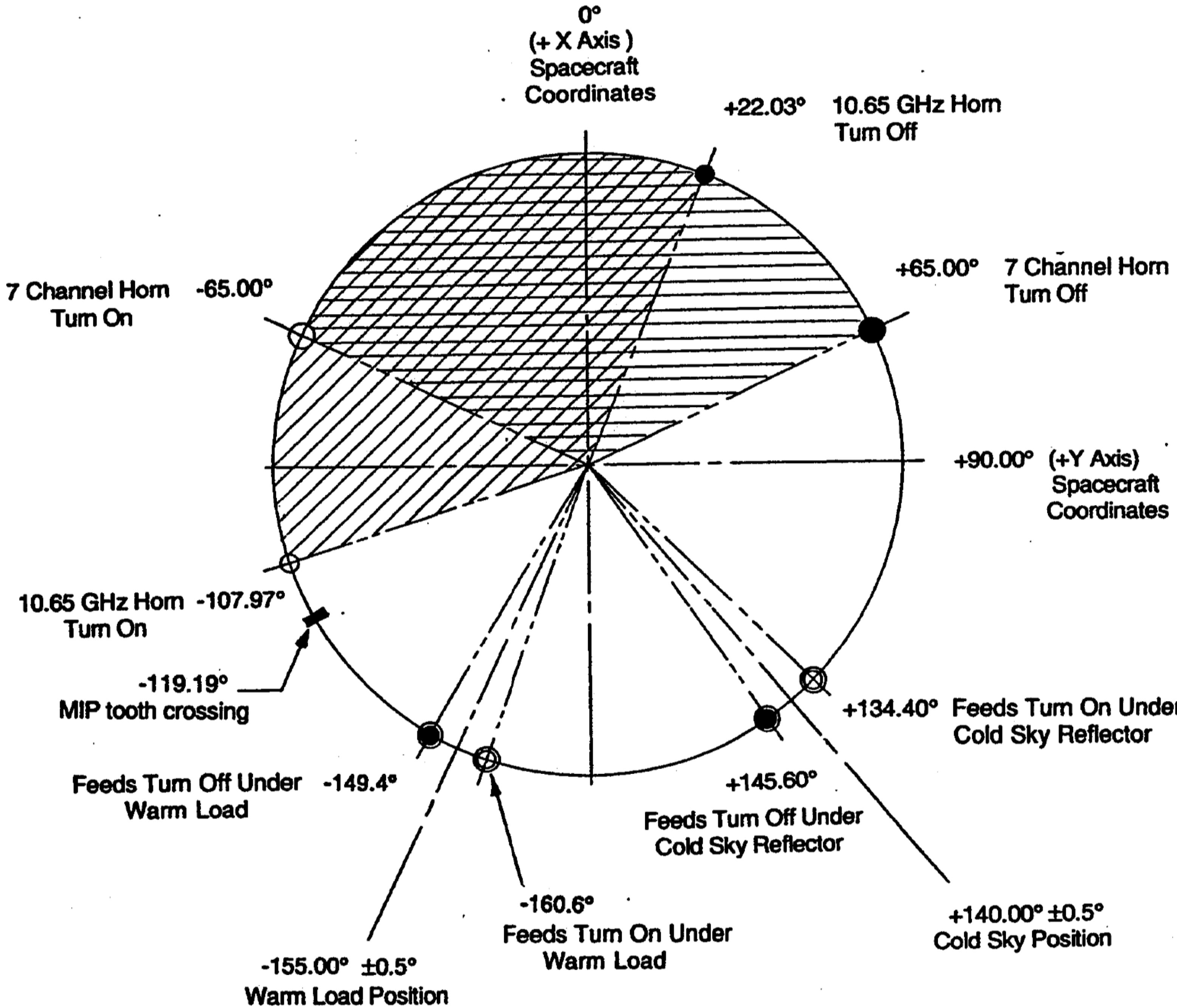
(a) (b)

Compliments of
Dave Kunkee

TMI SAMPLING PATTERN

HUGHES

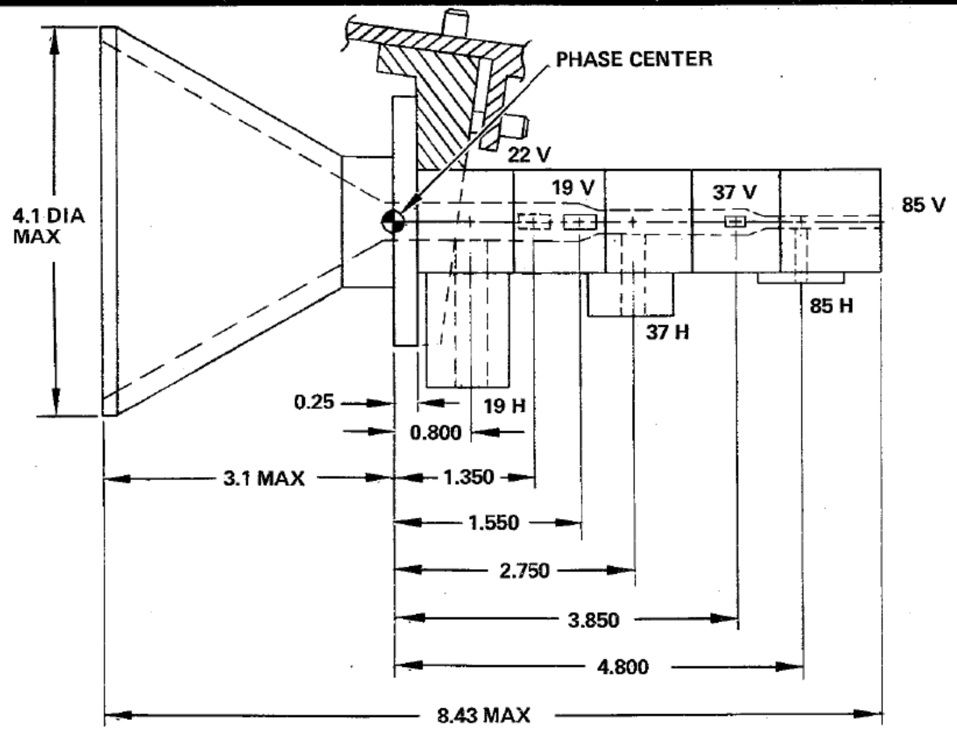



0°
(+ X Axis)
Spacecraft
Coordinates
+22.03°
10.65 GHz Horn
Turn Off
+65.00°
7 Channel Horn
Turn Off
7 Channel Horn
Turn On
-65.00°
+90.00°
(+Y Axis)
Spacecraft
Coordinates
10.65 GHz Horn
Turn On
-107.97°
-119.19°
MIP tooth crossing
+134.40°
Feeds Turn On Under
Cold Sky Reflector
Feeds Turn Off Under
Warm Load
-149.4°
+145.60°
Feeds Turn Off Under
Cold Sky Reflector
-160.6°
Feeds Turn On Under
Warm Load
+140.00° ±0.5°
Cold Sky Position
-155.00° ±0.5°
Warm Load Position

SSM/I CDR

SSM/I RADIOMETER FEED SYSTEM

HUGHES

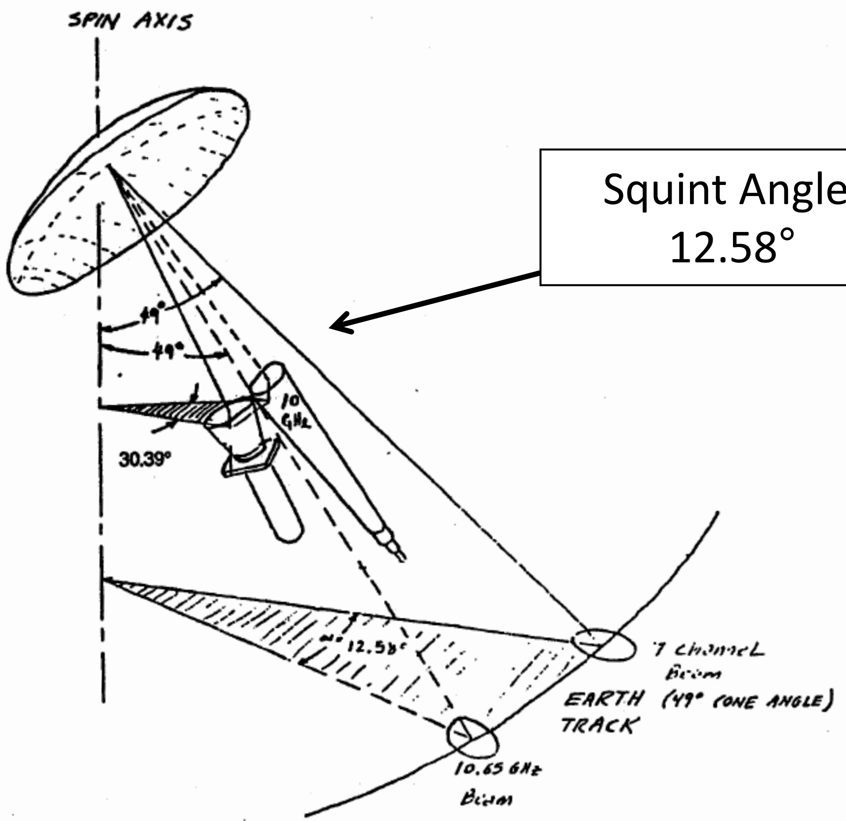


06133-85

10.65 GHz BEAM POSITIONING
Isometric View

HUGHES

CFRSL



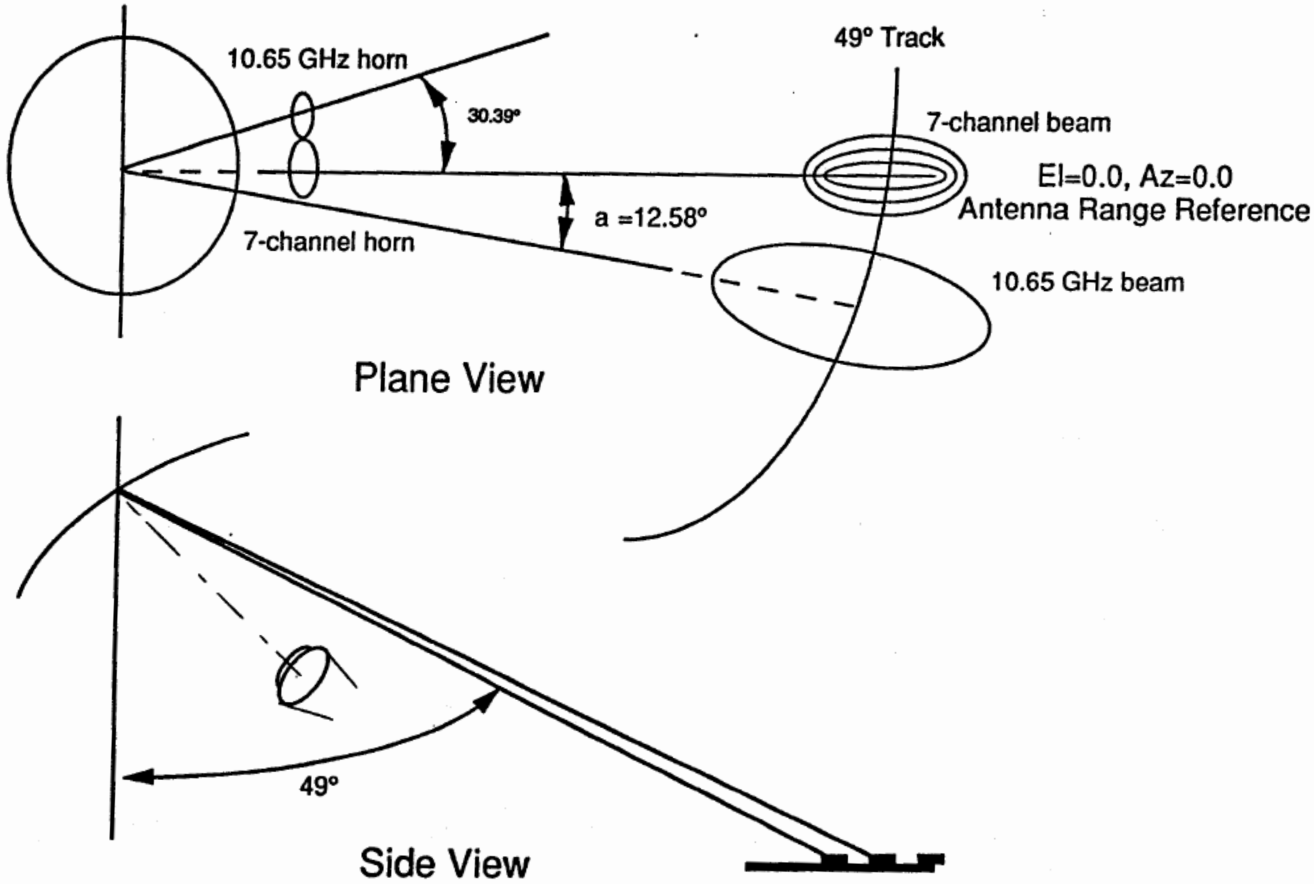
Squint Angle: 12.58°

3-15

10.65 GHz BEAM POSITION
Plane, Side View

HUGHES

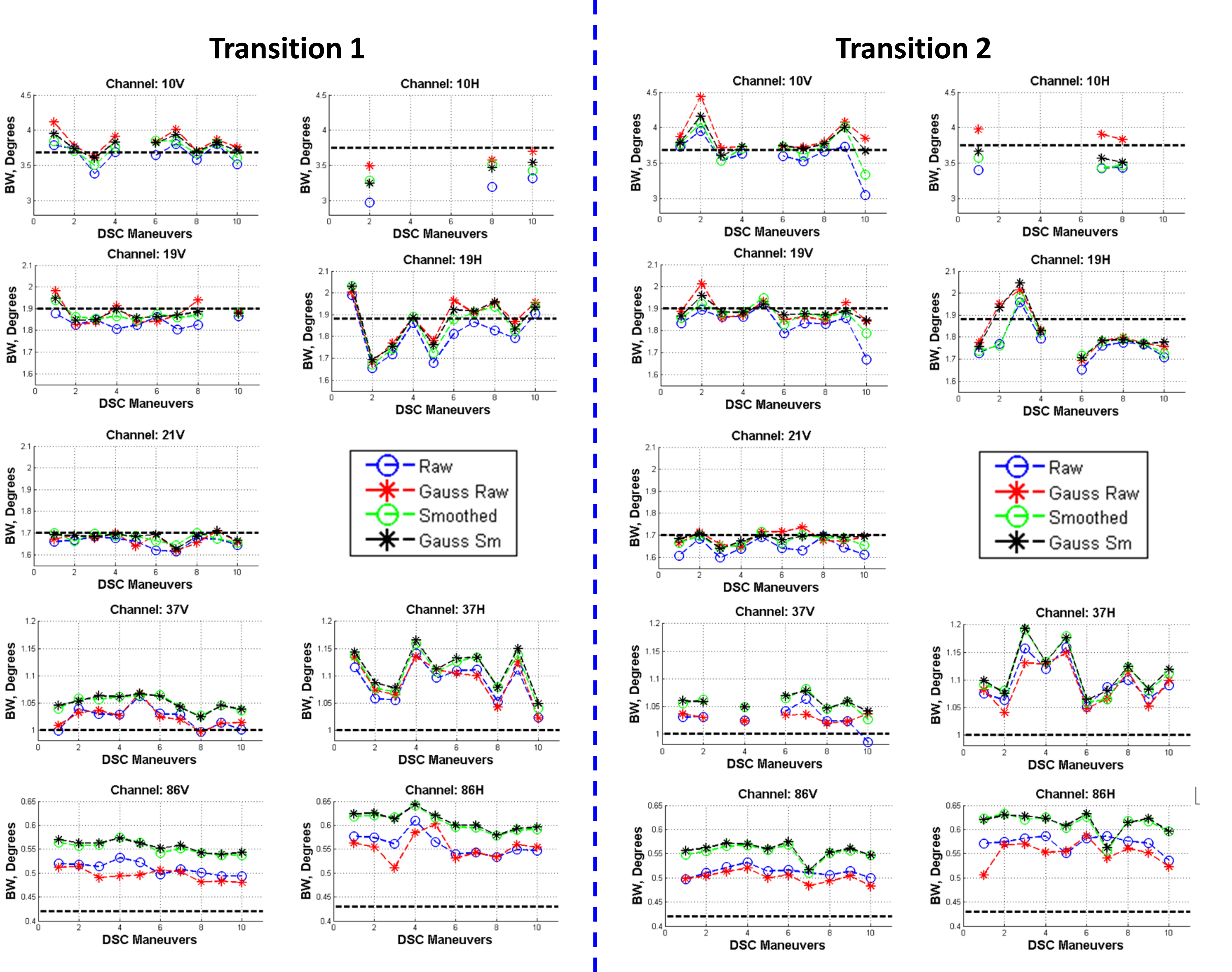
CFRSL



3-14

Back Up

Beam Width

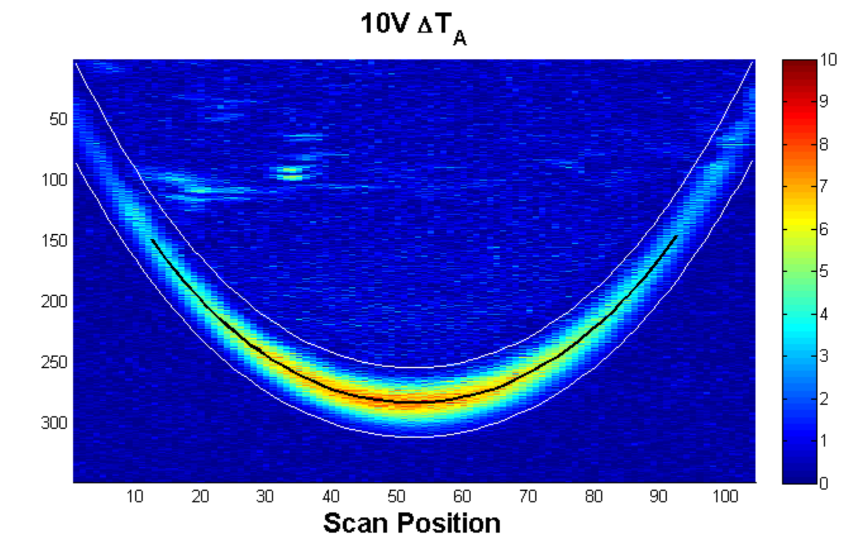


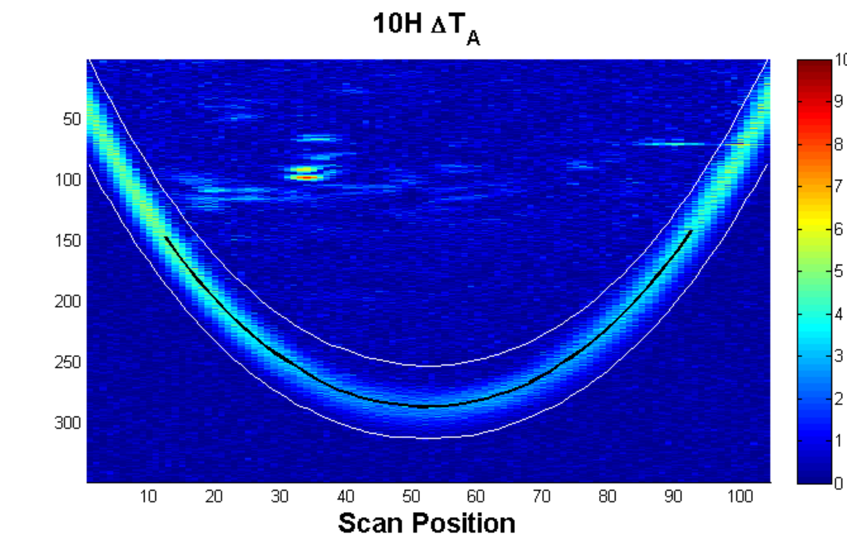
Transition 1
Transition 2
Channel: 10V
Channel: 10H
Channel: 19V
Channel: 19H
Channel: 21V
Channel: 37V
Channel: 37H
Channel: 86V
Channel: 86H
BW, Degrees
DSC Maneuvers
Raw
Gauss Raw
Smoothed
Gauss Sm

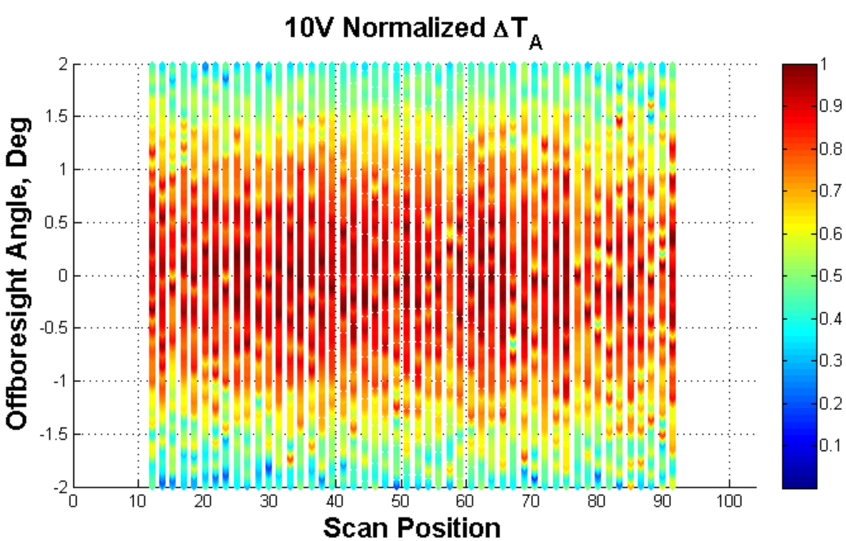
DSCM 2, Transition 1

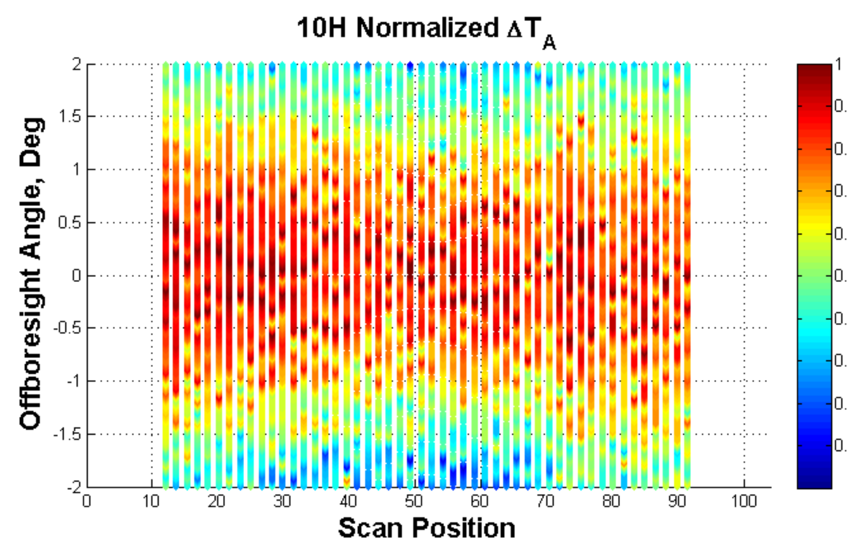
11 GHz Channels

CFRSL



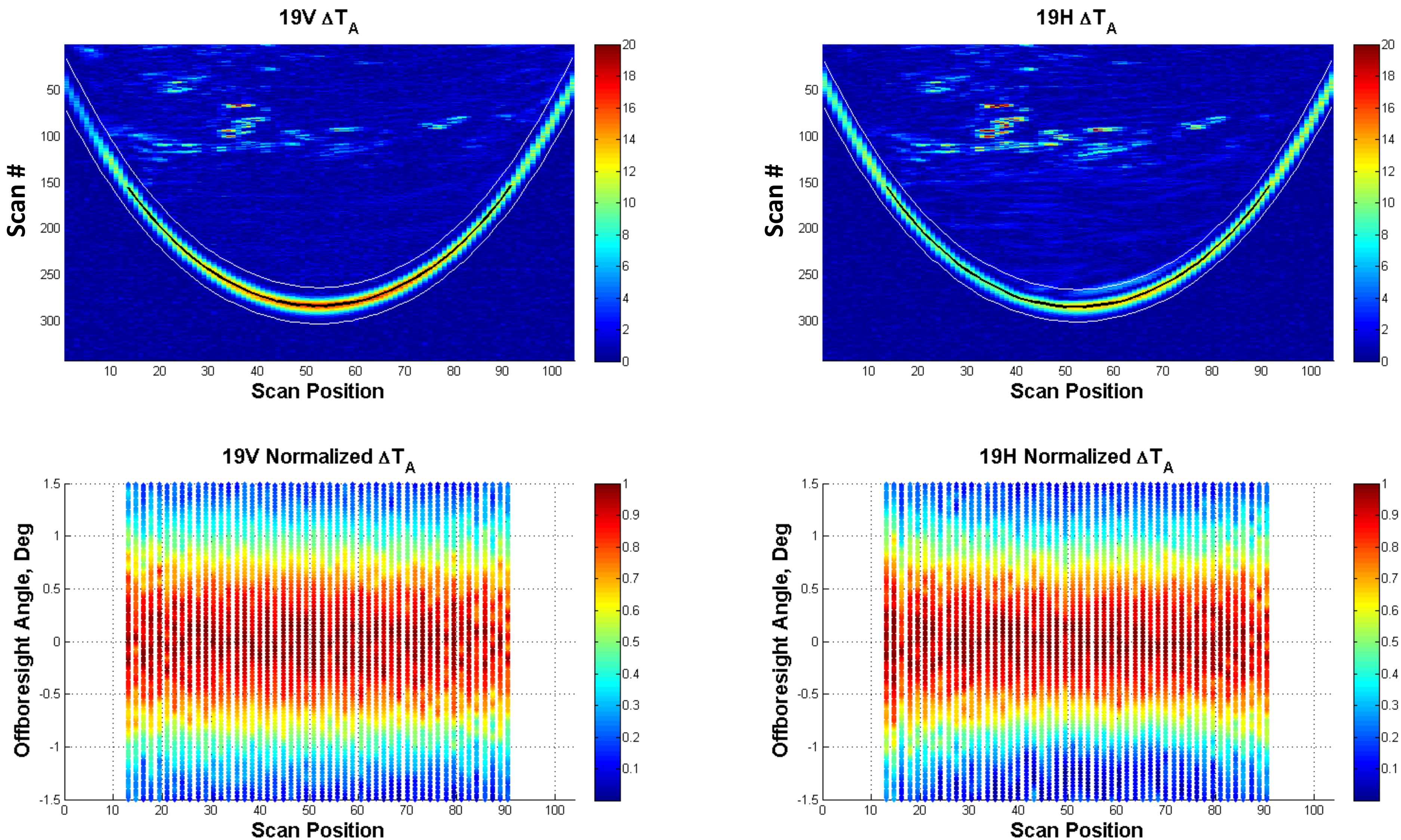






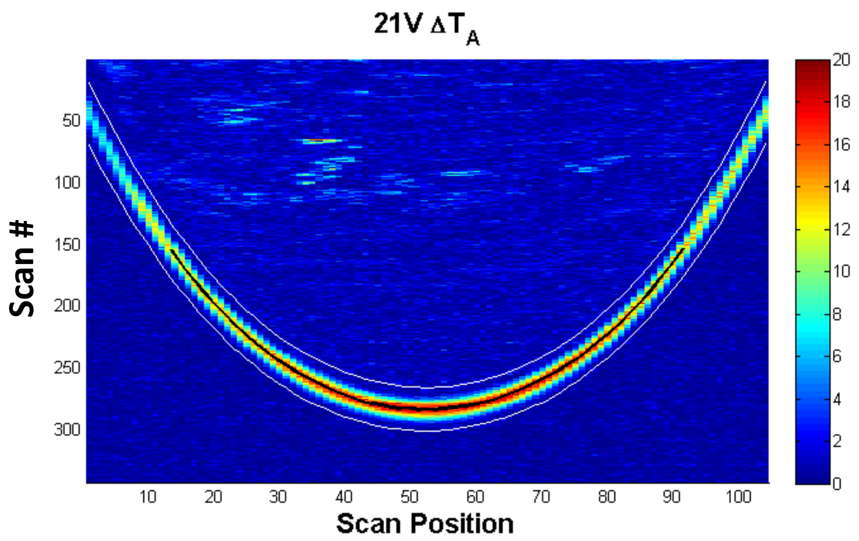
DSCM 2,
Transition 1

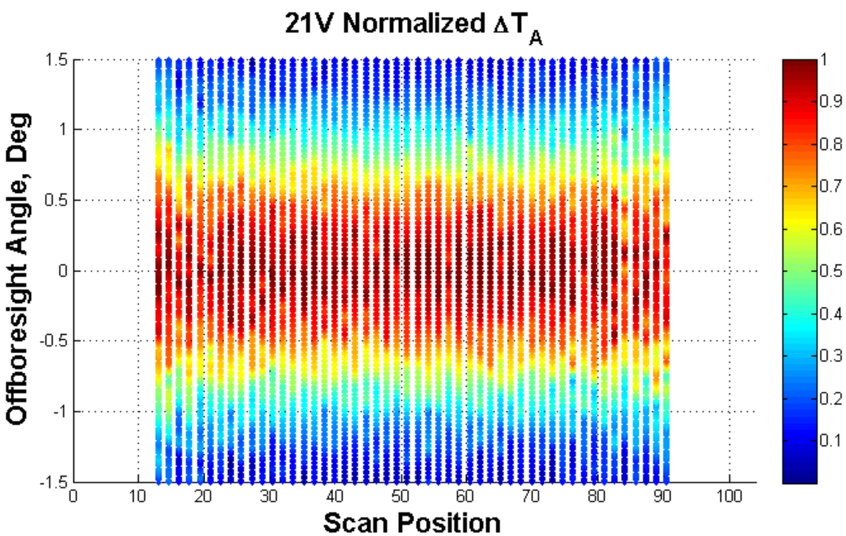
19 GHz Channels



DSCM 2, Transition 1

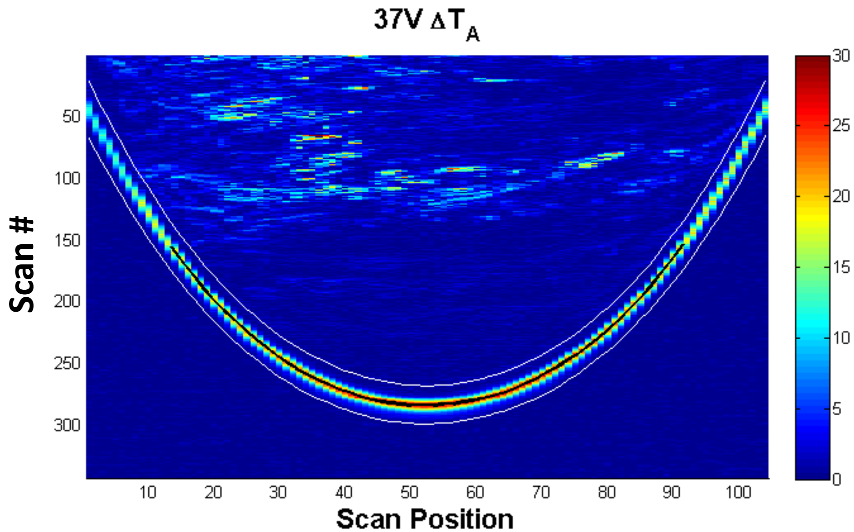
21 GHz Channel

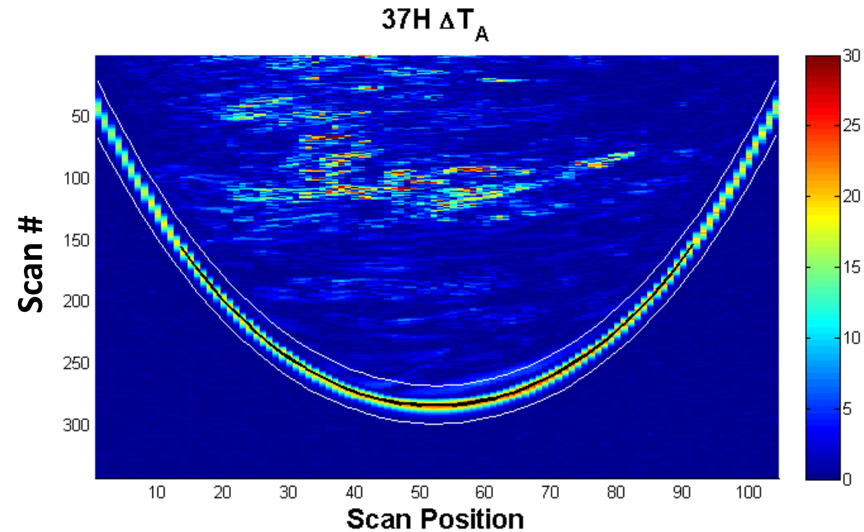


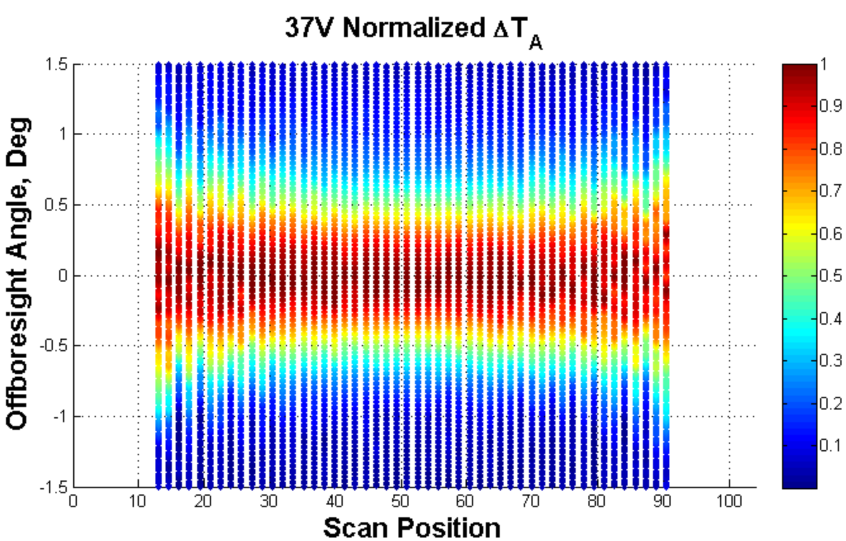


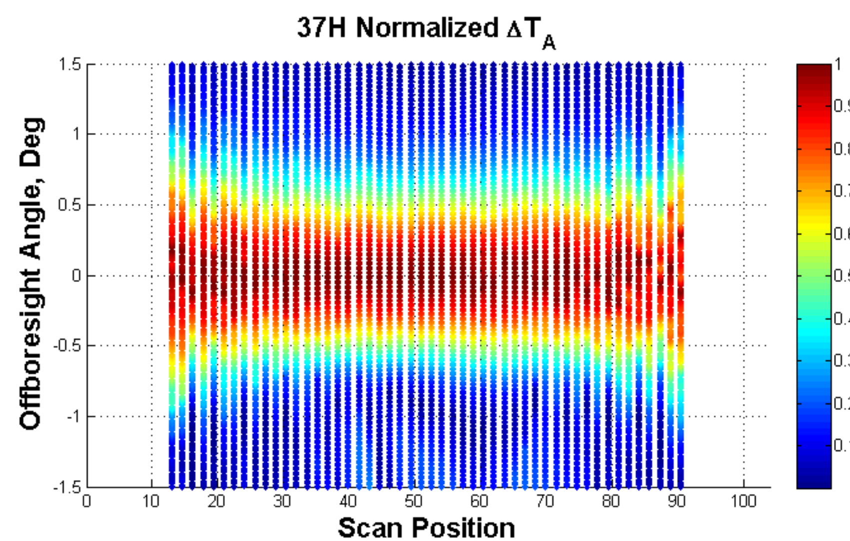
DSCM 2, Transition 1

37 GHz Channels



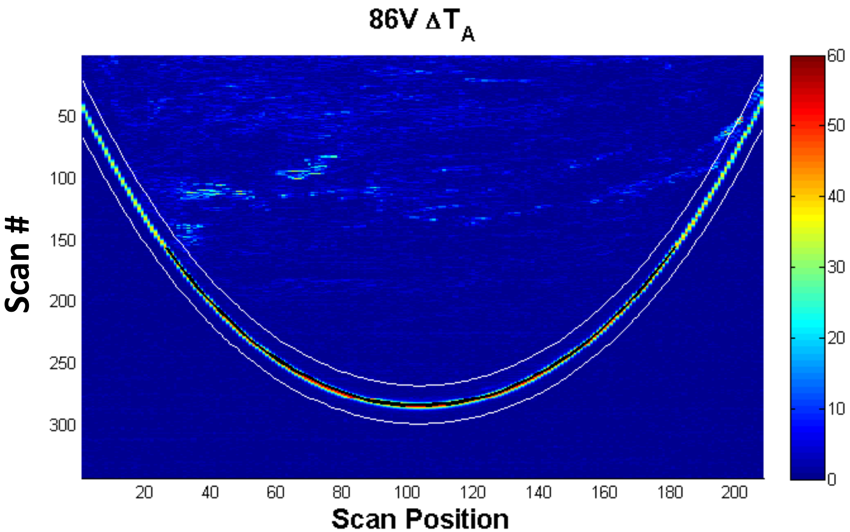


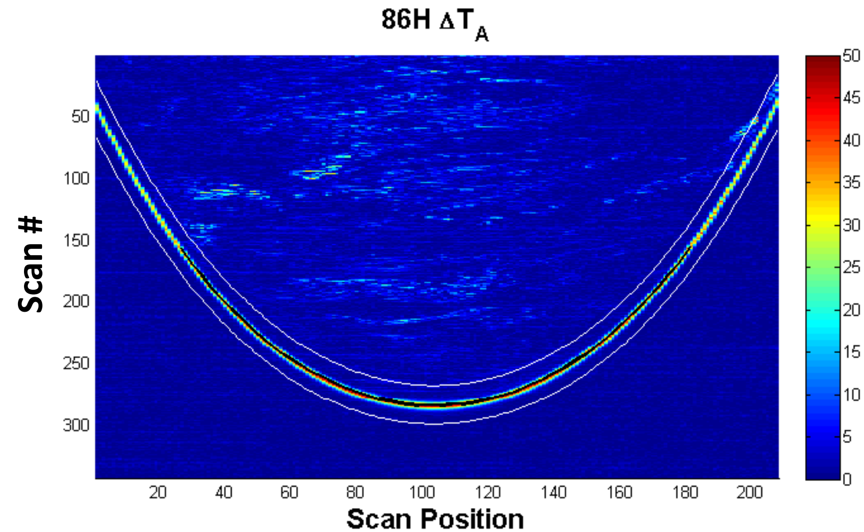


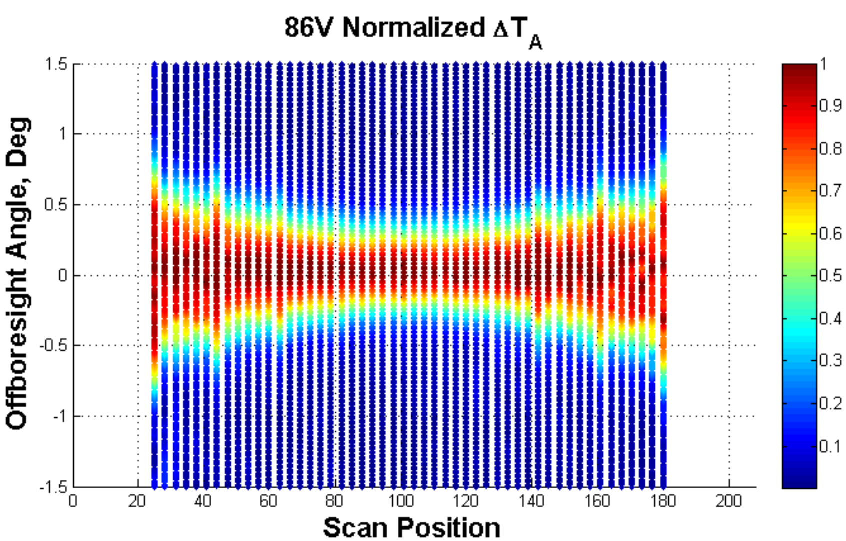


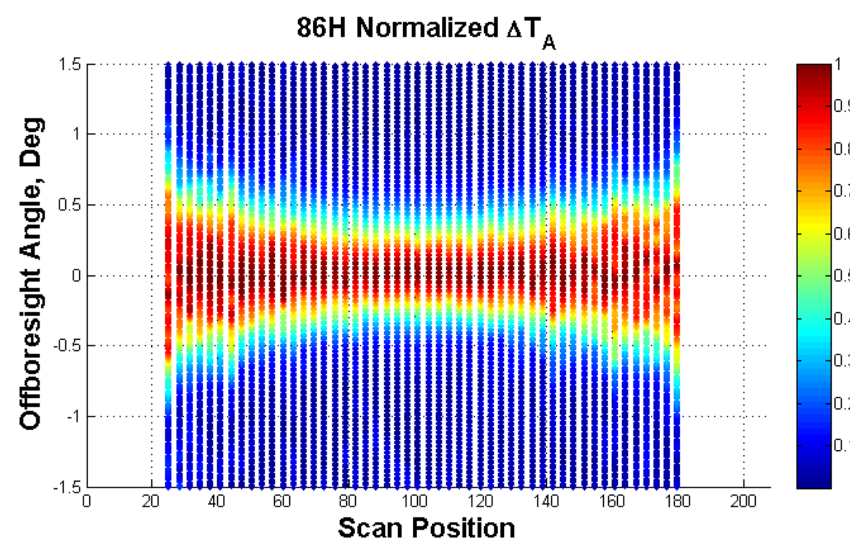
DSCM 2, Transition 1

86 GHz Channels









Back Up

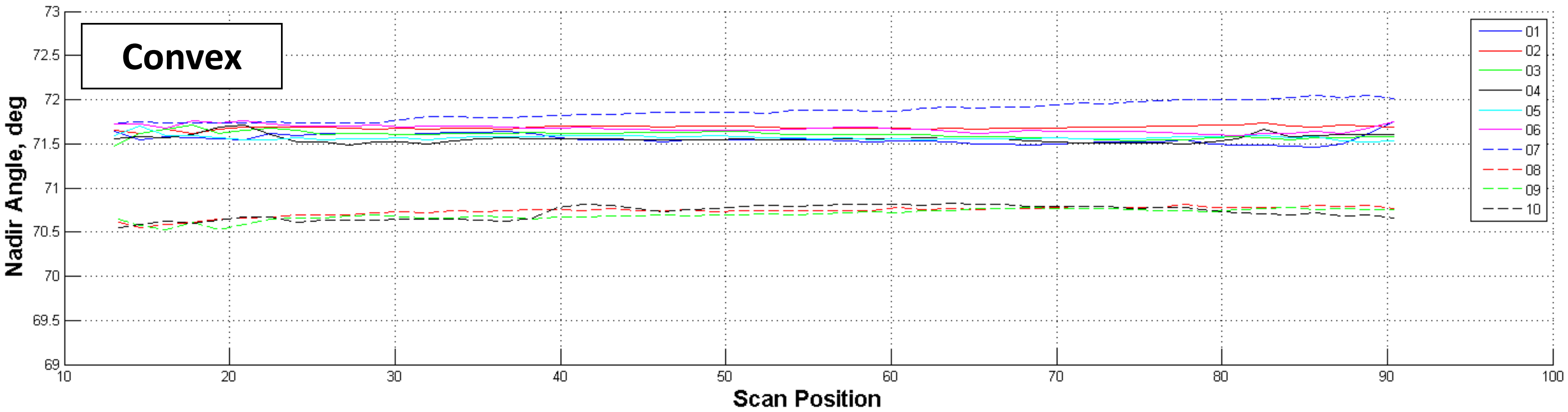
Boresight Pointing

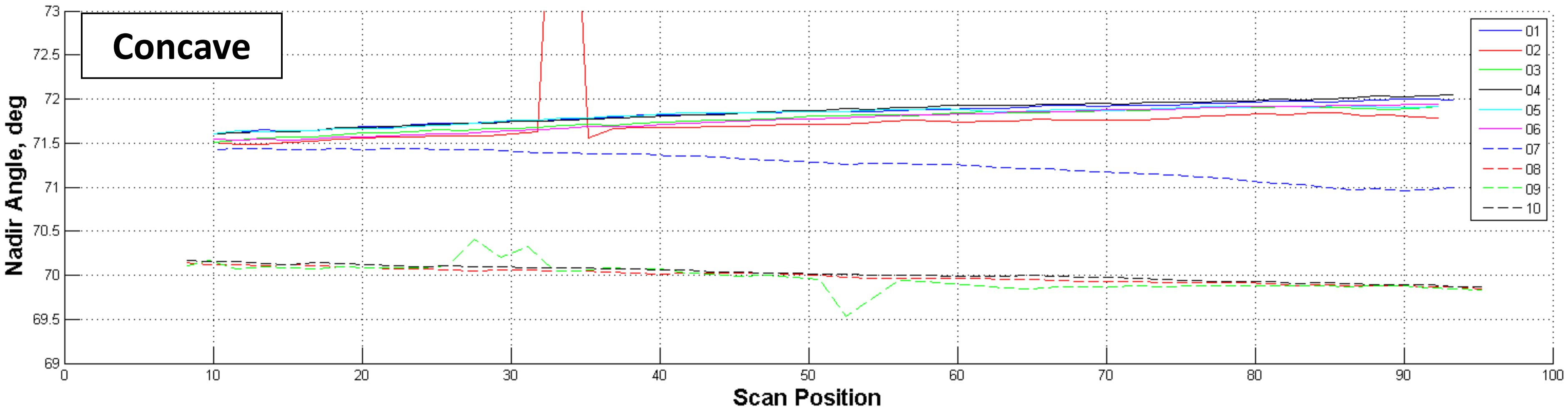
TMI Boresight Table

Channels	Offsets from Shiue Memo (deg)		Offsets from TMI Subsystem Test Doc (deg)	
	Along-track	X-Track	Along-Track	X-Track
10.65 V	0.555	-0.185	0.487	0.09
10.65 H	0.185	0.555	0.568	0.134
19.35 V	0	0	0.06	0.005
19.35 V	0	0	0.05	0.005
21.30 V	0	0	0.059	-0.025
37.00 V	0	0.1	0.073	-0.006
37.00 H	0.1	0	0.069	-0.001
85.50 V	0.1	0	0.049	-0.030
85.50 H	0.05	0.05	0.065	-0.010

TMI Subsystem Test Doc: Nov 07, 1994 (Outdoor test range)
Shiue Memo: 12-11-1997 (Measured by Hughes)

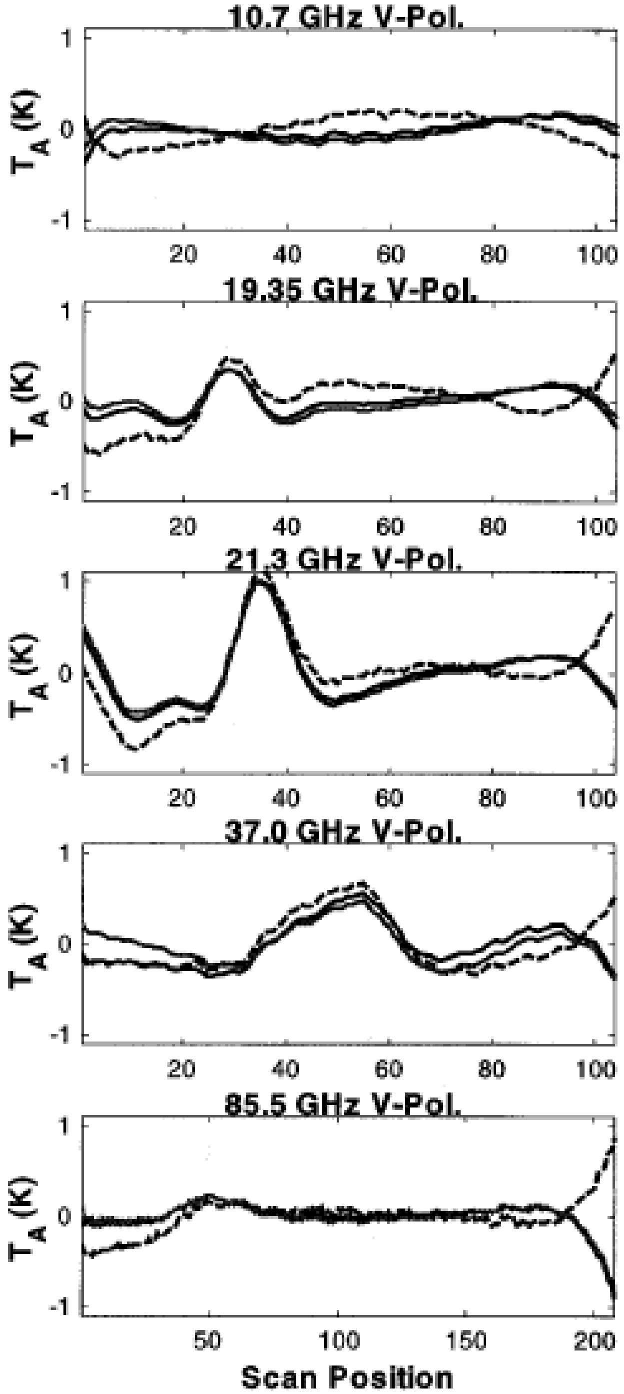
Convex & Concave Comparisons for 19 V-pol (DSCMs 1 to 10)

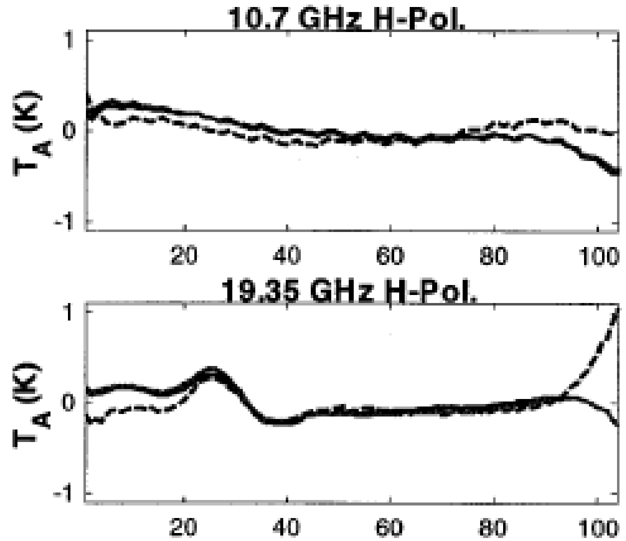




Back Up

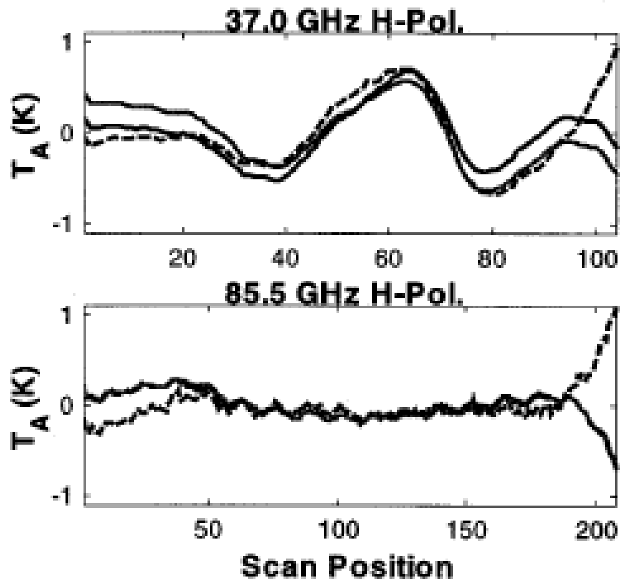
Along-scan Bias





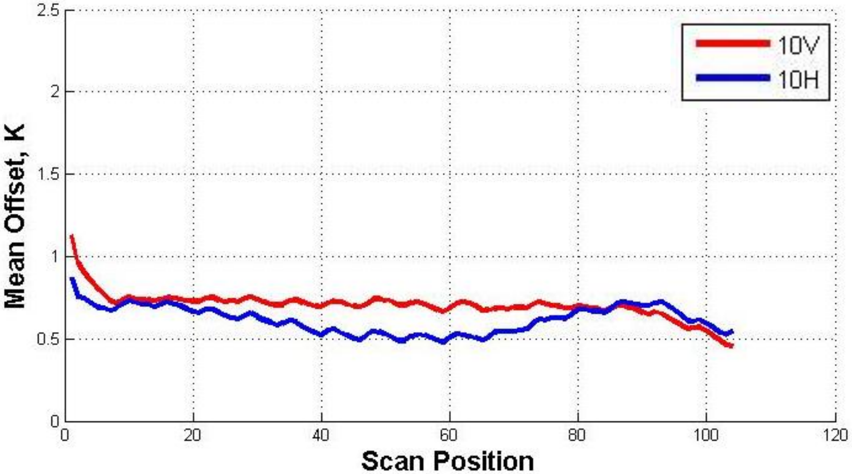
CFRSL

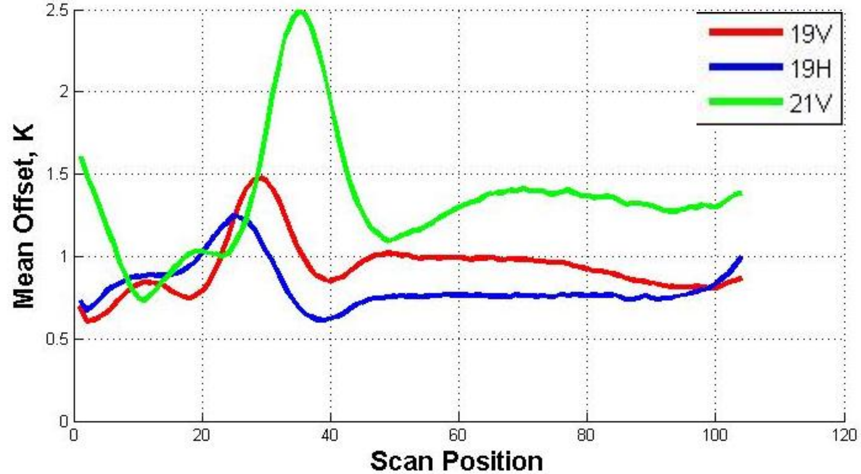
This is Wentz' Along-scan bias analysis for TMI's 9 channels. Comparison of the average along-scan error derived from ocean observations and from deep-space observations. The observed T_A anomaly is plotted versus scan position. The solid black and gray curves come from ocean observations for yaw orientations of 0 and 180, respectively, during 1998. **The dashed curves come from deep-space observations during January 1998**

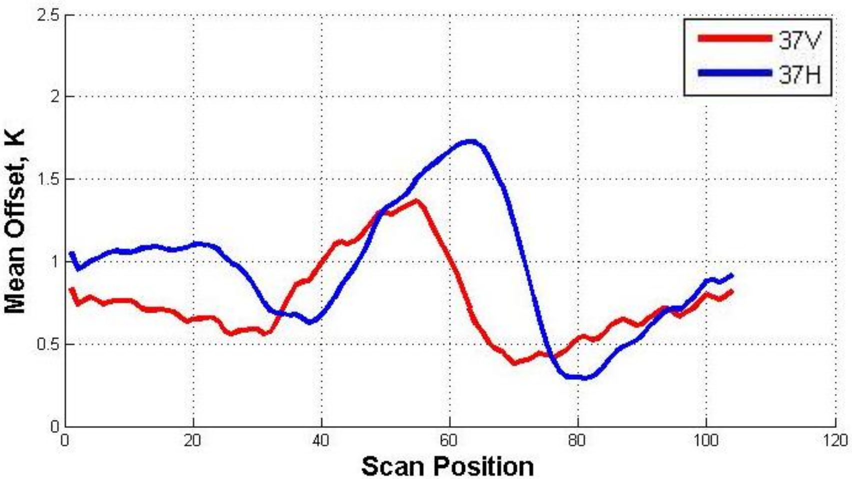


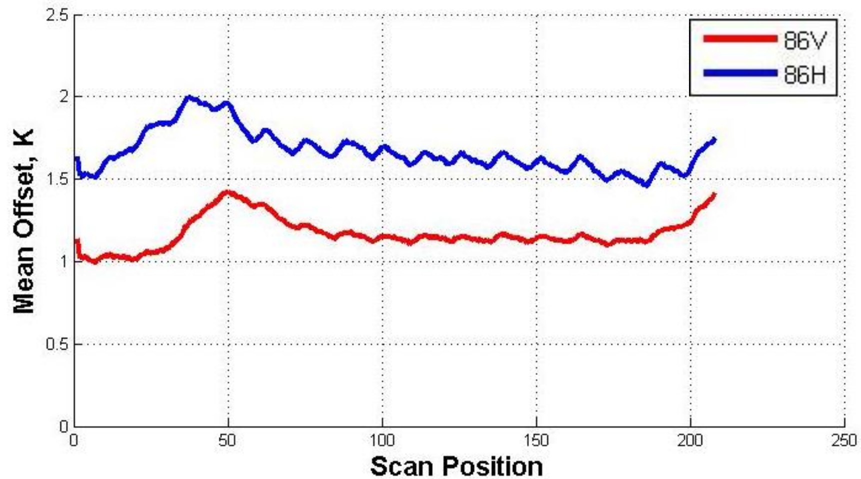
Full Range Data for DSCM
Set 1

Along Scan Bias

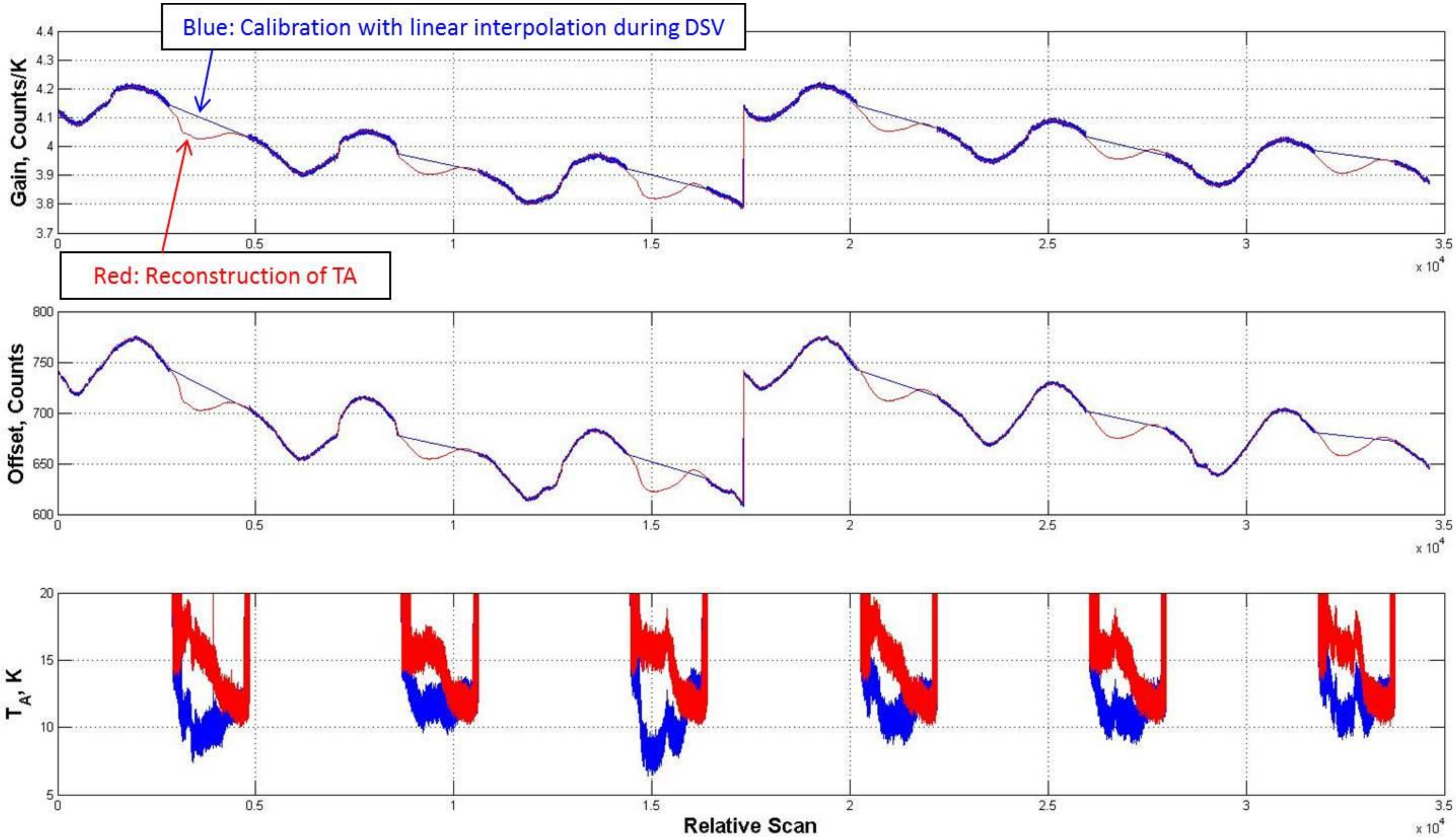




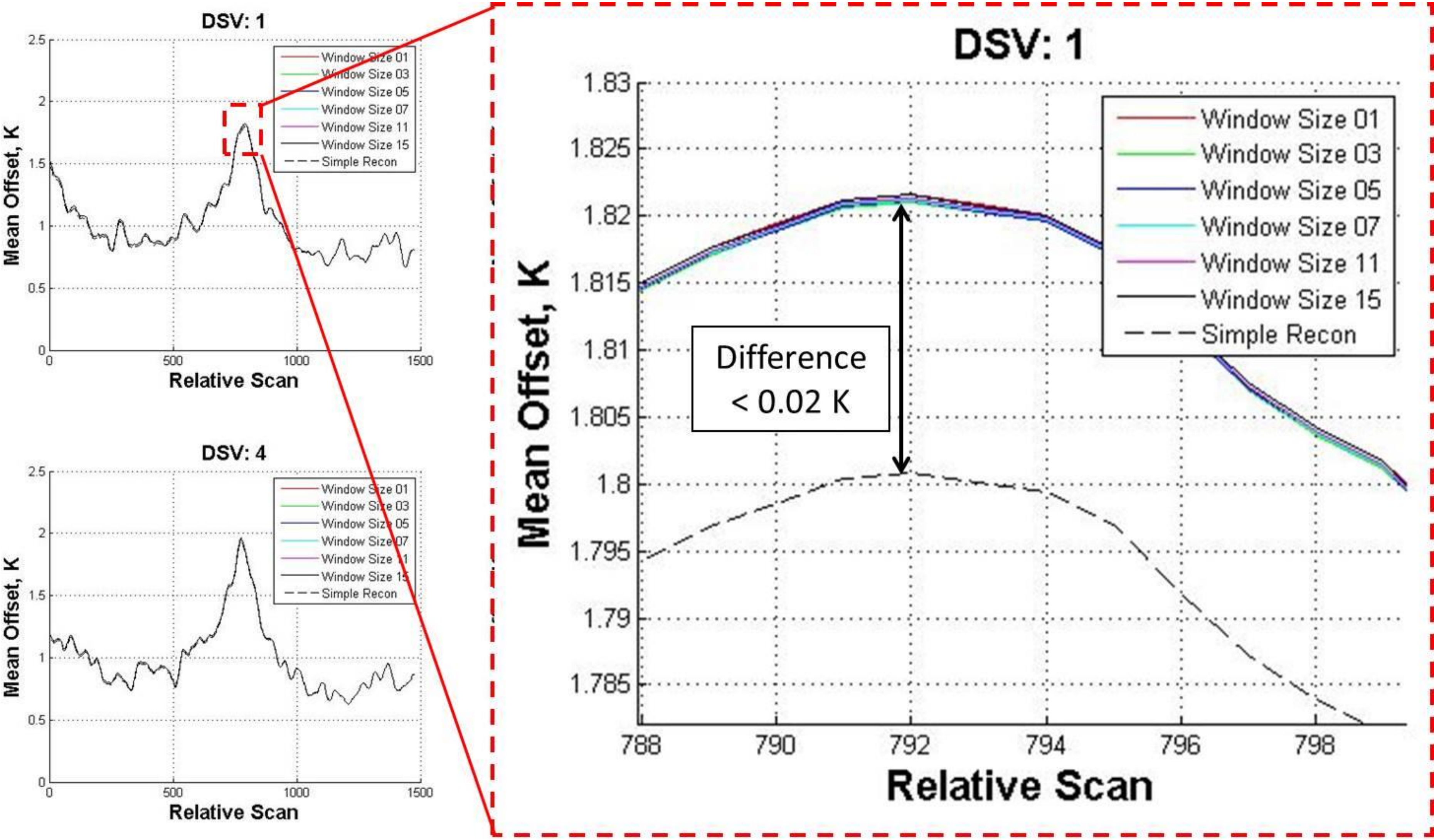




19 V-pol

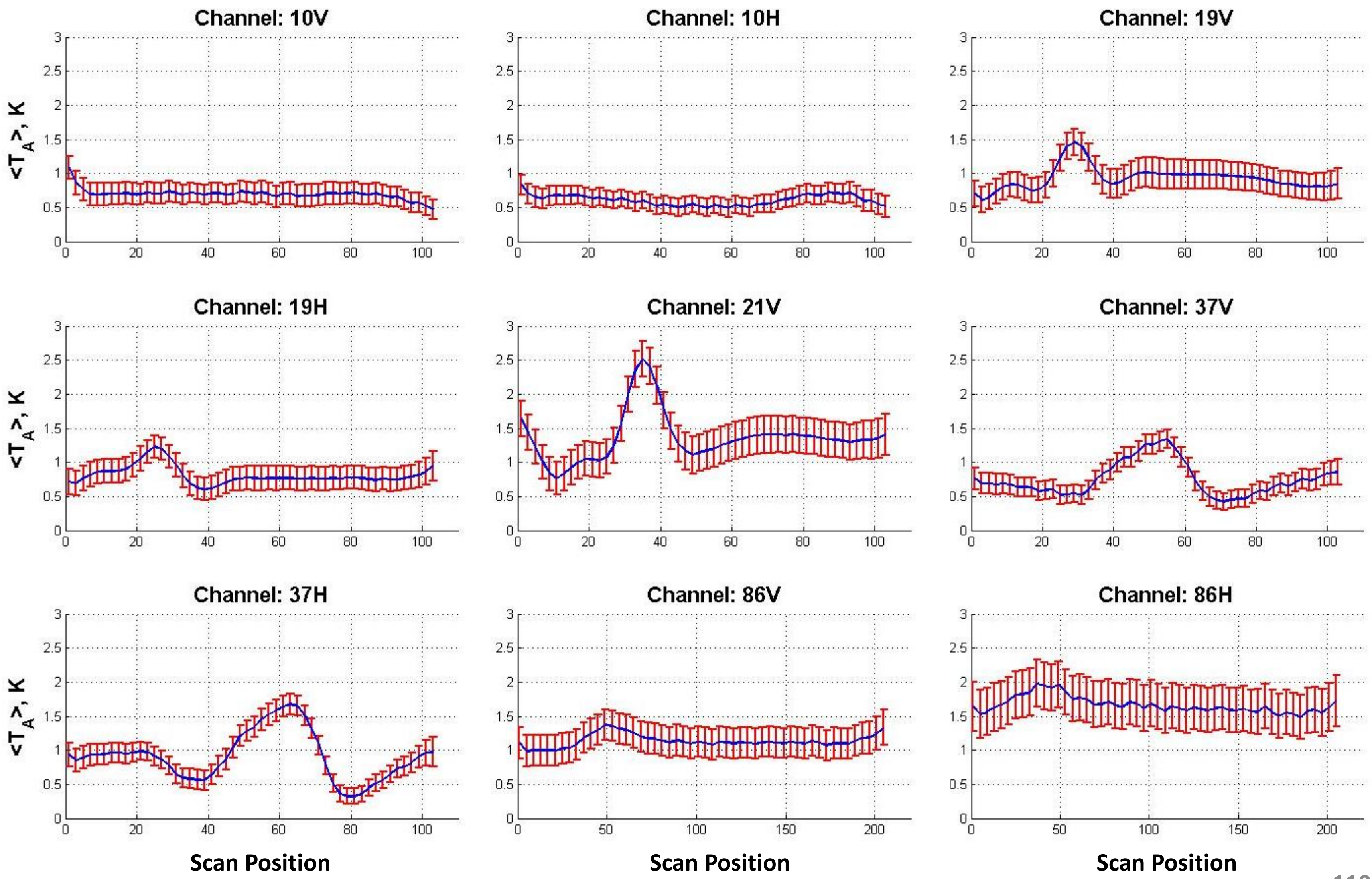

Blue: Calibration with linear interpolation during DSV
Red: Reconstruction of TA
Gain, Counts/K
Offset, Counts
T_A, K
Relative Scan
x 10^4

Insensitivity of Along-Scan Analysis to Reconstruction Errors

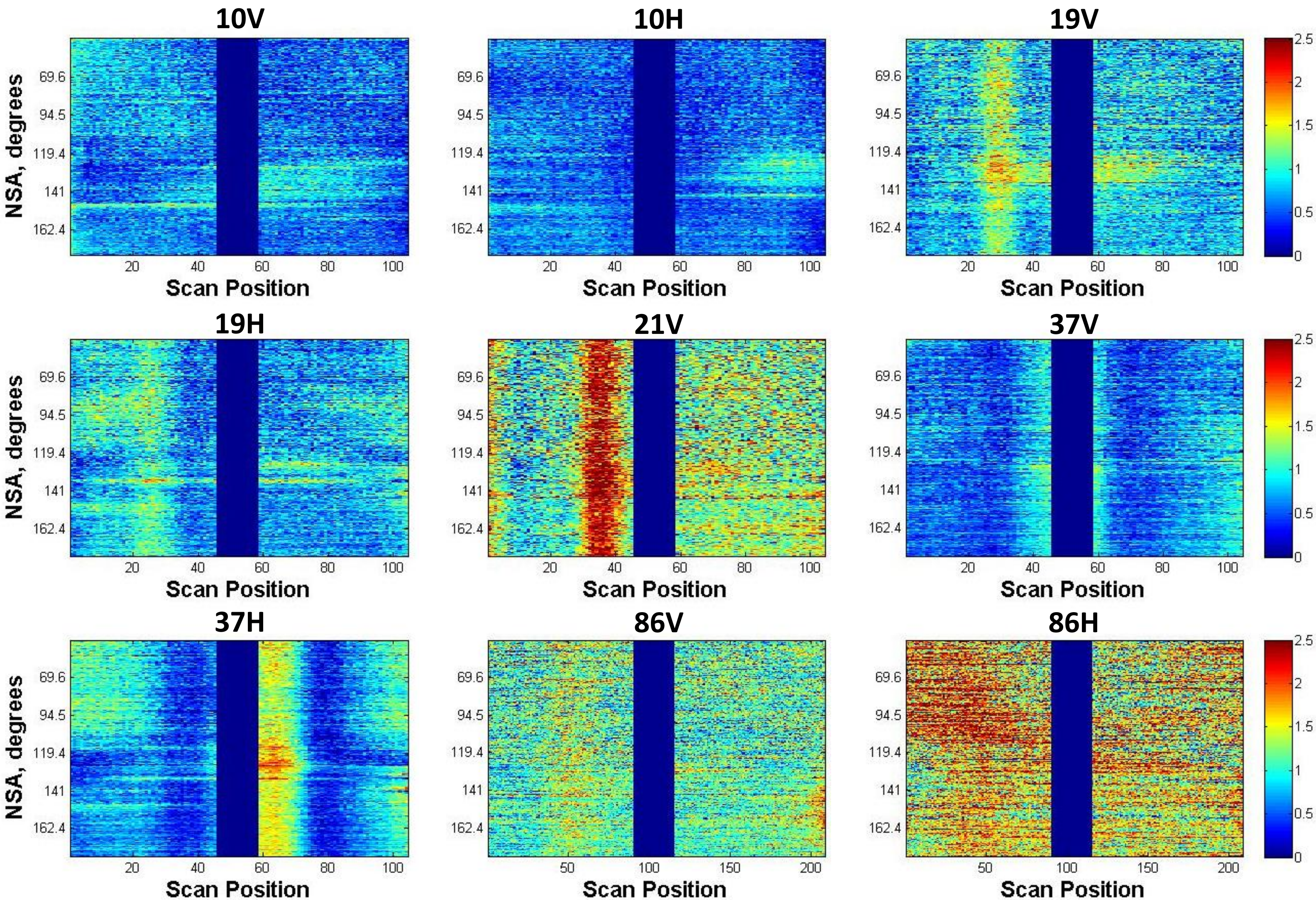


Combined DSC Sets

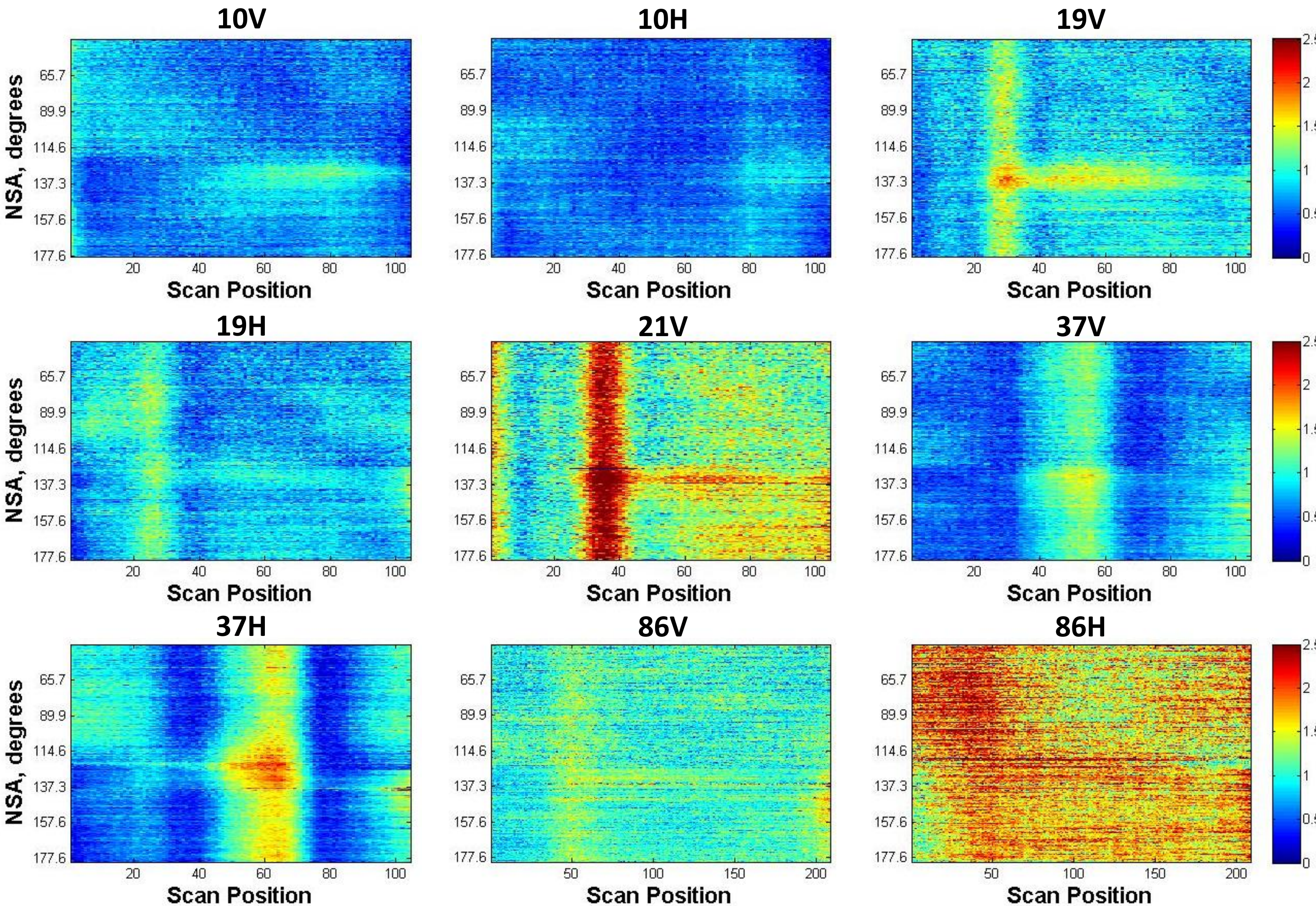
Limited Range Data
Bars length = 1σ



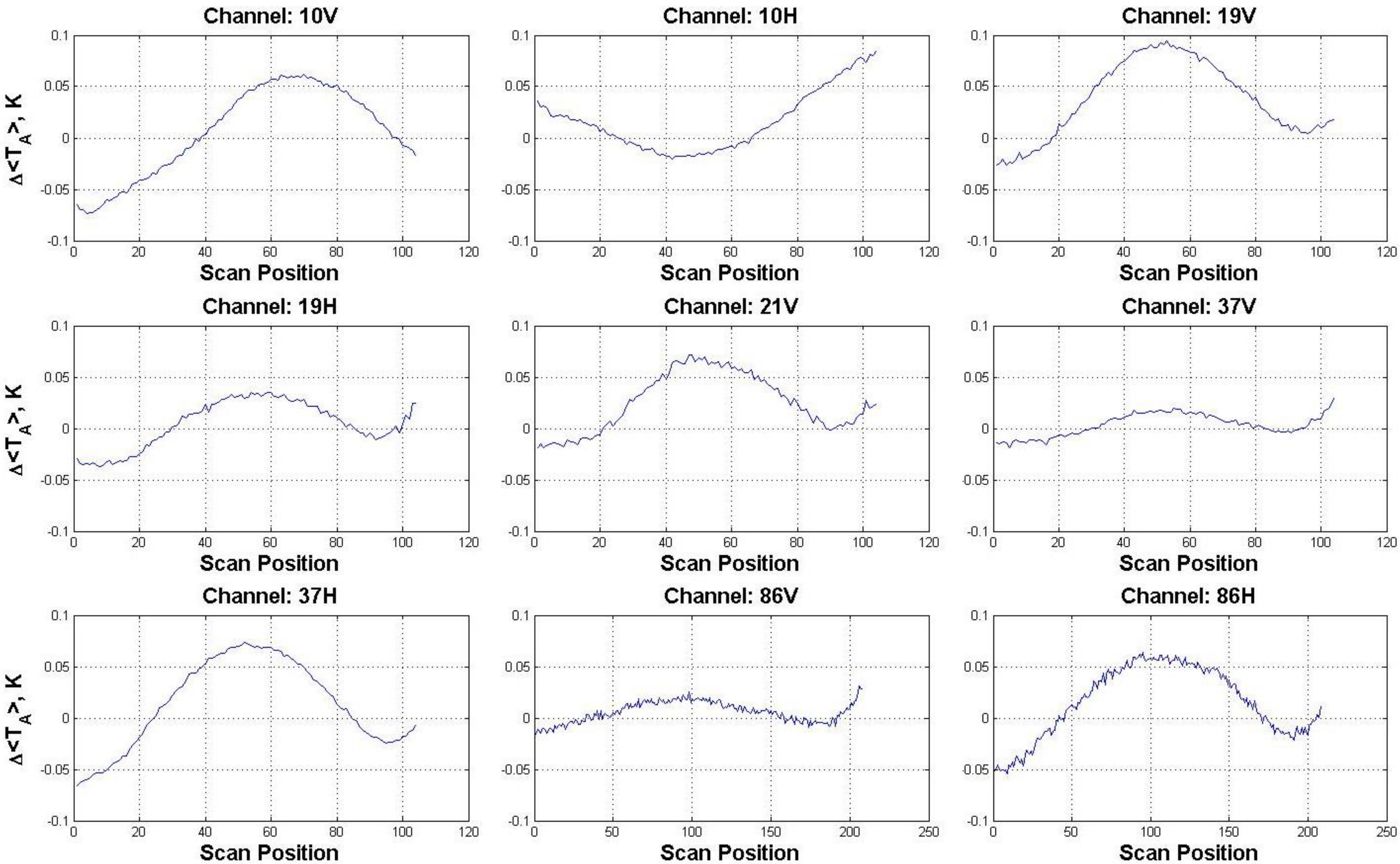
DSCM Set 2 – Averaged w.r.t. NSA



DSCM Set 3 – Averaged w.r.t. NSA



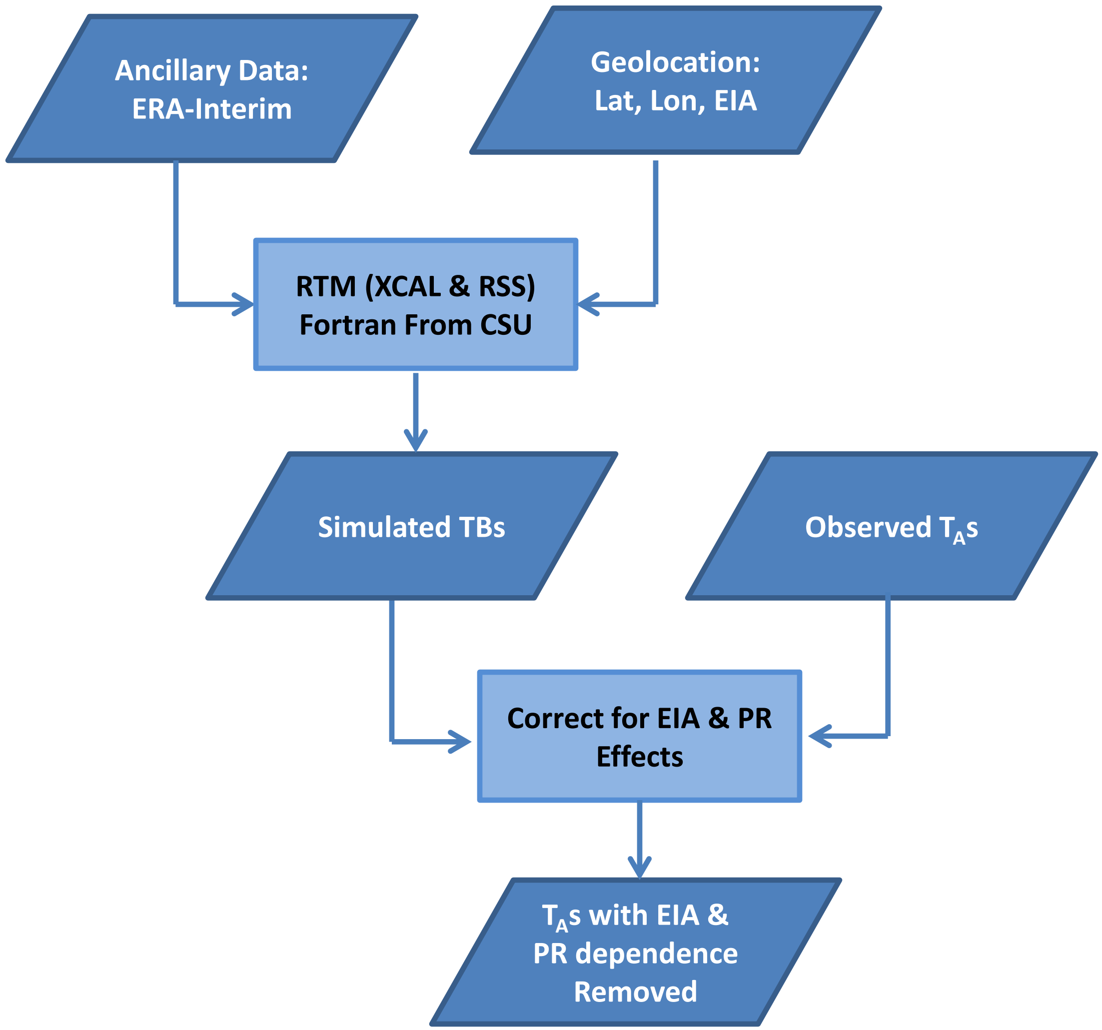
Comparing Biases for Range of Scans

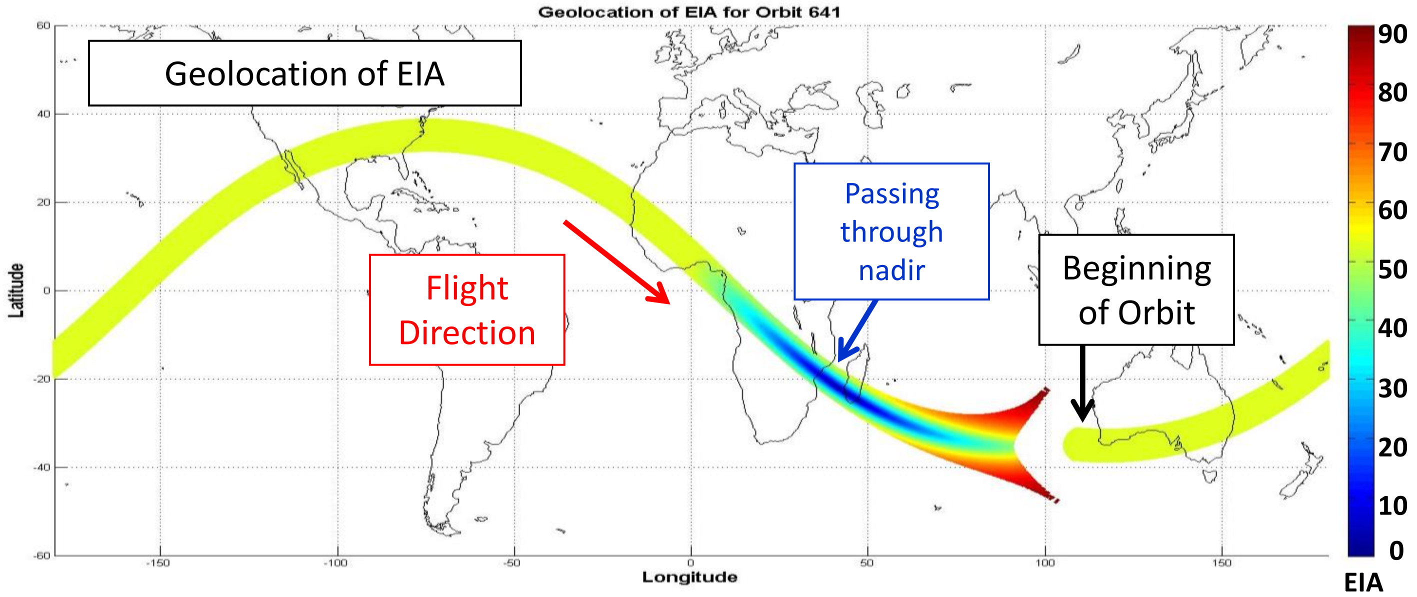


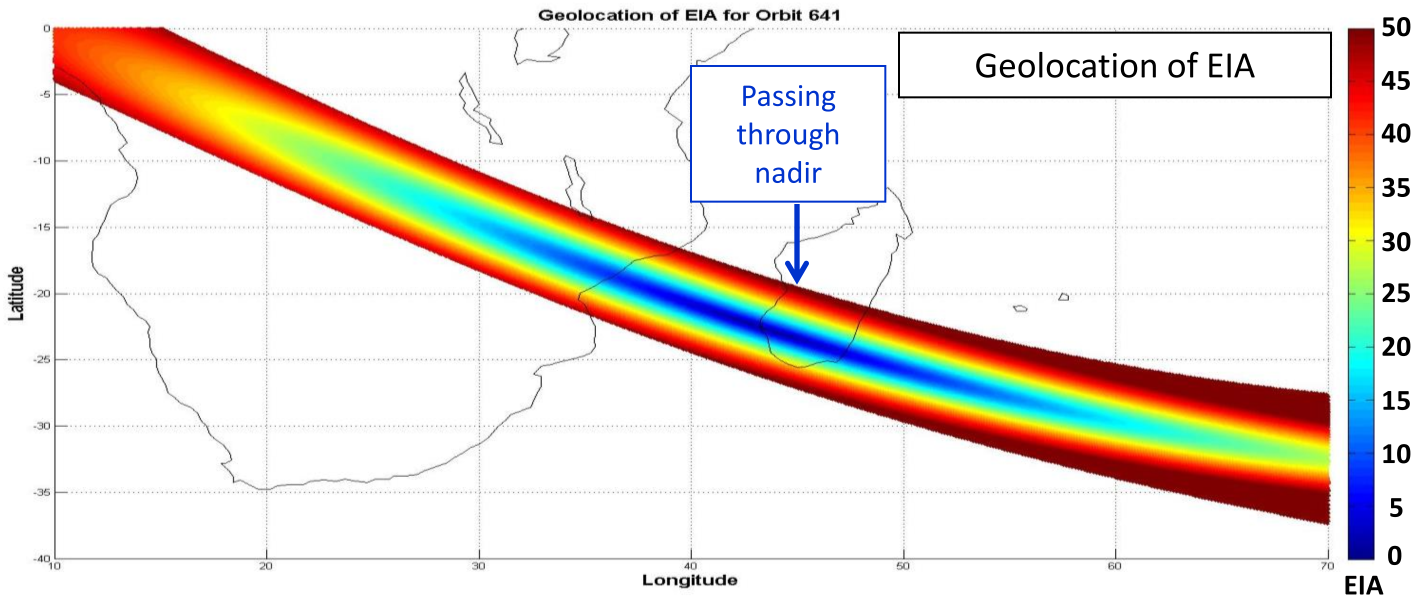
Back Up

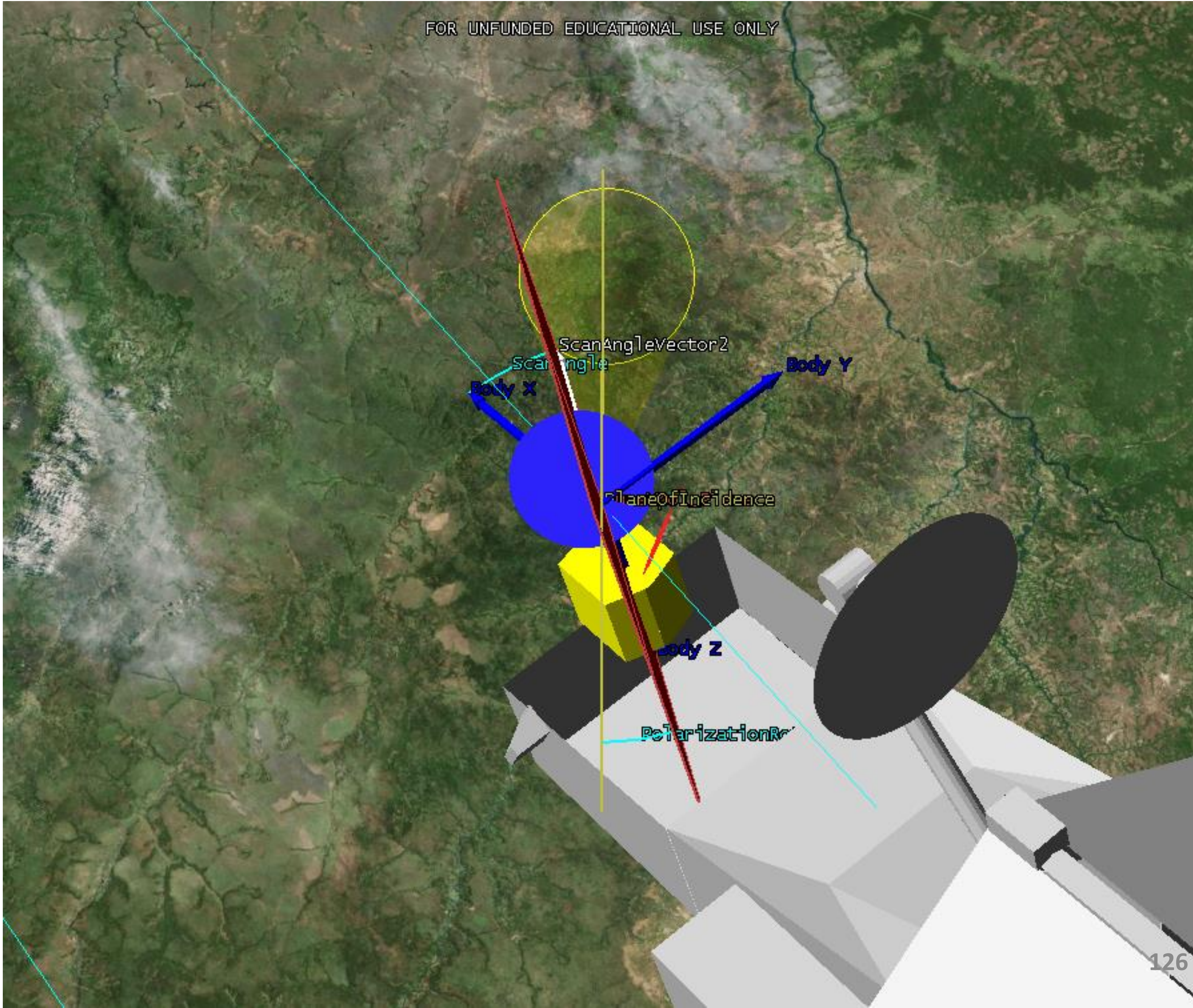
Second Stokes Analysis

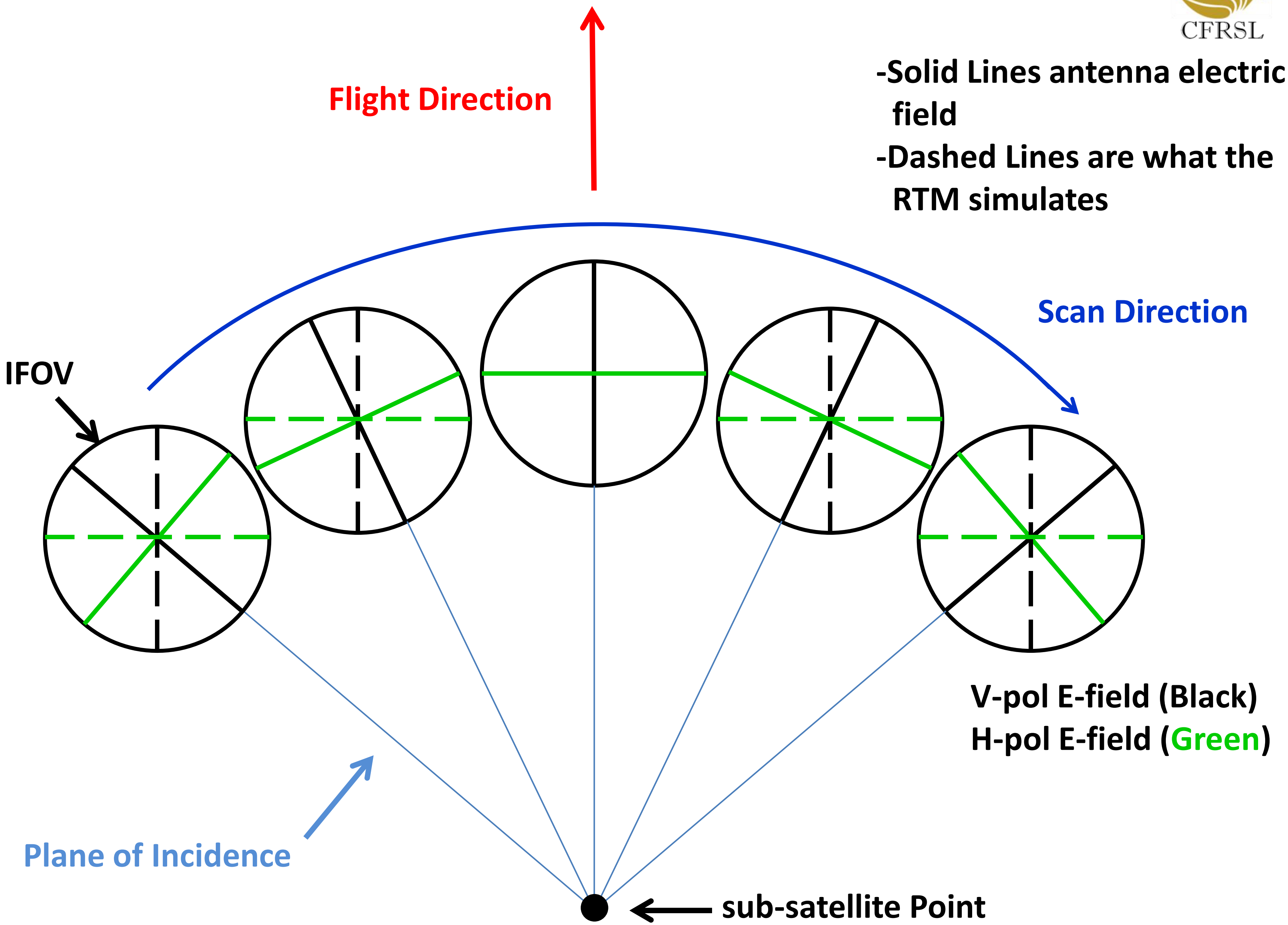
SS Analysis Over Ocean Flow Chart



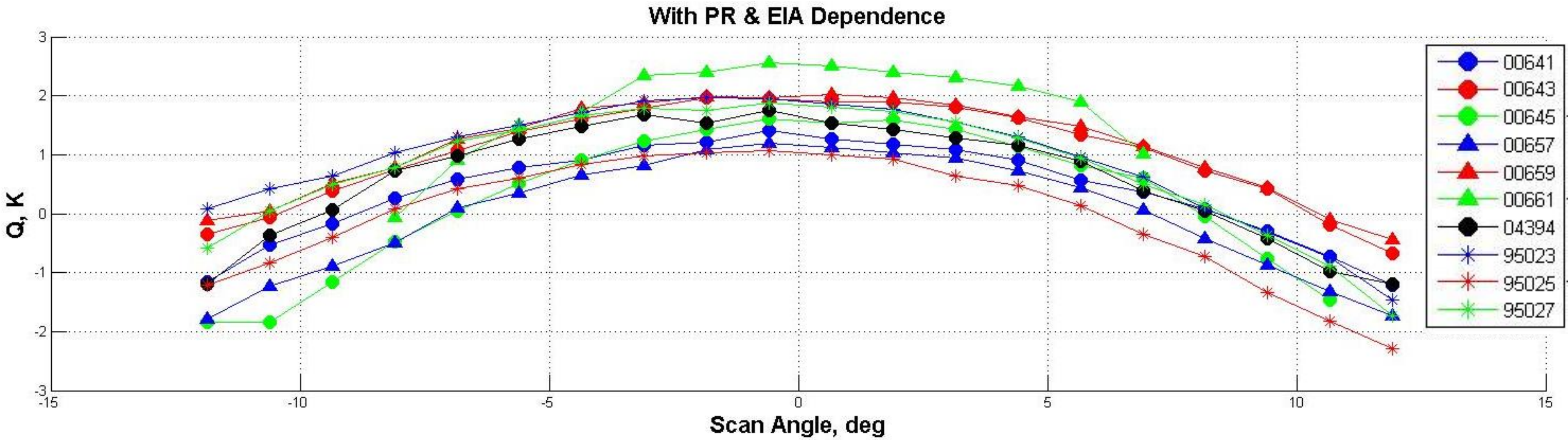

Geolocation of EIA for Orbit 641
Geolocation of EIA
Flight Direction
Passing through nadir
Beginning of Orbit
Latitude
Longitude
EIA

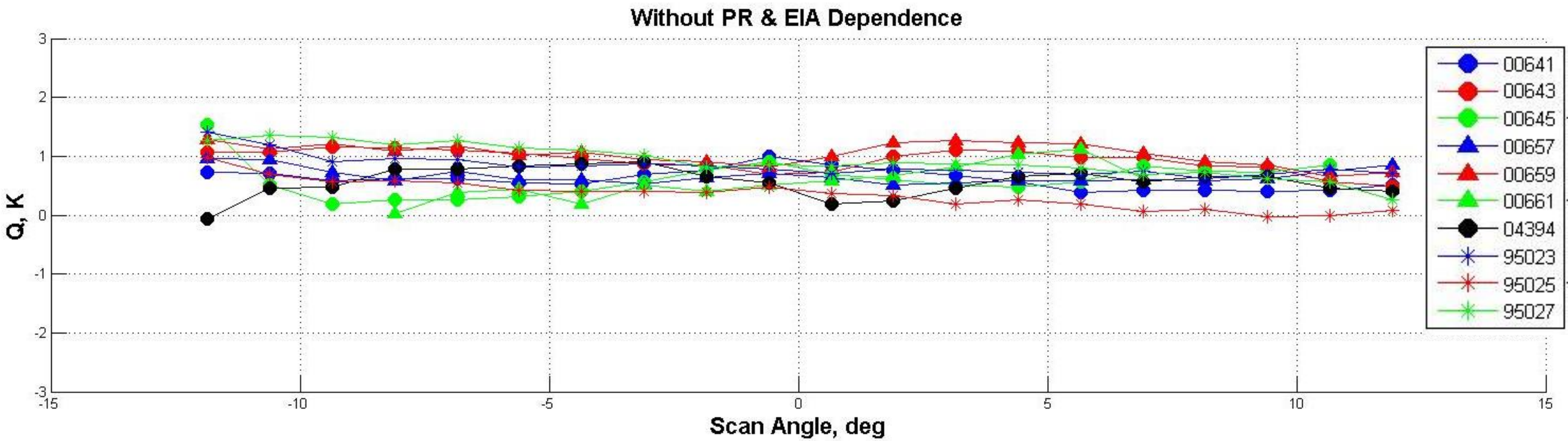

Geolocation of EIA for Orbit 641
Geolocation of EIA
Passing through nadir
Latitude
Longitude
EIA


FOR UNFUNDED EDUCATIONAL USE ONLY
ScanAngleVector2
Body Y
Body X
PlaneOfIncidence


-Solid Lines antenna electric field
-Dashed Lines are what the RTM simulates
Flight Direction
Scan Direction
IFOV
V-pol E-field (Black)
H-pol E-field (Green)
Plane of Incidence
sub-satellite Point

Before & After Correction: 11 GHz

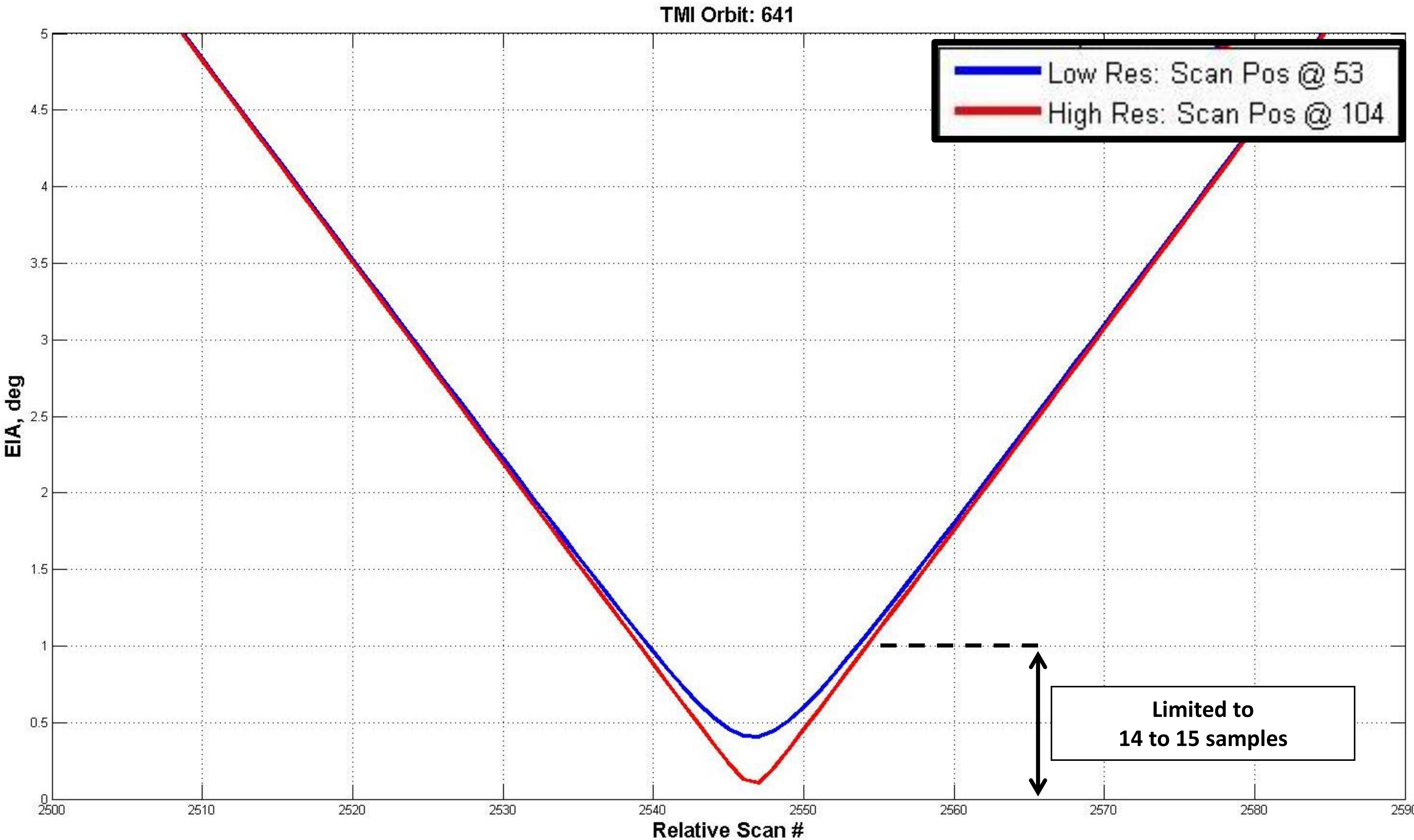




Thinking of
Removing

Sweeping Through Nadir

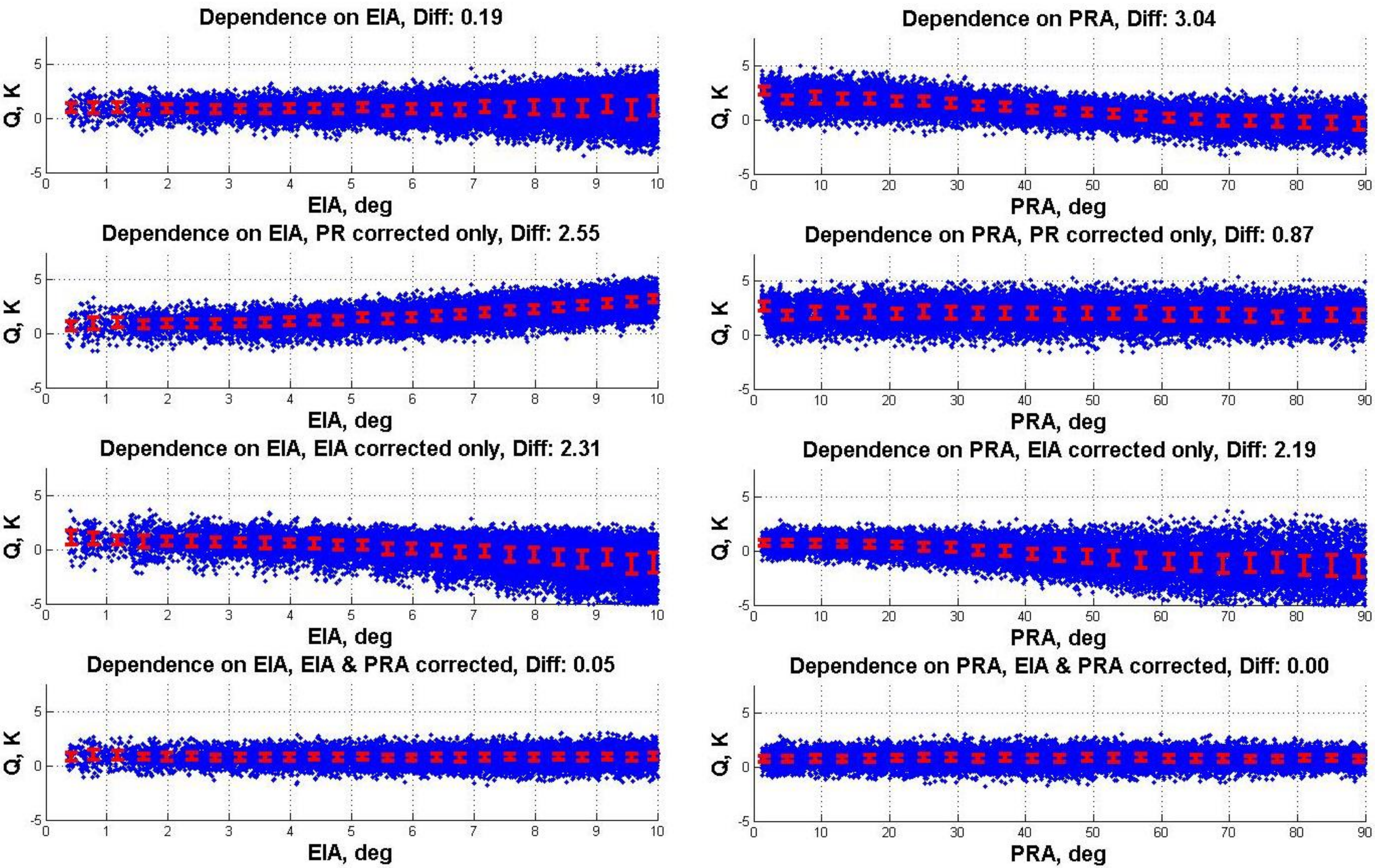
CFRSL



High Res Scan Angle Increment: 0.63°

Thinking of
Removing

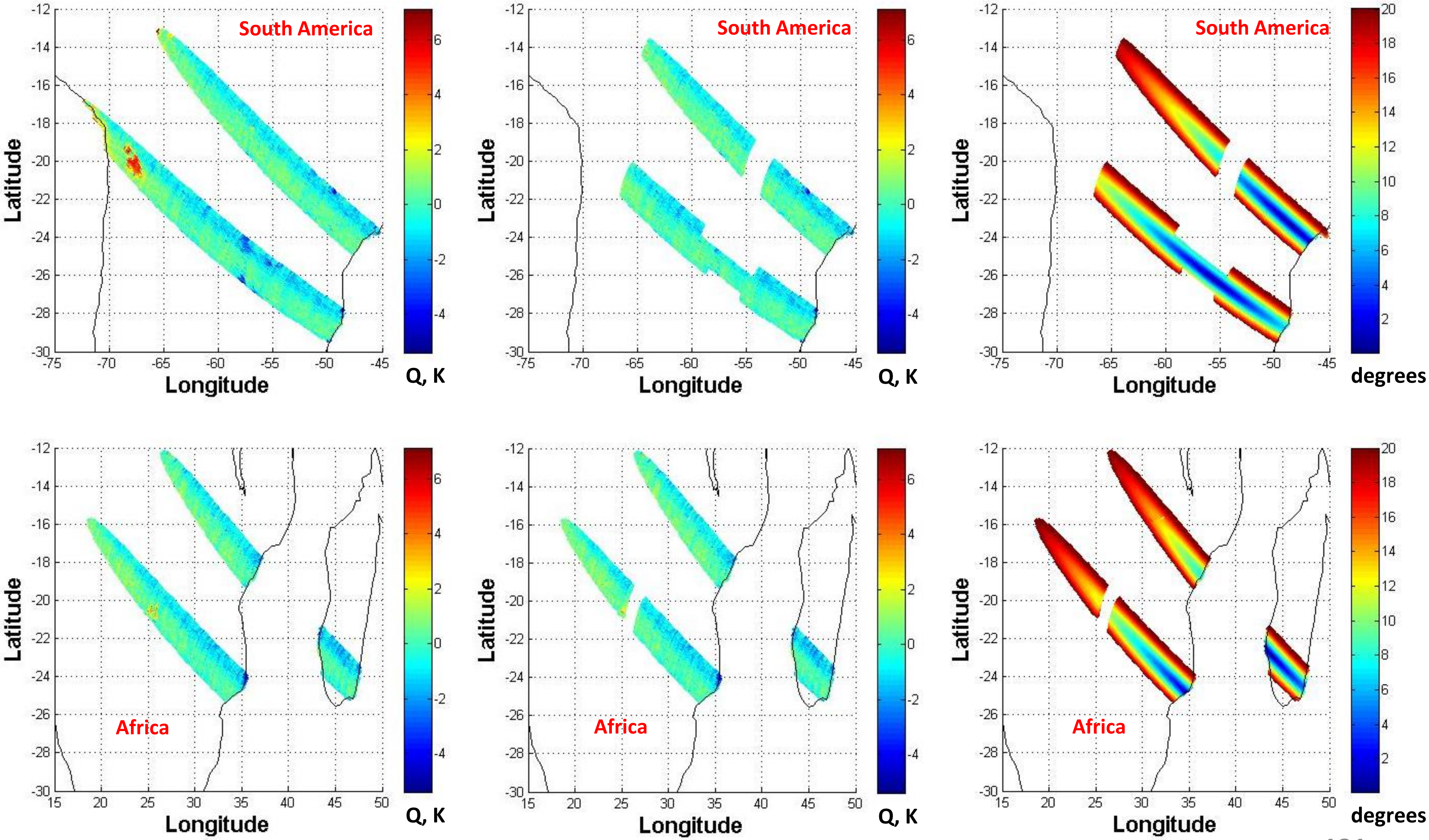
11 GHz



Geolocation of Q Over Land

CFRSL

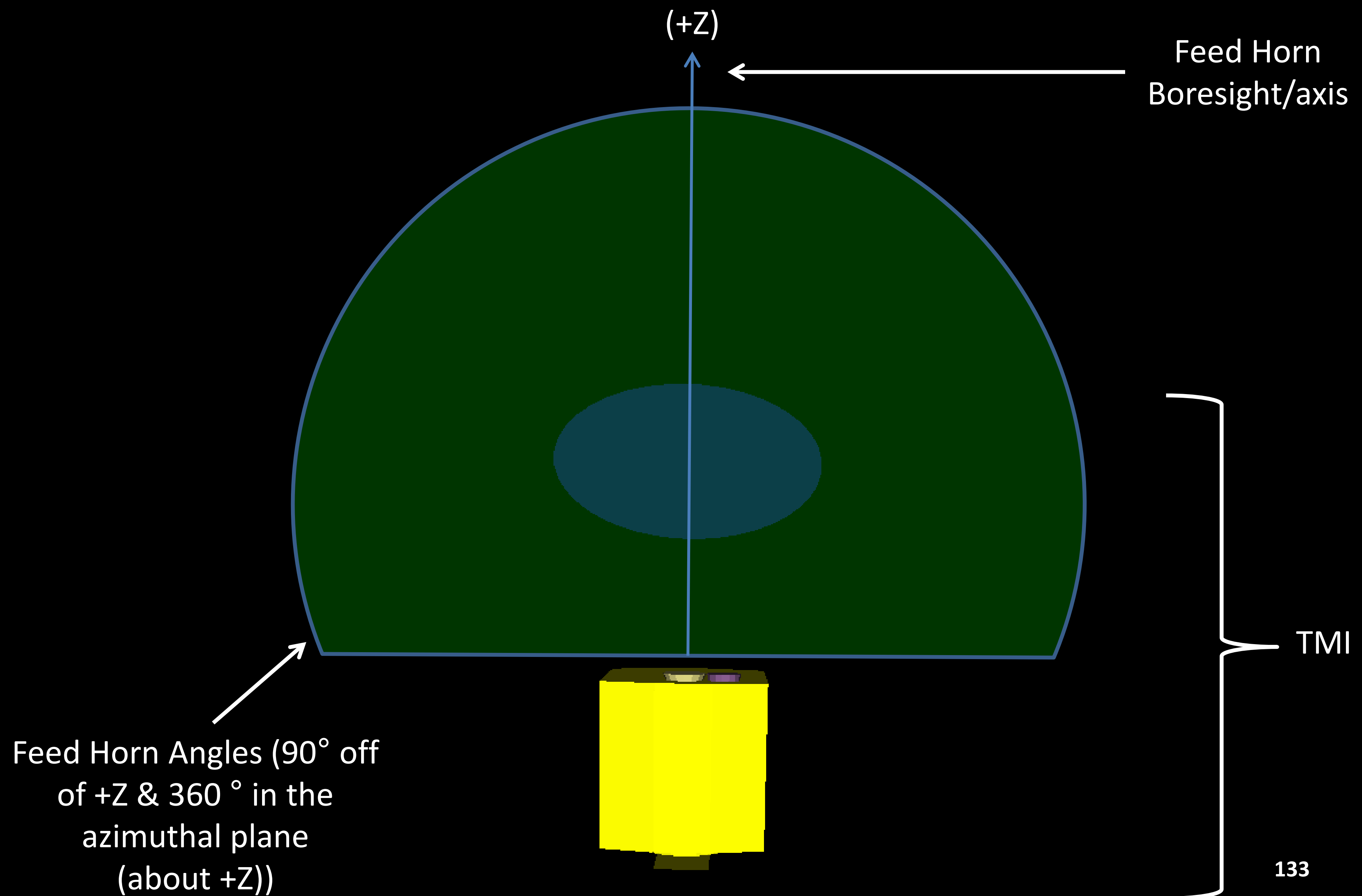
Q at 37GHz Before Removal Of Contaminated Areas | **Q at 37GHz After Removal Of Contaminated Areas** | **EIA After Removal Of Contaminated Areas**

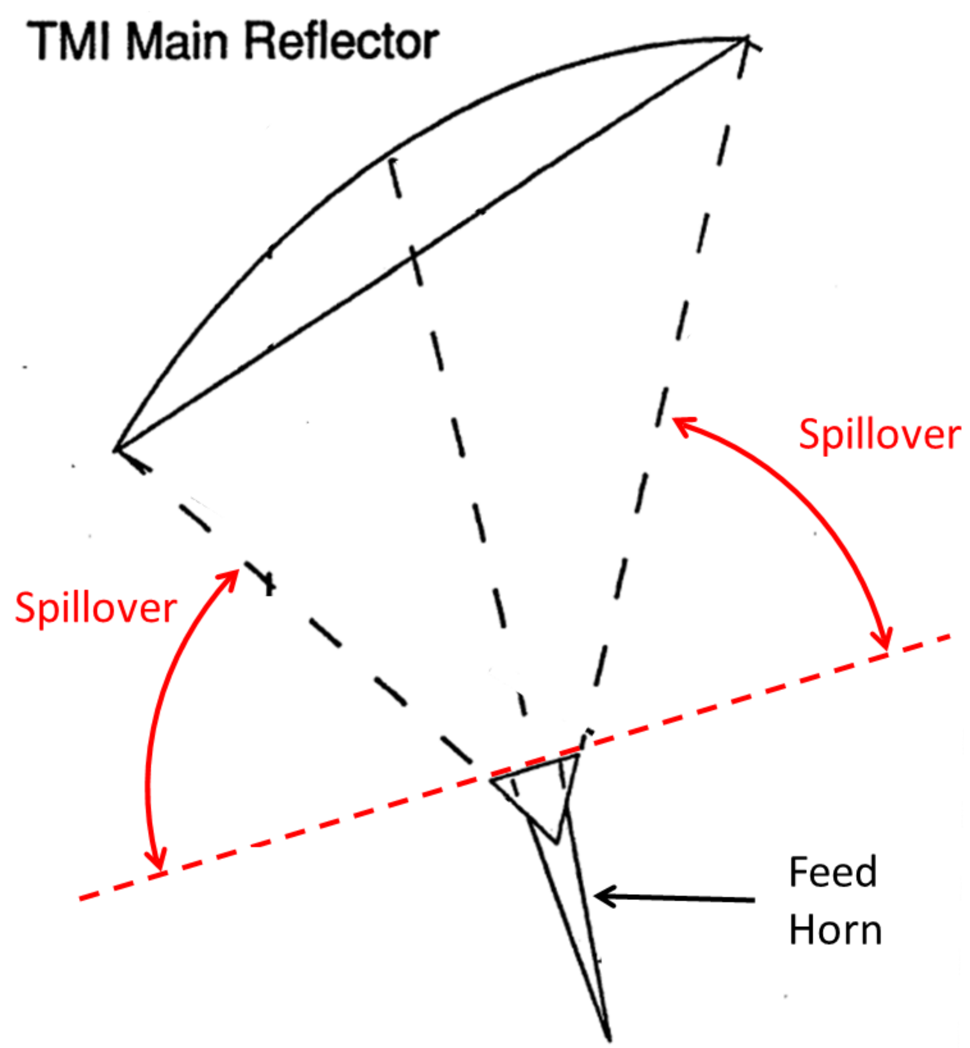


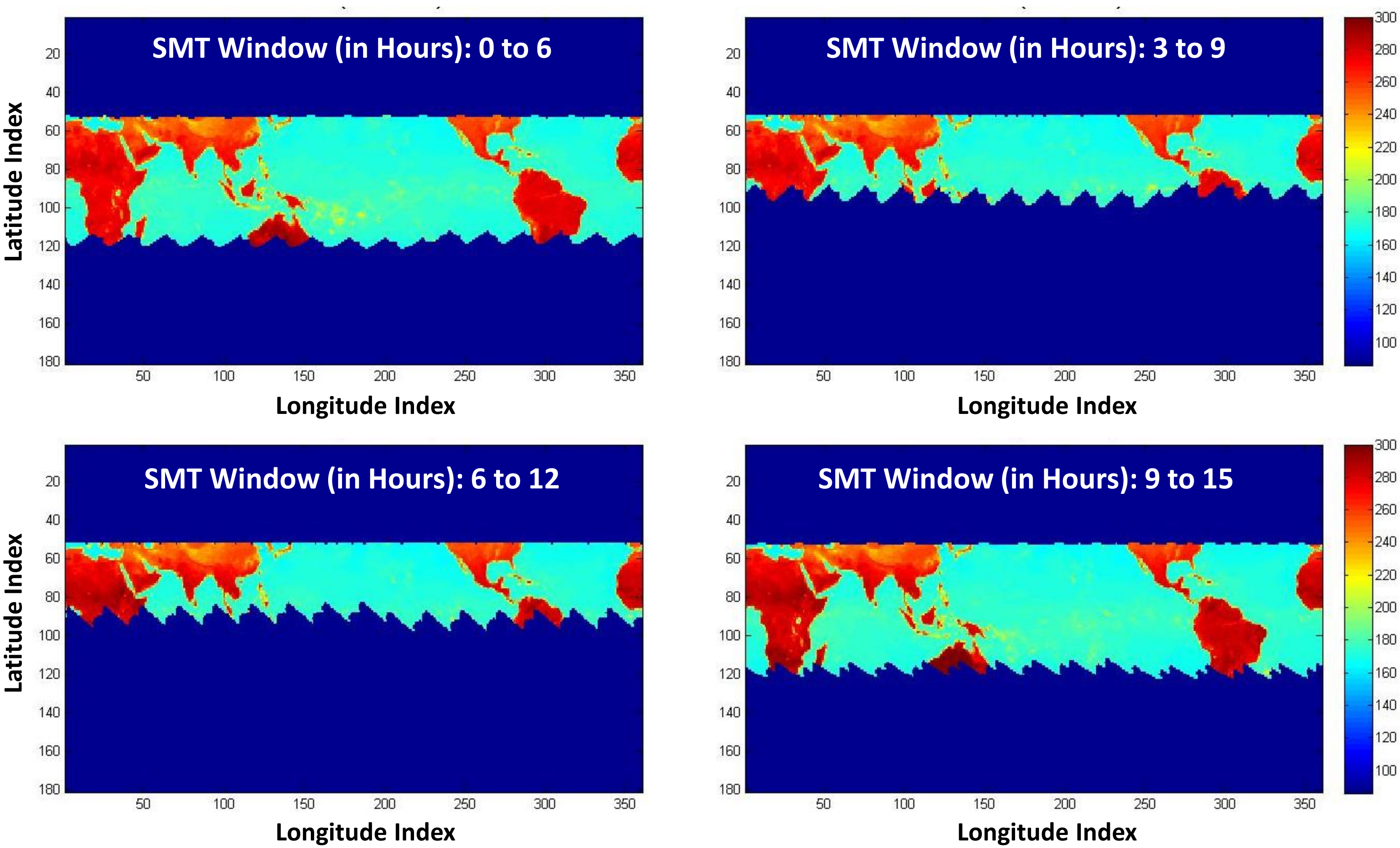
Back Up

Emissivity

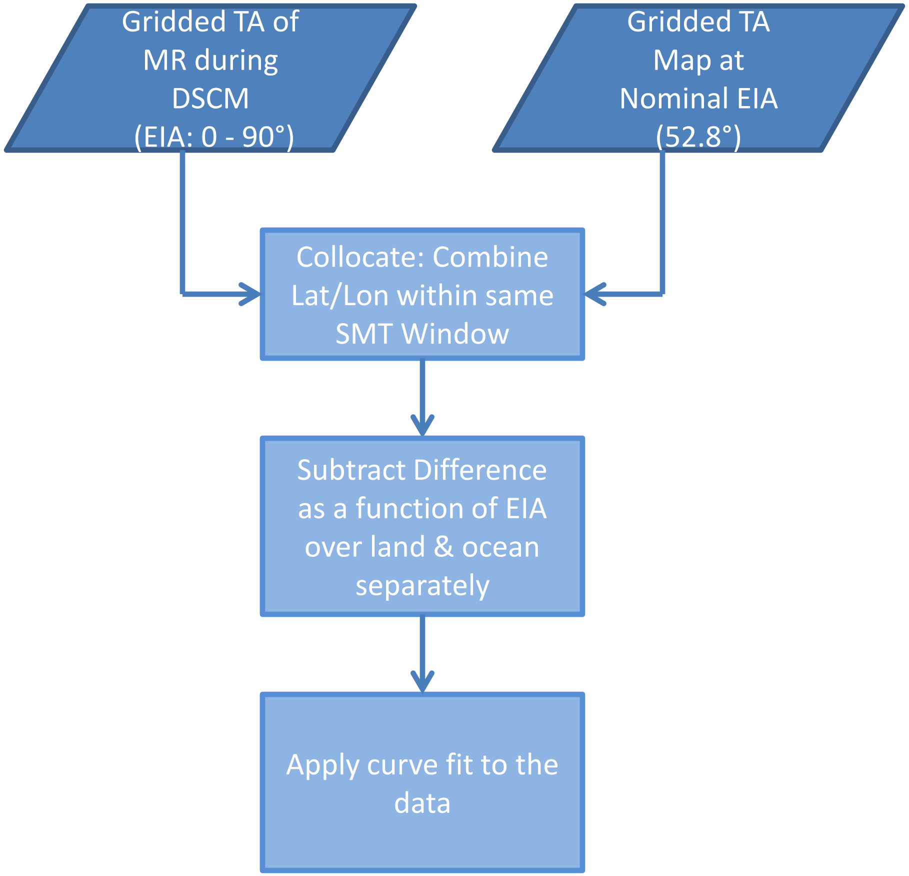
Angles Feed Horn is Defined As



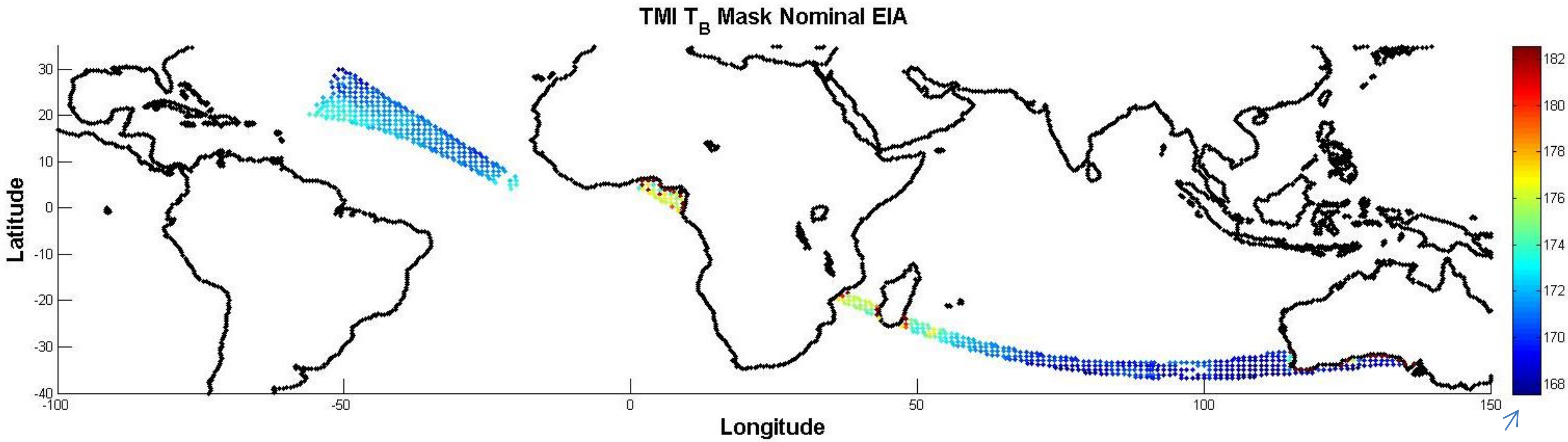

TMI Main Reflector
Spillover
Spillover
Feed
Horn


SMT Window (in Hours): 0 to 6
SMT Window (in Hours): 3 to 9
SMT Window (in Hours): 6 to 12
SMT Window (in Hours): 9 to 15
Latitude Index
Longitude Index

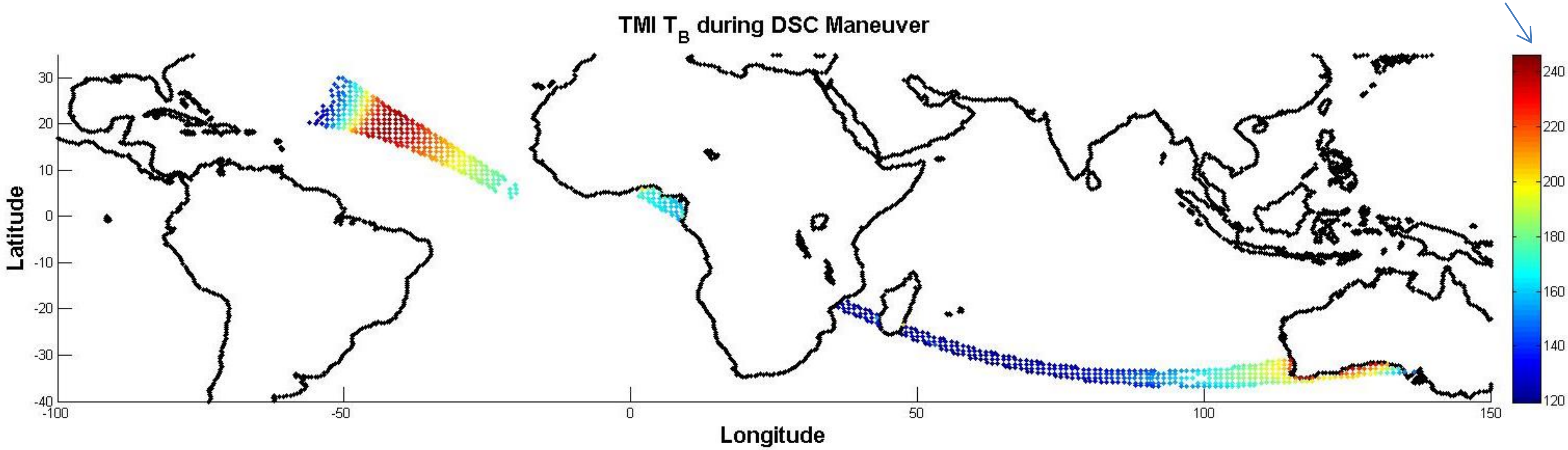
Empirical Method Flow Chart



Orbits: 641 & 642 (Ocean)



Different color scale



Orbits: 641 & 642 (Land)

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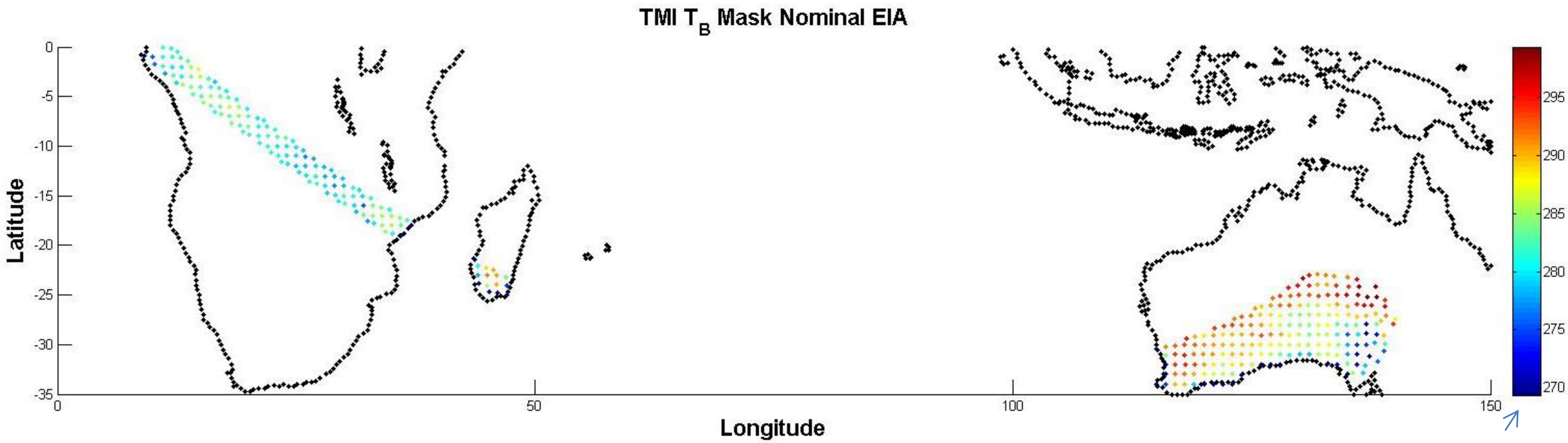
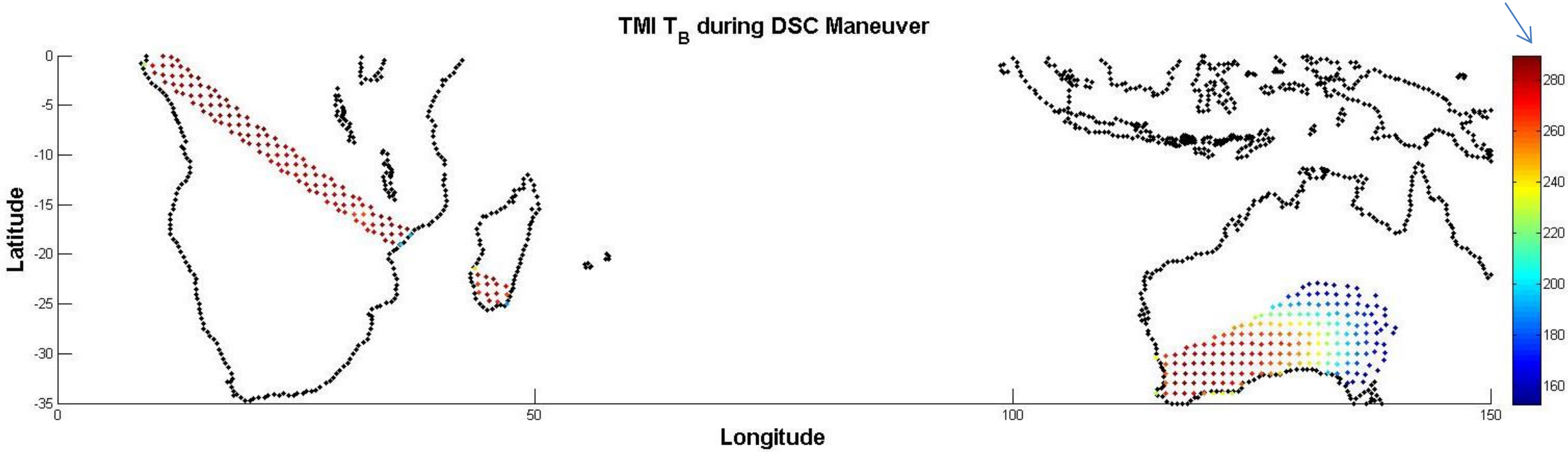
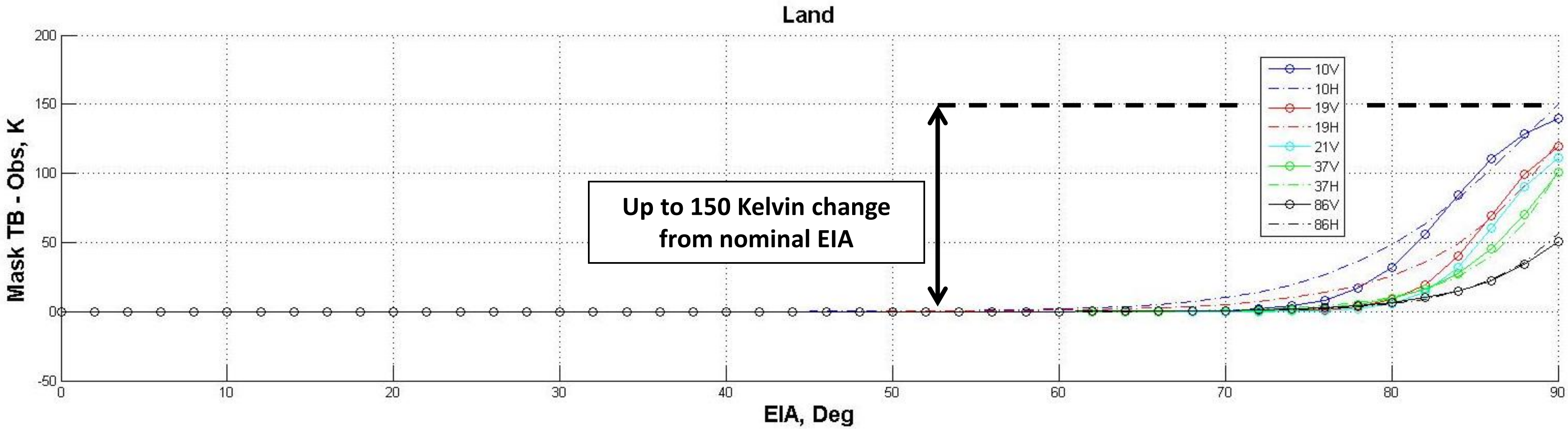
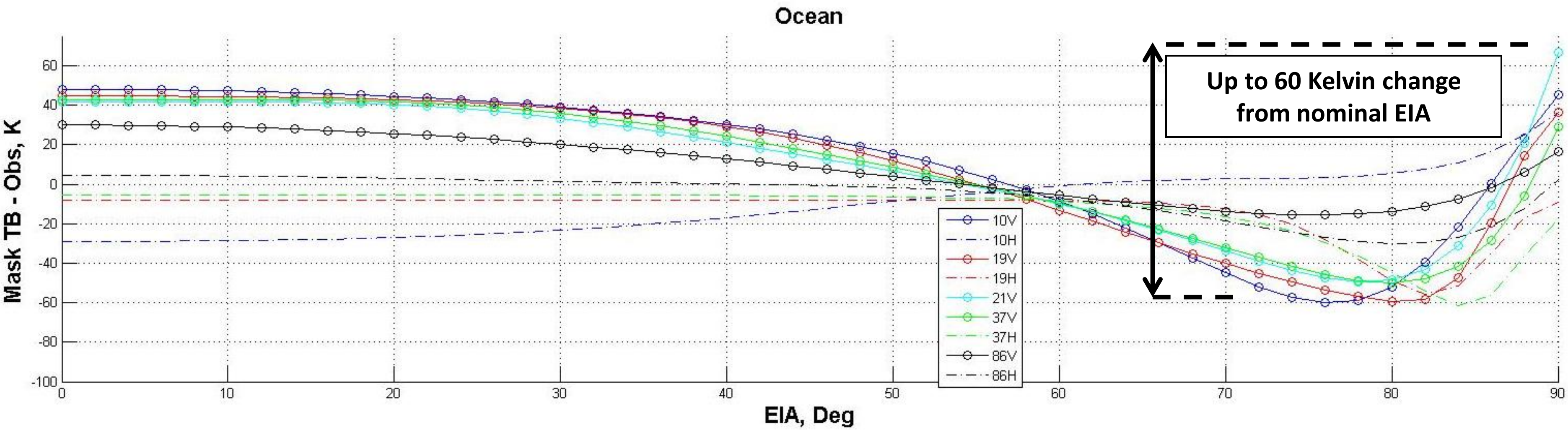


Different color scale

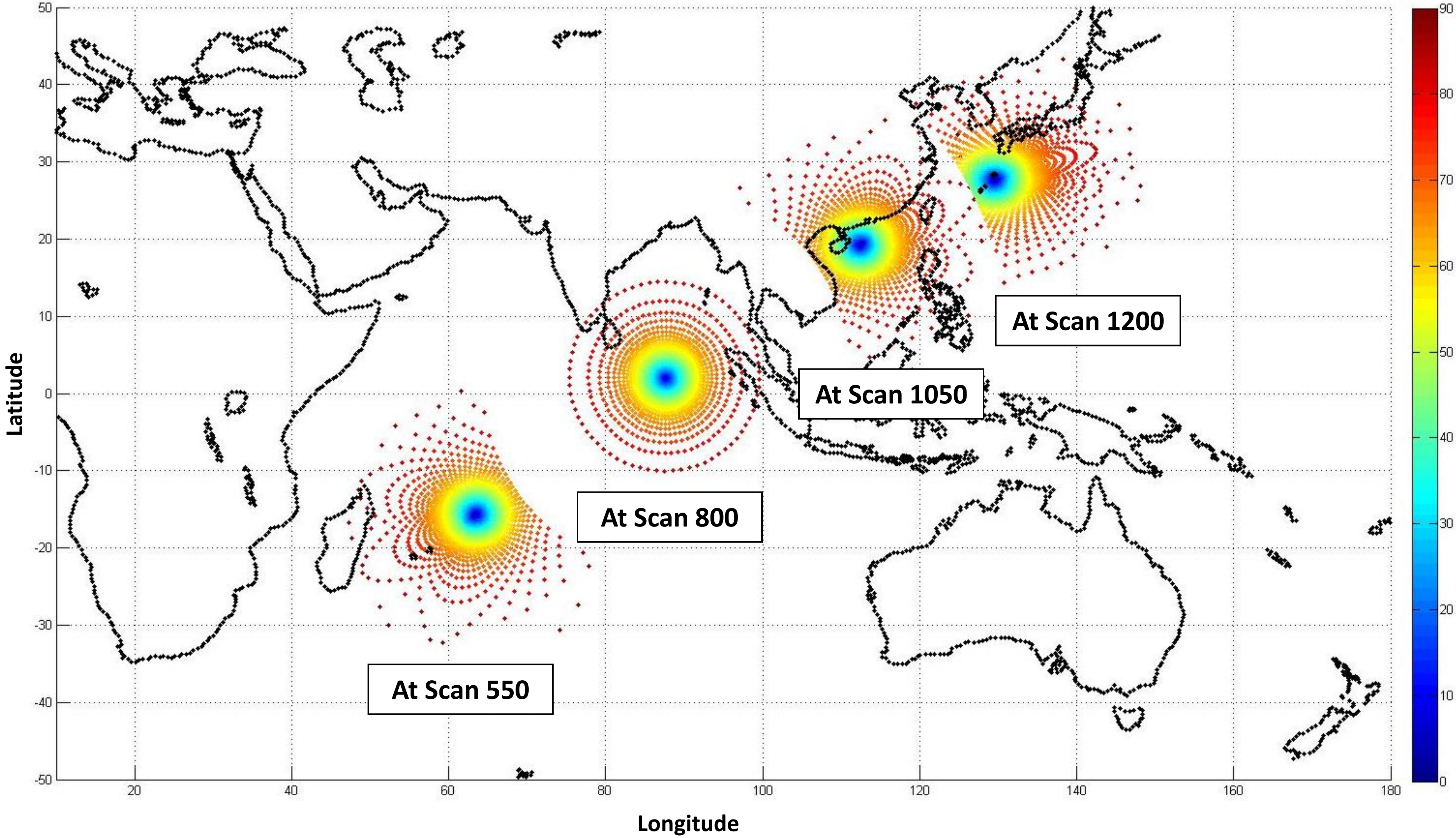


T_B to EIA Empirical Relationship





EIA of Spillover



Matching Simulated T_A to Truth: 10V

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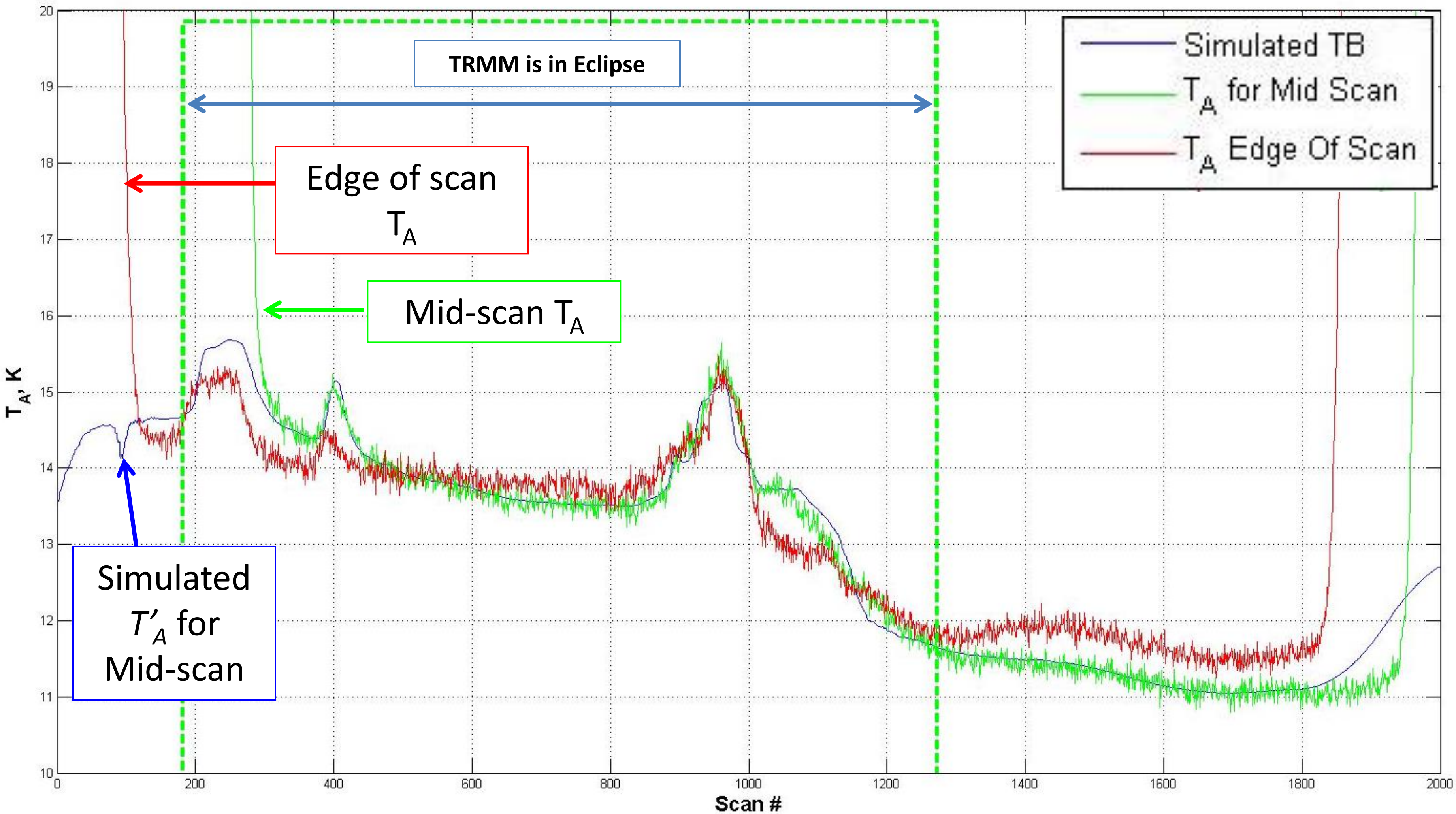
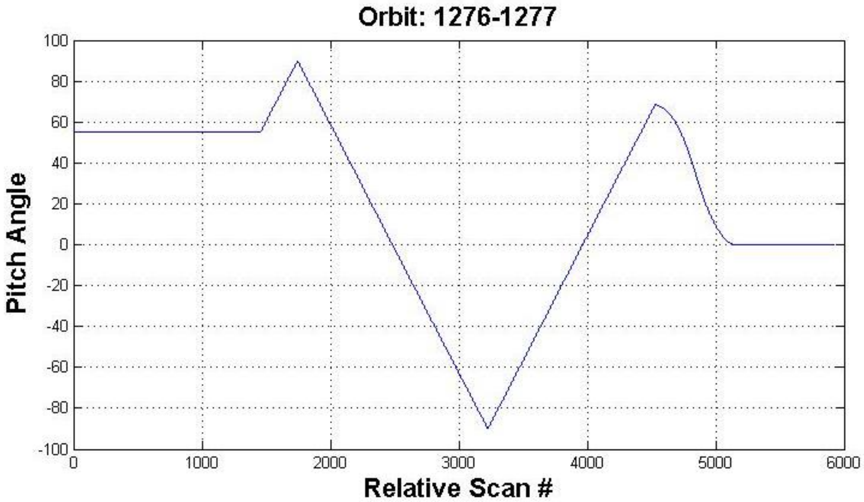
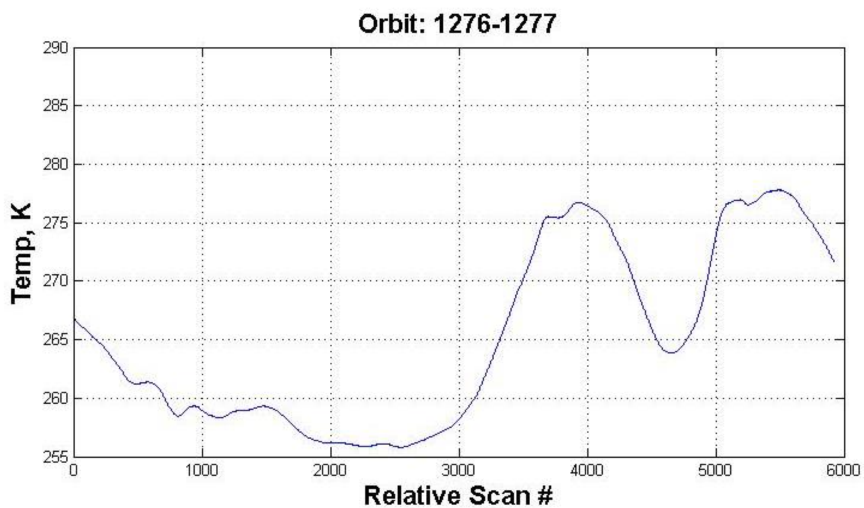


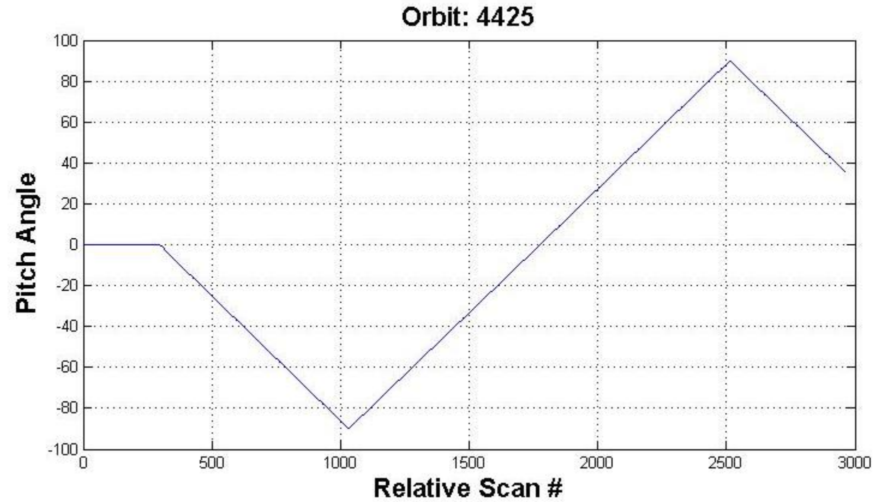
GMI MR Physical Temperature: Inertial Holds

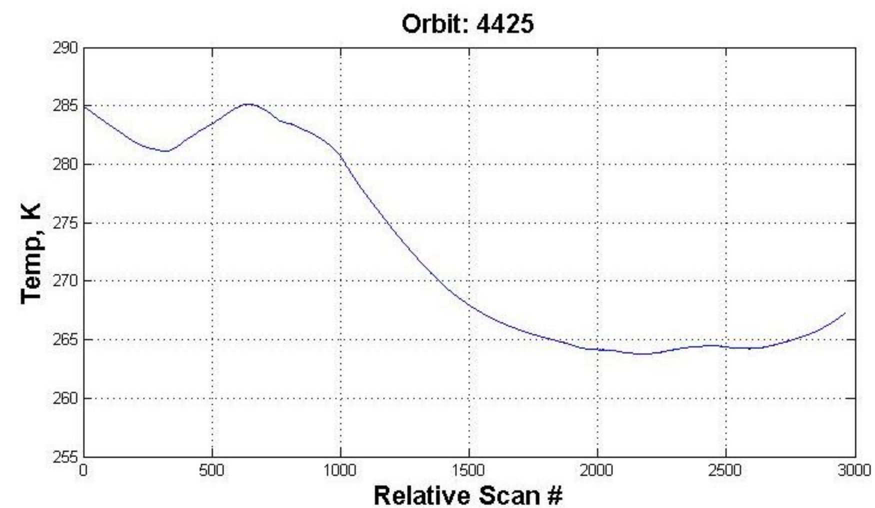
May 20, 2014 Maneuvers



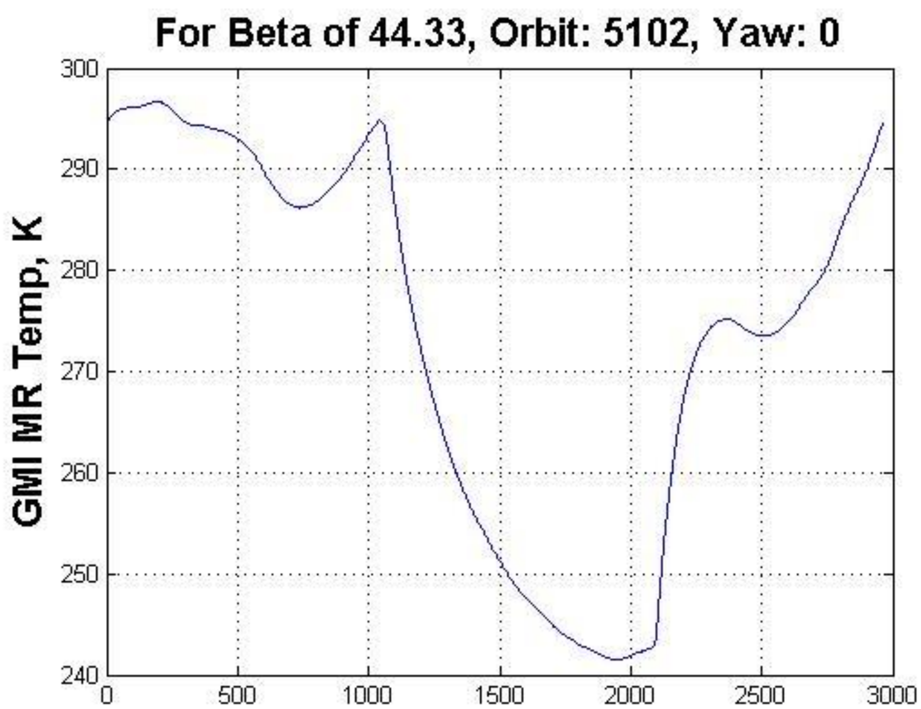


Dec 09, 2014 Maneuvers

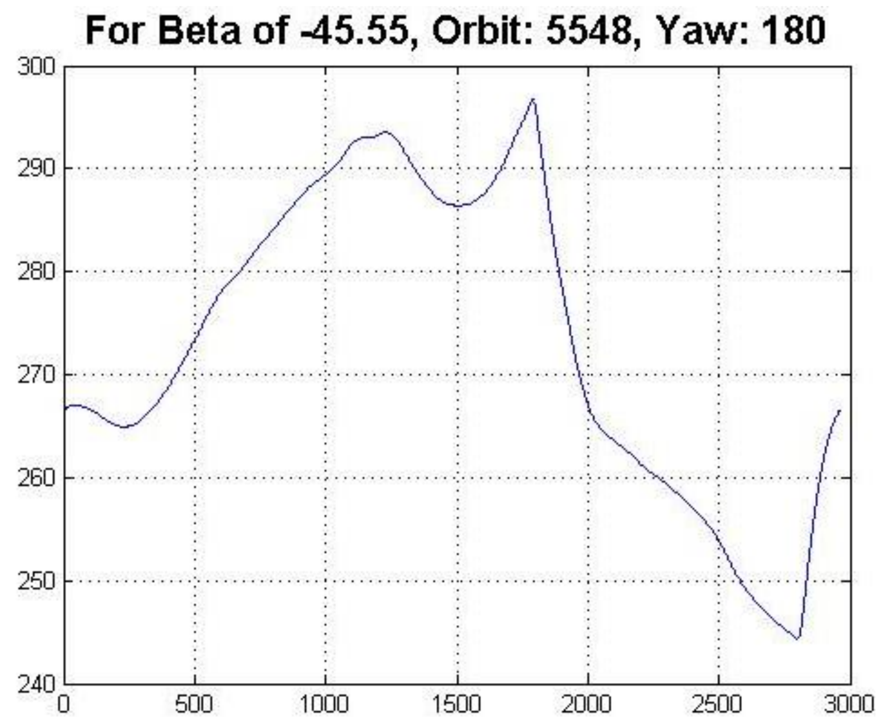




GMI MR Physical Temperature: Normal Orbit



Relative Scan #

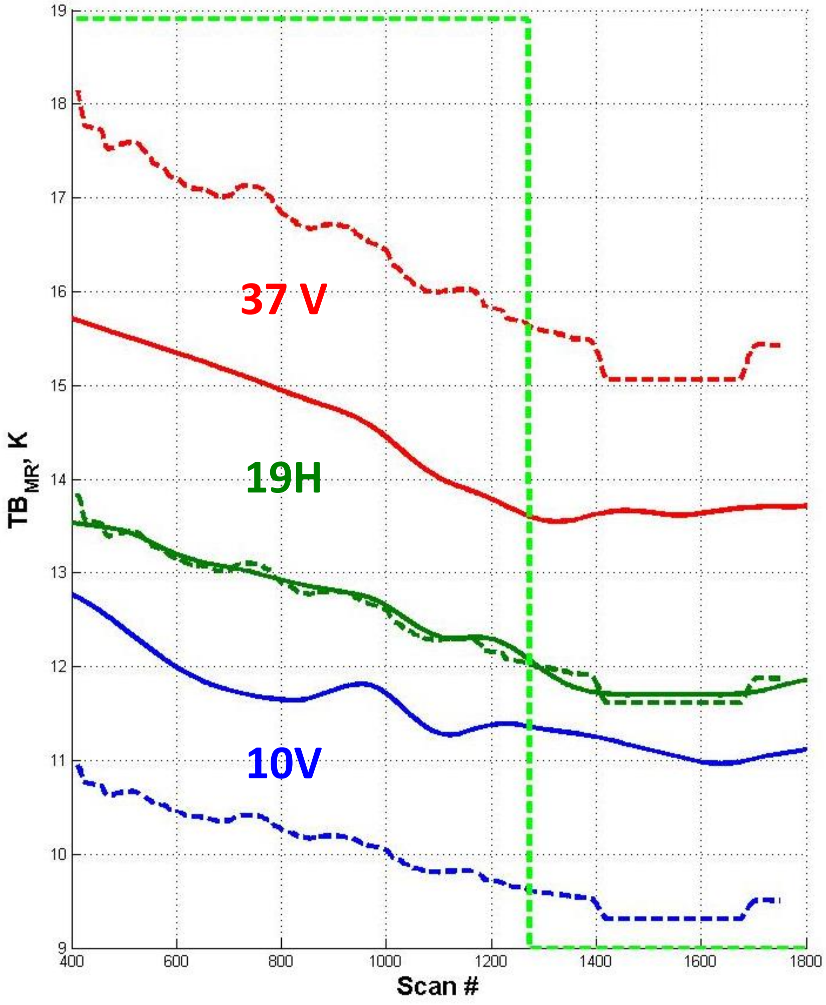


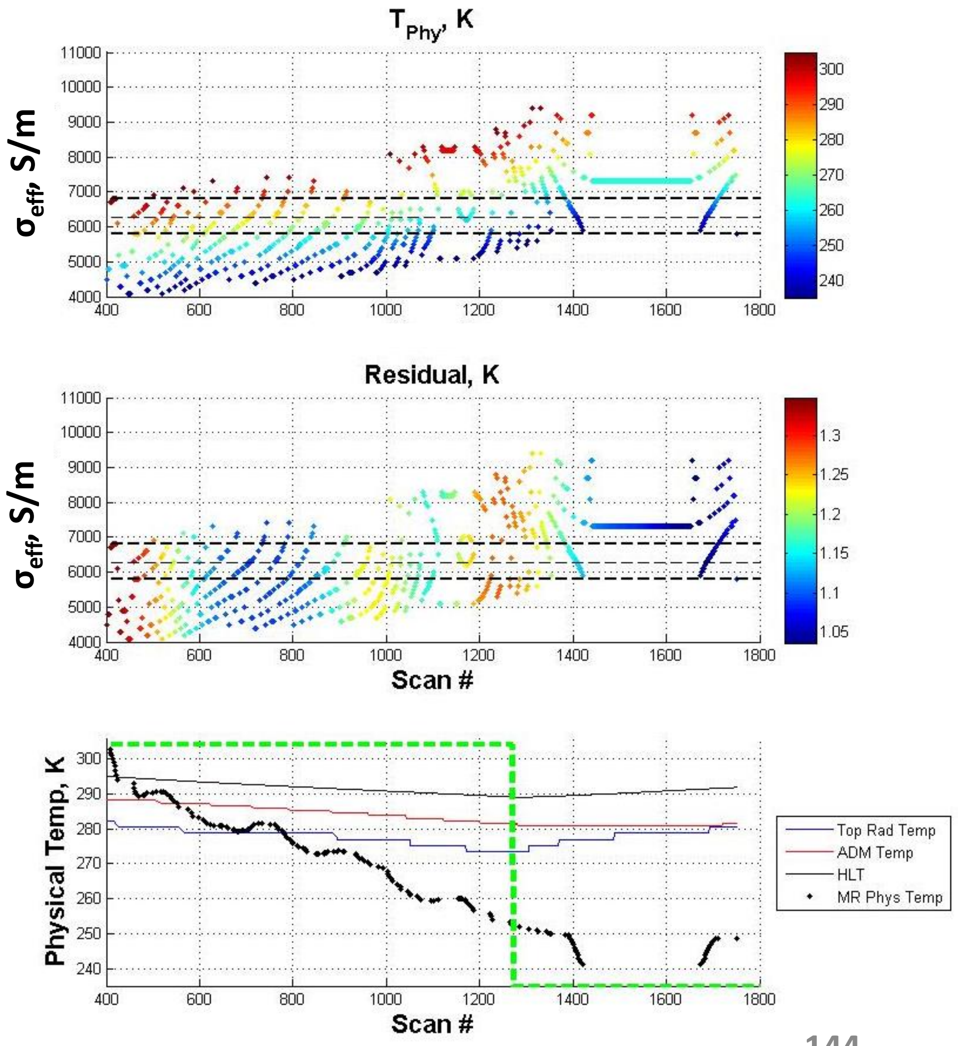
Relative Scan #

Determining Conductivity

-------- Lines: Is what I use determine σ_{eff}
——— Lines: Using σ_{eff} and $T_{MR,Phys}$ to recalculate TB,MR

Scan Bias Correction off

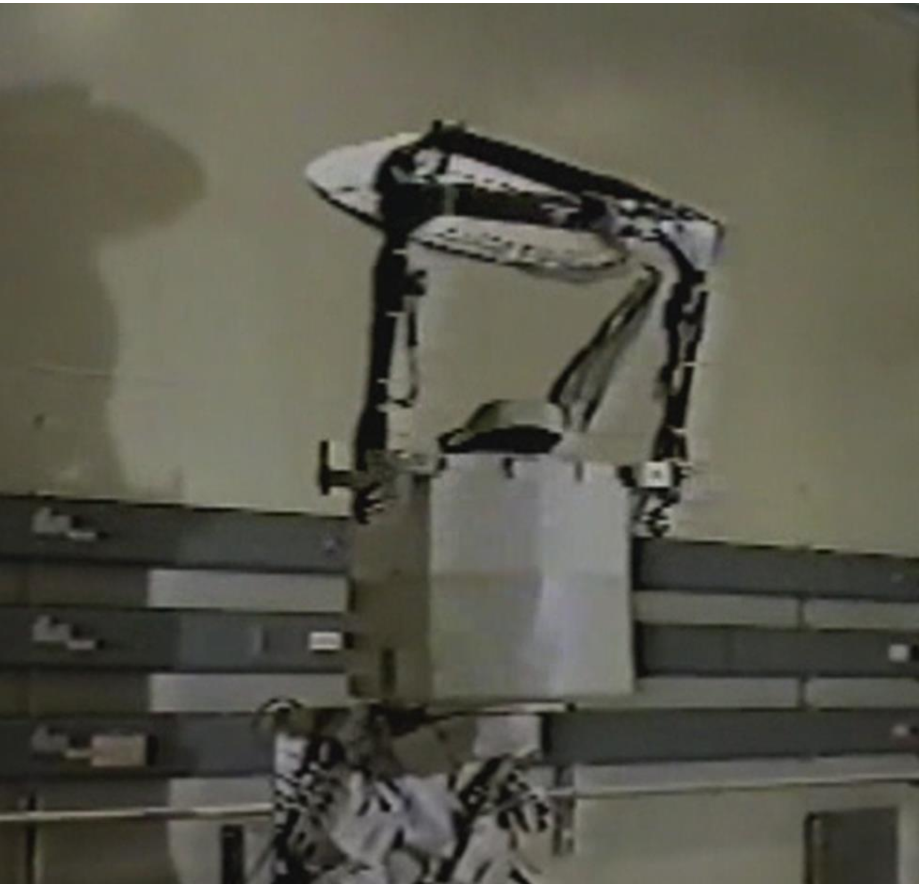




Reasons for Disagreement in Conductivity

- Reconstructed TA is imperfect
- Scan Angle Bias is not corrected for
- There can be an entire TB offset that we are not correcting for
- Imperfections in the Spillover Map – maybe use ERA-I
- Polarization Rotation should be corrected in while using the Spillover Map?
- Feed Horn Pattern is not correct
- 10 GHz feed horn squint angle is not applied

Why I Believe Sun Intrusion into the Warm Load Occurs



BackUps From Proposal

Cosmic Background

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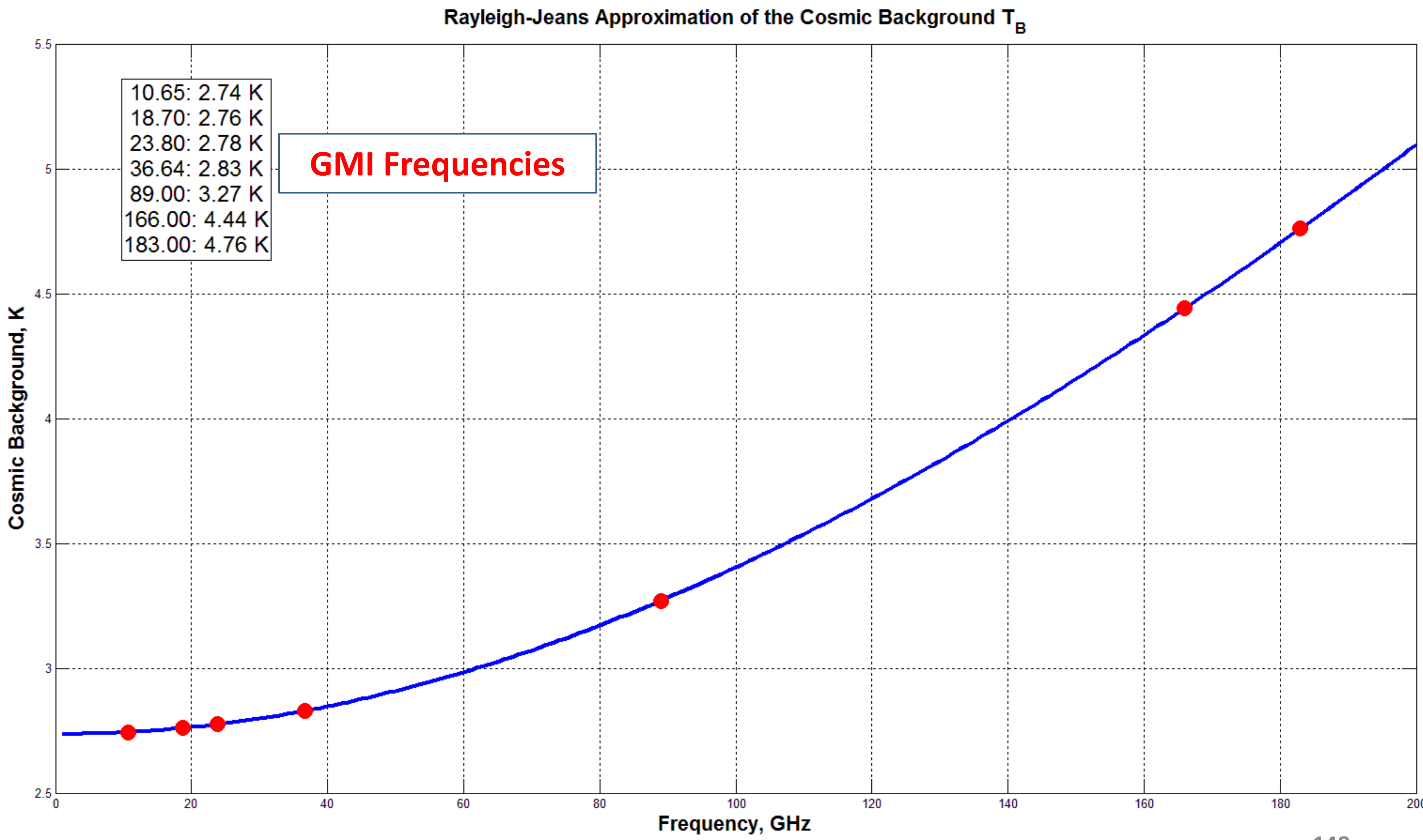

Notes 2:

CFRSL

- Cosmic Microwave Background (CMB)
  - Thermal radiation left over from the Big Bang of cosmology, i.e., radiation left over from an early stage in the development of the universe
  - Is a cosmic background radiation that is fundamental to observational cosmology because it is the oldest light in the universe