Brightness Temperature Calibration of SAC-D/Aquarius Microwave Radiometer (MWR)

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Outline

- Introduction
  - SAC-D/Aquarius Project
  - Role of MWR
  - MWR sensor (overview & geometry)
- Microwave Radiometer Calibration
- Dissertation Objectives
- Pre-Launch Calibration
  - Receiver Calibration
  - Antenna Switch Matrix Calibration
- On-orbit Calibration
- Summary & Conclusions

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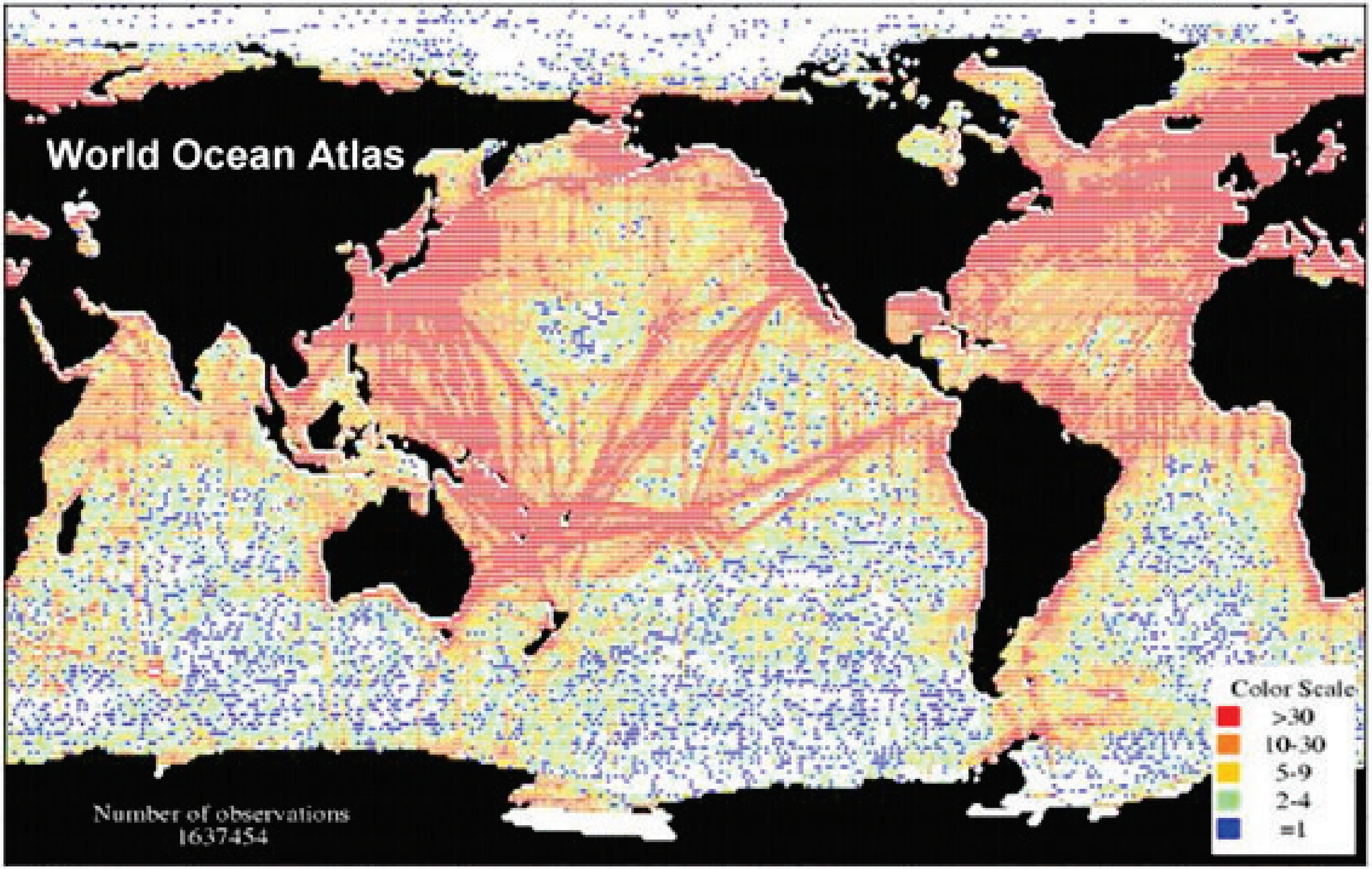
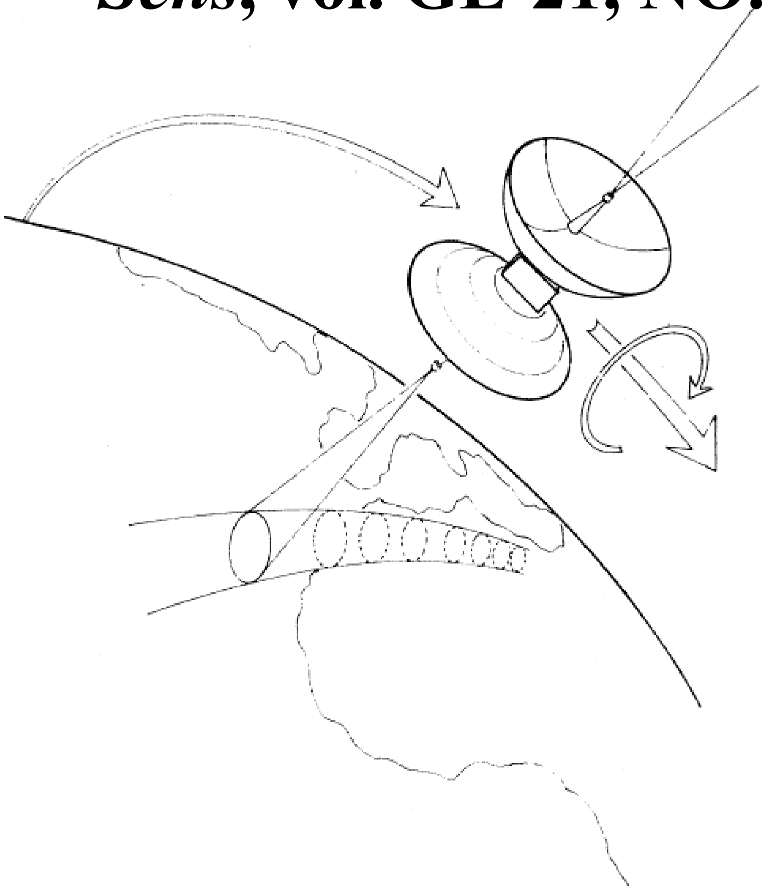
Historical Surface Salinity Measurements

Sampling Distribution of *All* Historical Surface Salinity Measurements
(red shows >30 samples, blue = 1 sample, white shows no samples)



1983: OSS Remote Sensing Concept

- **CALVIN T. SWIFT and ROBERT E. McINTOSH, "Consideration for Microwave Remote Sensing of Ocean-Surface Salinity", *IEEE Trans. GeoSci. Rem. Sens*, vol. GE-21, NO. 4, October 1983.**

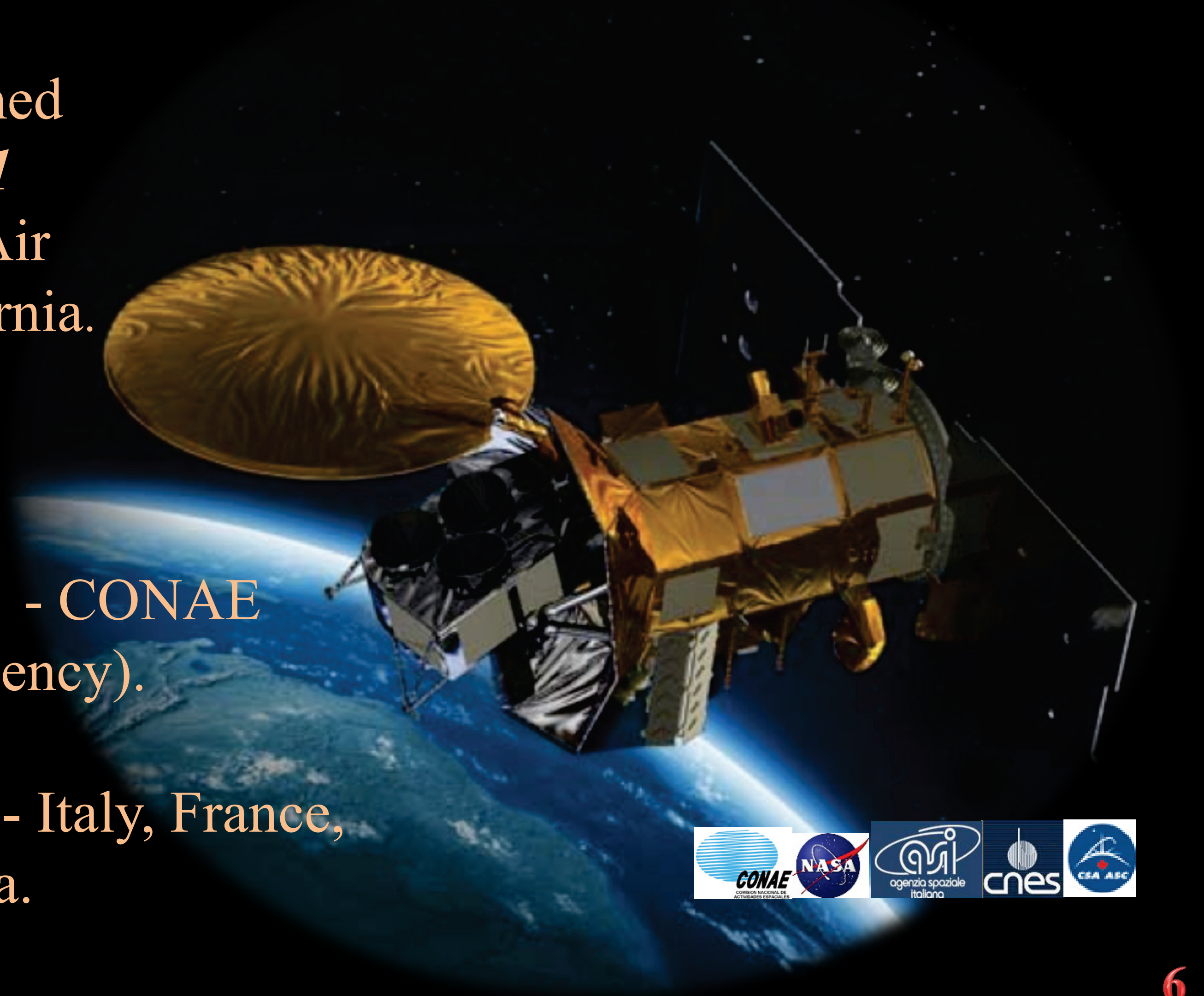


- Back to back reflector antenna (3.7m diameter)
- 800 MHz receiver
- 100km spatial resolution

2011: SAC-D/Aquarius Mission

- Aquarius (AQ) is a mission of "Original Exploration" – First NASA mission to measure Sea Surface Salinity (SSS) from space.

- SAC-D was launched on ***June 10th , 2011*** from Vandenberg Air Force Base, California.



- Aquarius - NASA
- SAC-D spacecraft - CONAE (Argentine Space Agency).
- **MWR - CONAE**
- Other instruments - Italy, France, Canada and Argentina.

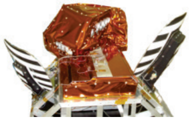
AQ Mission Error Budget: Role of MWR

- Required Accuracy: 0.2 psu

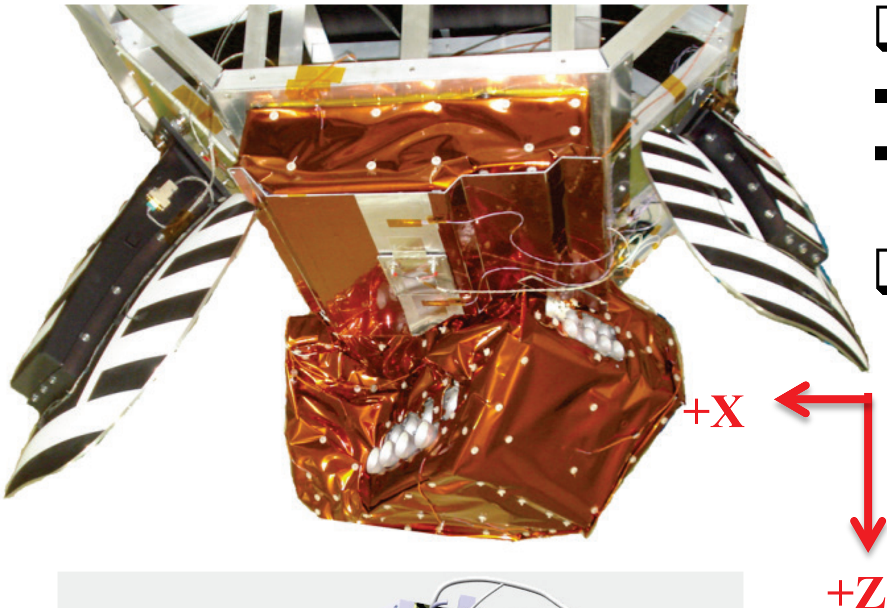
- Major sources of error in the SSS retrieval: (Table 1)
  - Sea Surface Roughness (WS 1m/s; 1psu)
  - Sea Ice
  - Atmosphere(0-70mm;0.2psu)
  - Rain
- **MWR makes measurements in K & Ka band**
  - **Wind induced roughness model function which can be translated to L-band**
  - **Rain flag**
  - **Sea Ice flag**
  - **Atmospheric Water Vapor Content**

Table 1: AQ Mission Error Budget

Error Sources	3 Beam RMS	
	Allocation	CBE
Radiometer	0.15	0.09
Antenna	0.08	0.01
System Pointing	0.05	0.02
Roughness	0.28	0.20
Solar	0.05	0.02
Galactic	0.05	0.004
Rain (Total Liquid Water)	0.02	0.01
Ionosphere	0.06	0.043
Atmosphere (Other)	0.05	0.02
SST	0.10	0.07
Antenna Gain Near Land & Ice	0.10	0.10
Model Function	0.08	0.07
Brightness Temperature Error Per Observation	Baseline Mission	
	Allocation	CBE
Total RSS (K)	0.38	0.27
Margin RSS (K)	0.27	0.27

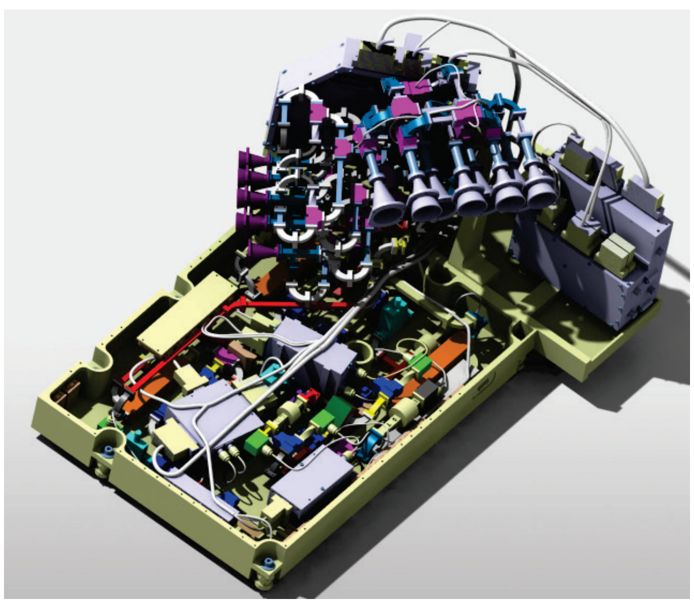


MWR Instrument Overview



- ❑ Two Frequency Bands
  - ▪K – Band (23.8 GHz) : H-Pol Only
  - ▪ Ka – Band (36.5 GHz): V,H,+45° & -45° Pol

- ❑ Two reflector antenna



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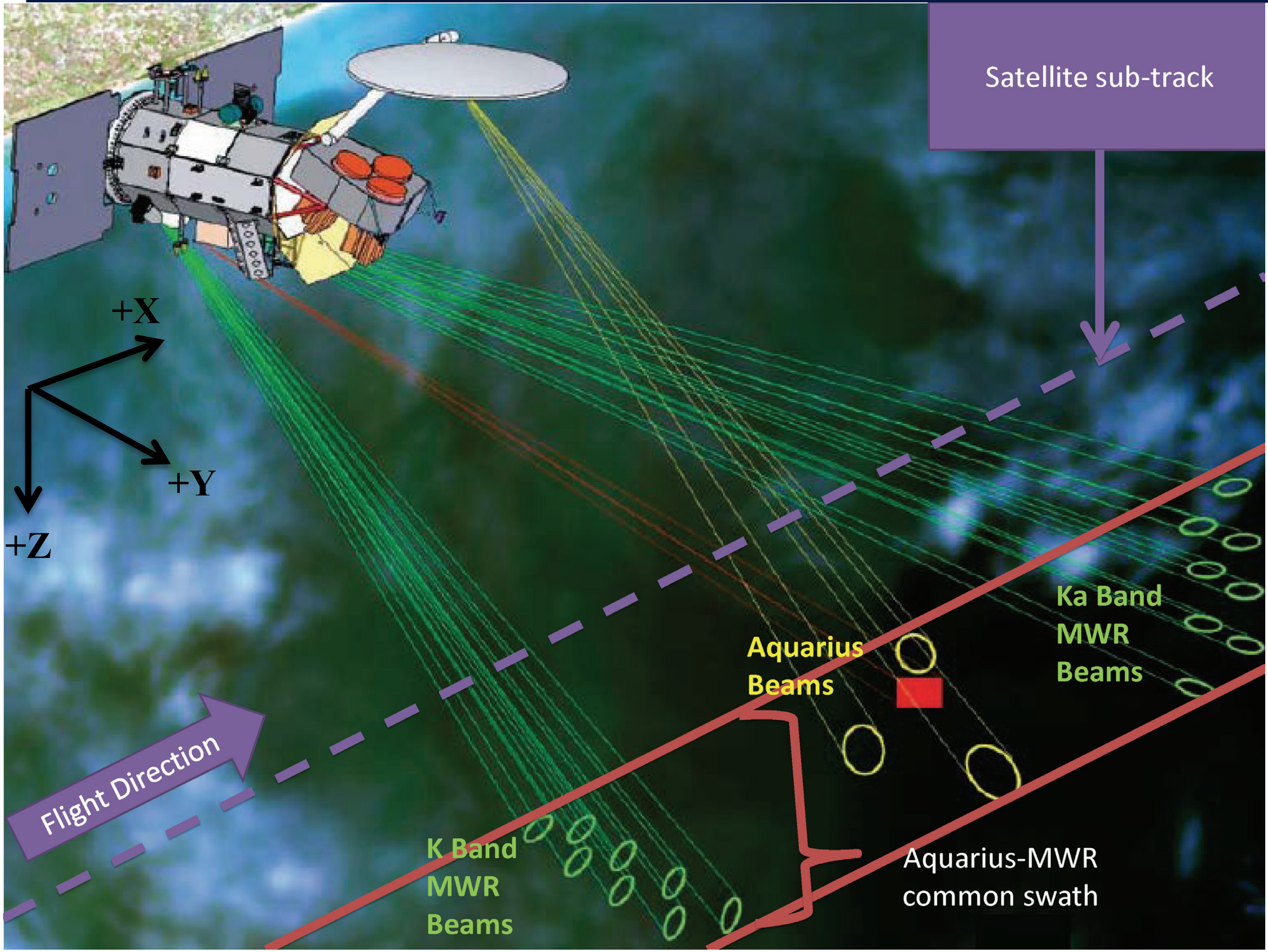
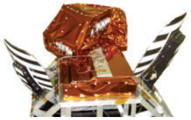
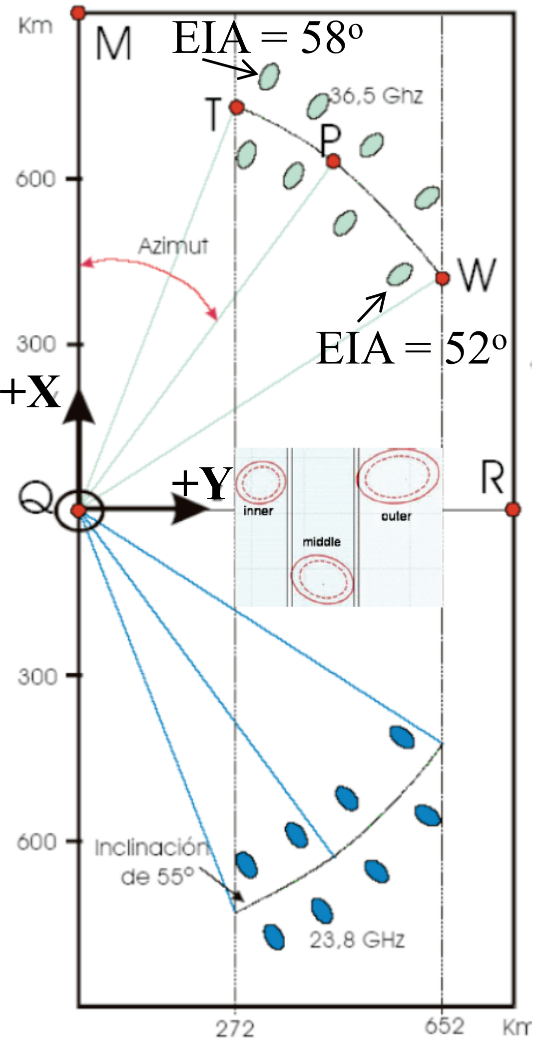
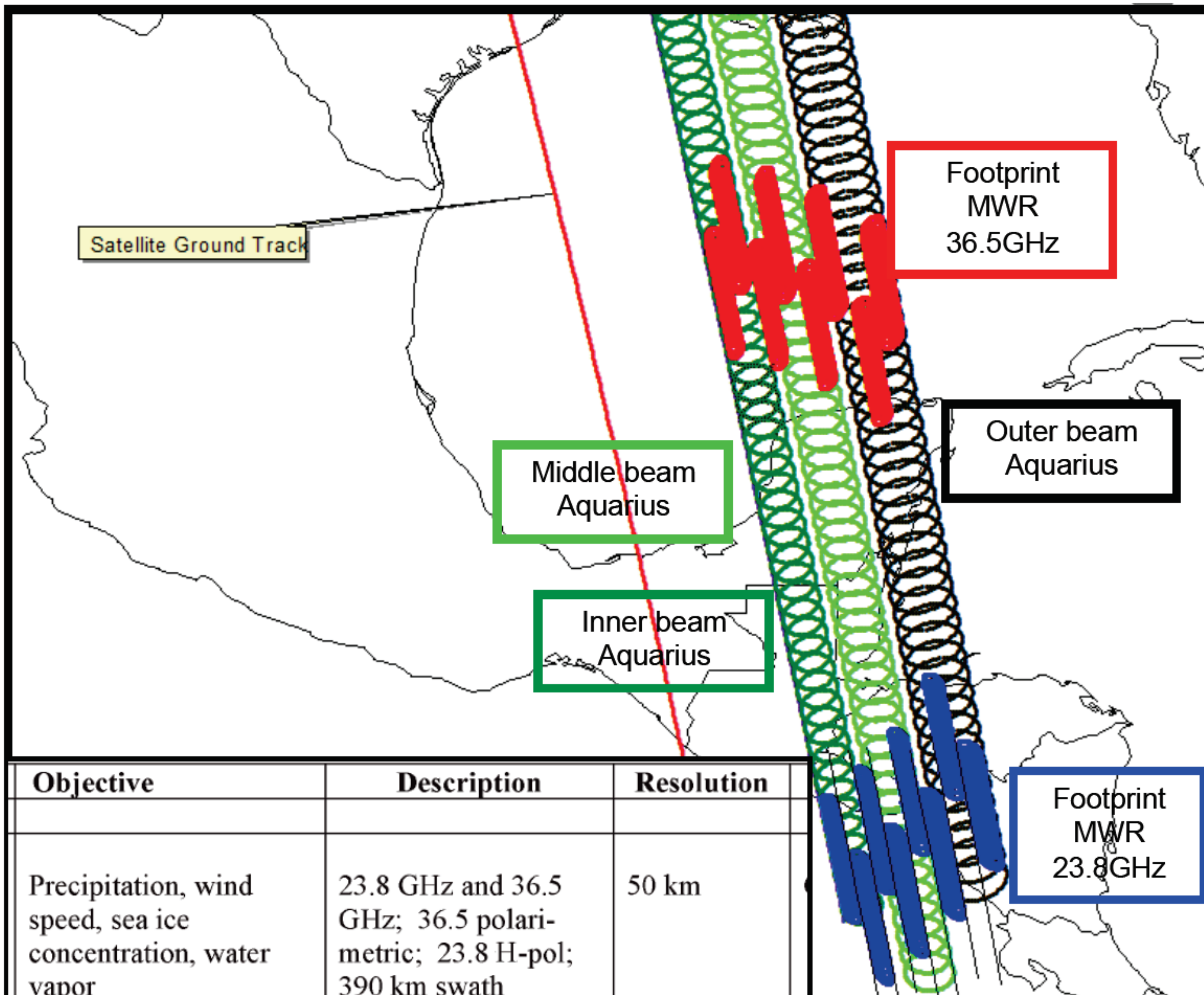
MWR Sensor Geometry





MWR Sensor Geometry





Objective	Description	Resolution
Precipitation, wind speed, sea ice concentration, water vapor	23.8 GHz and 36.5 GHz; 36.5 polari-metric; 23.8 H-pol; 390 km swath	50 km

EIA – Earth Incidence Angle

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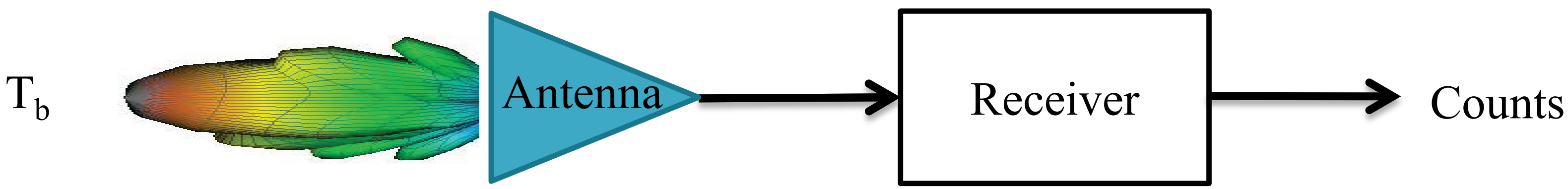
Microwave Radiometer Calibration

- A microwave radiometer is a very sensitive instrument used to measure the <u>absolute power</u> of electromagnetic thermal noise radiation expressed as brightness temperature (T_b), in the microwave region of the spectrum
  - Two parts: an antenna and a receiver



- Received Signal is very weak.
  - Demands high sensitivity
- Unwanted component in the measurements
  - External - Antenna performance
  - Internal - Receiver gain fluctuations and Equivalent noise temperature
- Calibration is necessary to characterize all unwanted measurement components

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Dissertation Objective

- To develop a calibration algorithm to convert MWR's raw measurements (digital counts) to antenna bore-sight brightness temperatures (T_b)

Towards Achieving the Objective

- *Pre-launch development*
  - Receiver Calibration:
    - Analysis of radiometric calibration test data
    - Determination of injected noise diode temperature (Tn)
  - Calibration of Antenna Switch Matrix:
    - Development of theoretical transfer function
      - Model inputs from manufacturer data sheet
  - Analysis of Thermal Vacuum (TV) Test data/ Model validation
  - Development of regression based calibration model
- *Post-launch on-orbit tuning*
  - Determination of Antenna Pattern Correction (APC) coefficients
  - Beam balancing (MWR 8 beams/channel)

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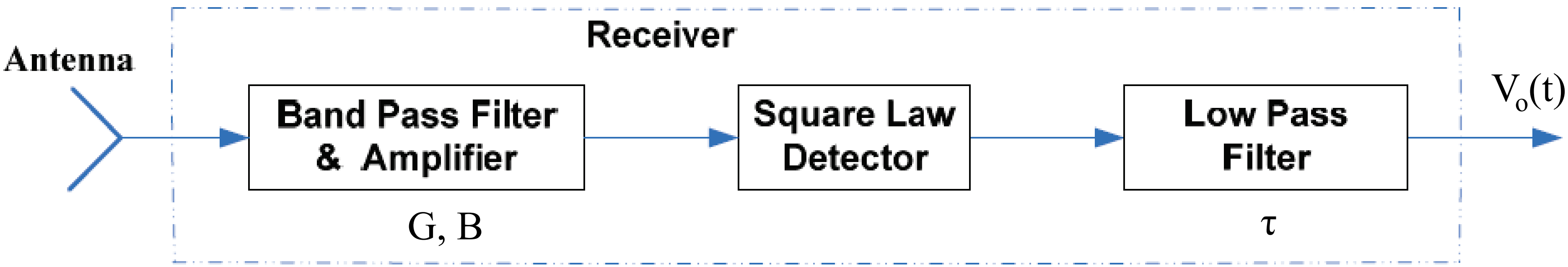
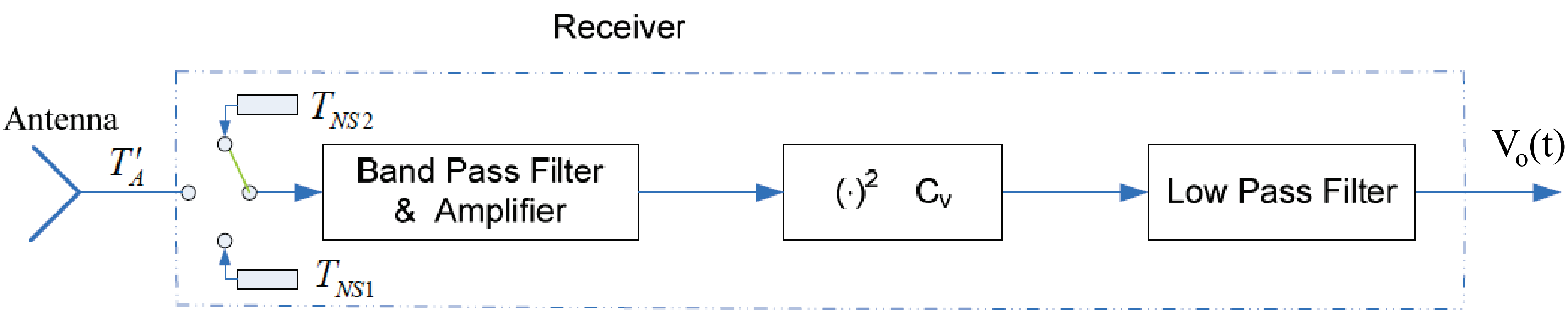
Rx. Cal.: Output Noise Fluctuations



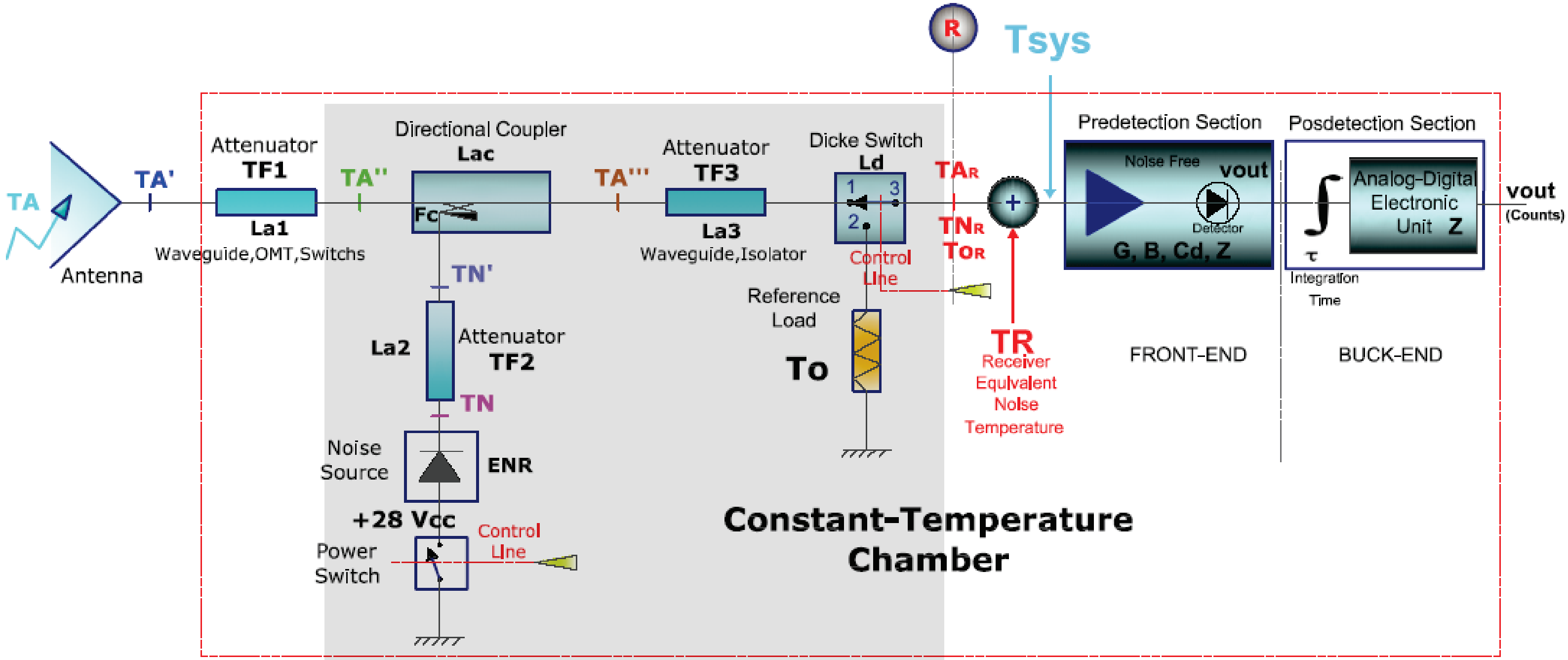
- Received Power: $P_r = kT_{sys}B$
- The receiver output fluctuation :

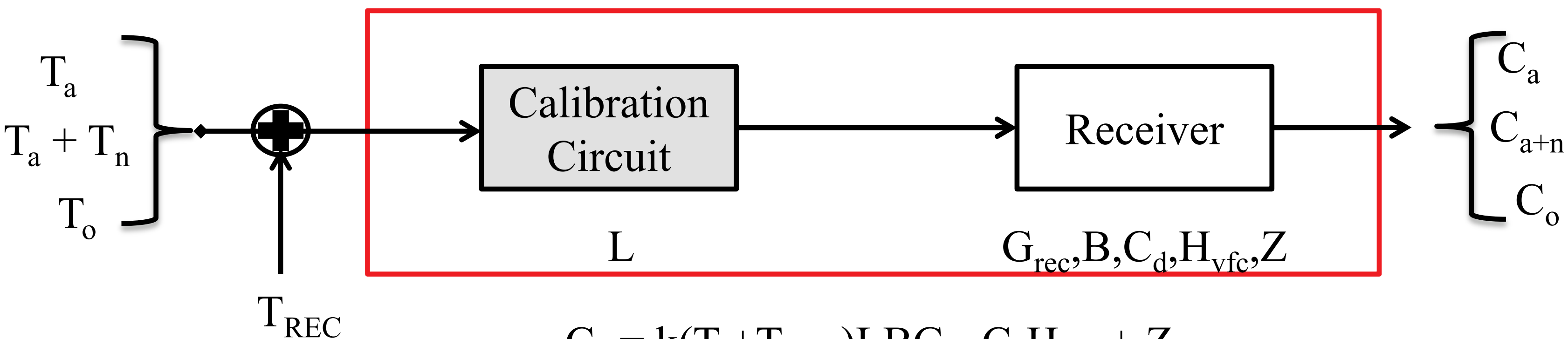
$$\sigma_{total} = T_{sys}[(1/B\tau) + (\Delta G/G)^2]^{1/2} \text{ (units of K)}$$

- ΔG calibration using 'known' noise sources



Rx. Cal.: MWR Internal Calibration



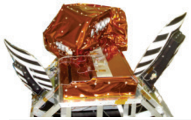


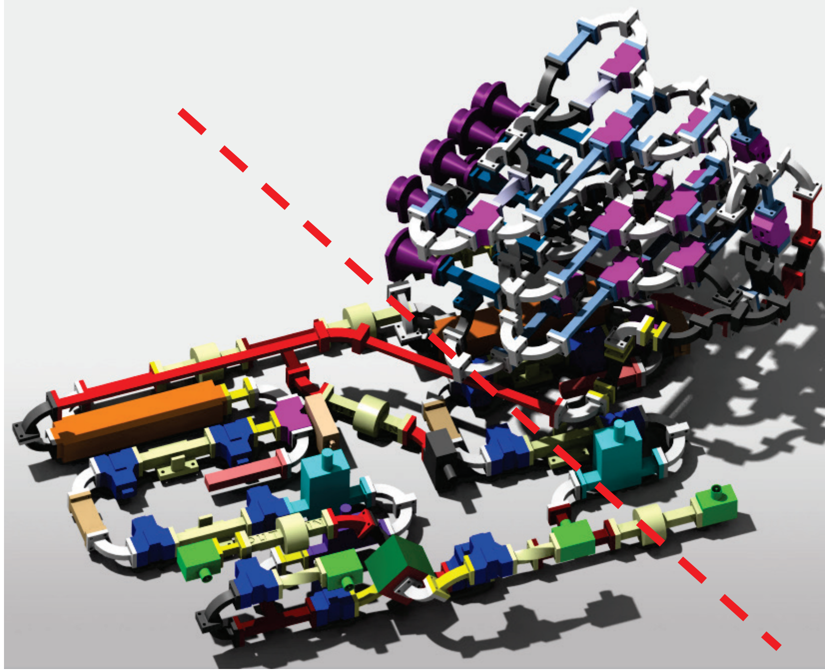
$$C_a = k(T_a + T_{REC}) L B G_{rec} C_d H_{vfc} + Z$$

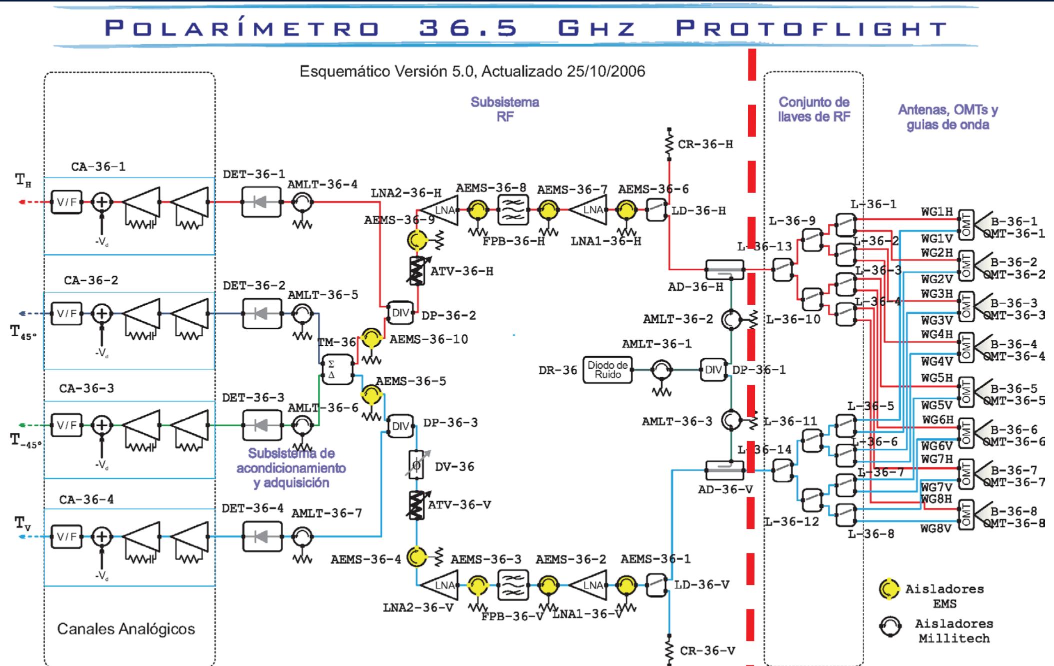
$$= (k L B G_{rec} C_d H_{vfc}) T_a + (k L T_{REC} B G_{rec} C_d H_{vfc} + Z)$$

gain offset

MWR Int. Cal. : Simplified Model







- Three State Dickie Radiometer

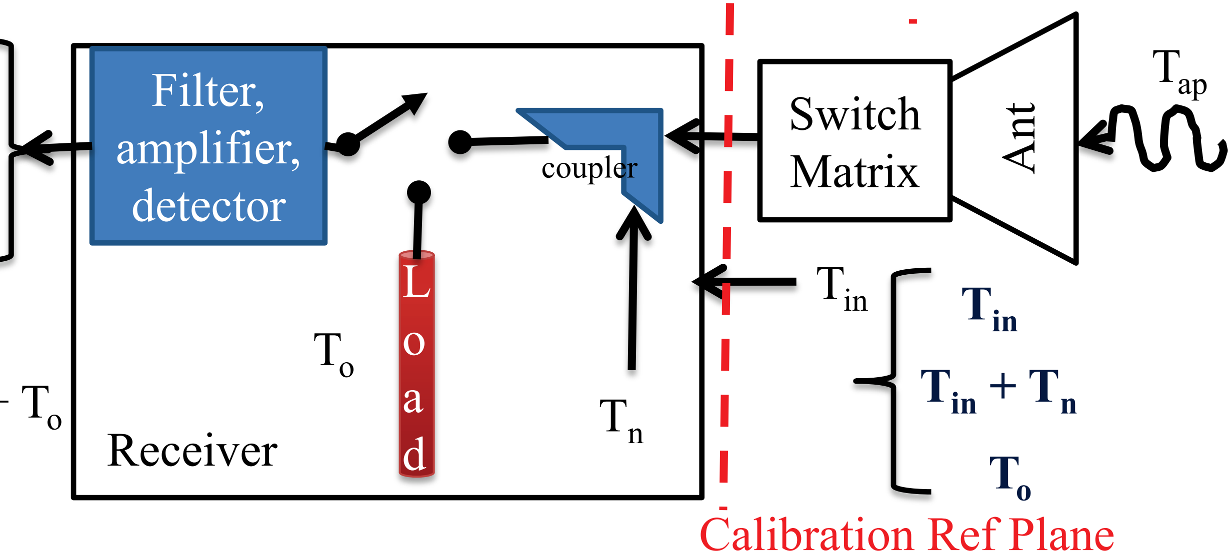
$$C_{in} = GT_{in} + offset$$

$$C_{in+n} = G(T_{in} + T_n) + offset$$

$$C_o = GT_o + offset$$

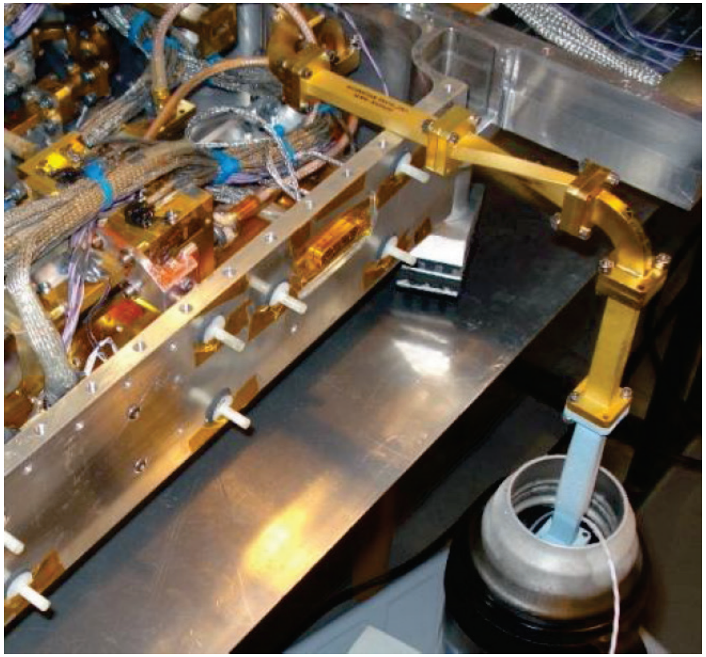
- Calibration Equation:

$$T_{in} = \{(C_{in} - C_o)/(C_{in+n} - C_{in})\} * T_n + T_o$$



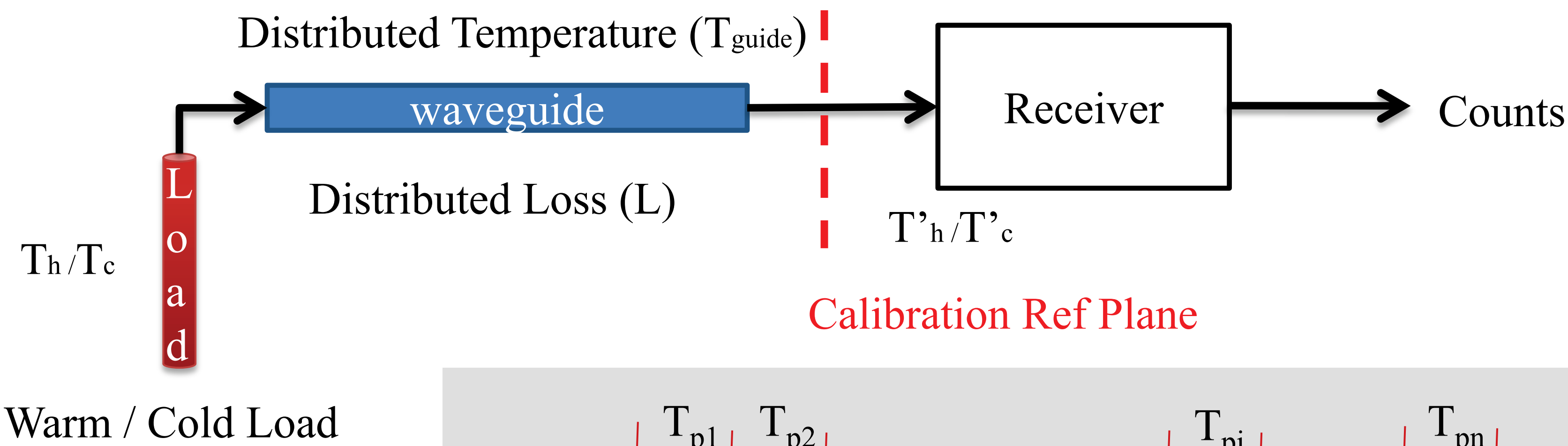
Receiver Calibration: External

- Primary Goal: Determine T_n for each receiver
- Test Setup
  - Receiver & antenna switch matrix disconnected at the calibration reference plane



- Receiver connected to an external calib waveguide, terminated in matched load
- Termination (blackbody)
  - heated (warm water)
  - cooled (liquid nitrogen)
- Termination temperature measured

Rx Calibration: Forward Model



<u>HOT LOAD</u>

$C_h = G(T'_h)+\text{offset}$ (1)

$C_{h+n} = G(T'_h+T_n)+\text{offset}$ (2)

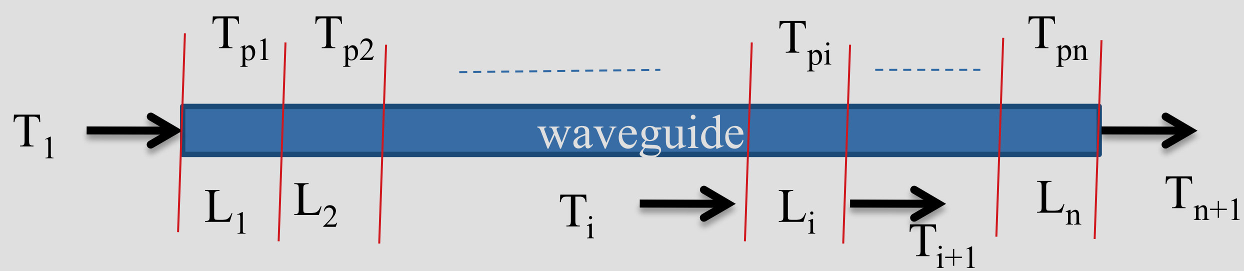
$C^h_{ref} = G(T_{ref})+\text{offset}$ (3)

<u>COLD LOAD</u>

$C_c = G(T'_c)+\text{offset}$ (4)

$C_{c+n} = G(T'_c+T_n)+\text{offset}$ (5)

$C^c_{ref} = G(T_{ref})+\text{offset}$ (6)

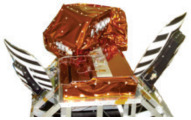


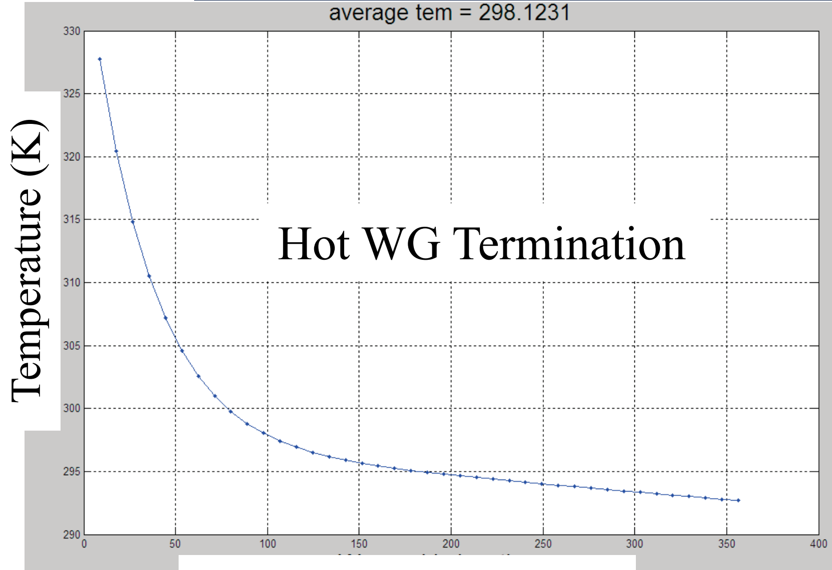
$T_{i+1} = L_iT_i + (1-L_i)T_{pi}$

$$T_{n+1} = \left(\prod_{i=1}^{n} L_i\right)T_1 + \sum_{k=1}^{n}(1-L_k)T_{pk}\left(\prod_{j=k+1}^{n} L_j\right)$$

- Radiative transfer through the waveguide
  - Waveguide is divided into n =40 equal sections
  - Assumed temperature profile (exponential)
  - Known boundary conditions: Load Temperature, T_o

Rx Calibration: WG Temperature Profile



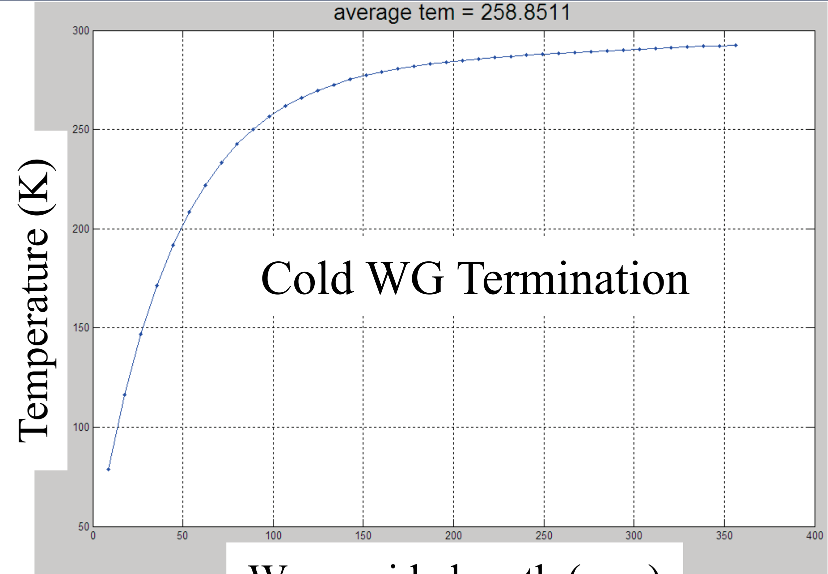


Load end

Rx end

Assumed Temp Distribution In the waveguide

T_{guide}



Load end

Rx end

T_{guide}

waveguide

$T_{hot\ (out)} = 329.5$ K

$T_{cold(out)} = 84.8$ K

$T_{hot\ (in)} = 330.86$ K

$T_{cold(in)} = 77.4$ K

Load

Length (mm)	Loss
356.30	0.9589

Calibration Ref Plane

Hot / Cold Load

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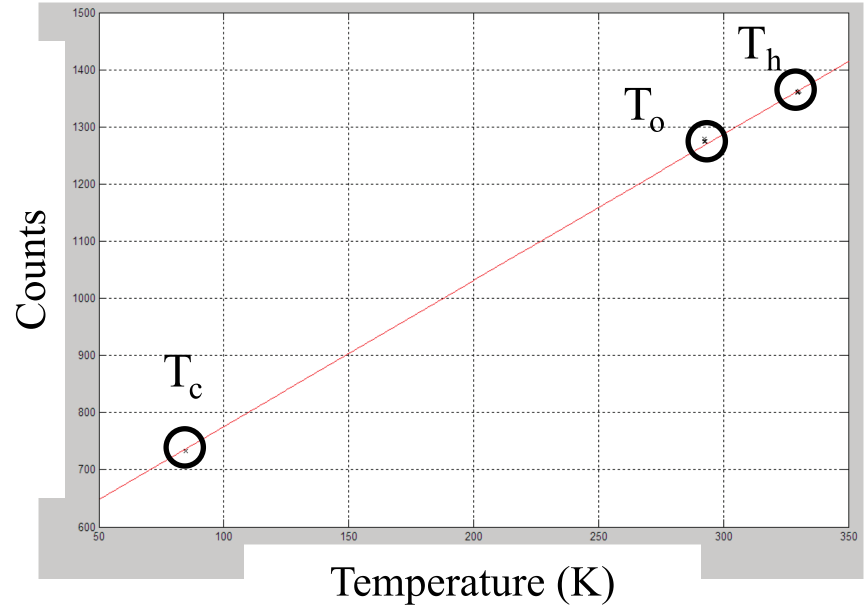
Rx Calibration: T_n Computation

- Assume linear receiver
- Least-squares linear regression through three calibration points
  - (T_c, T_o and T_h)
- Slope = radiometer Gain (G)
- Using cold load deflection solve for injected noise brightness:

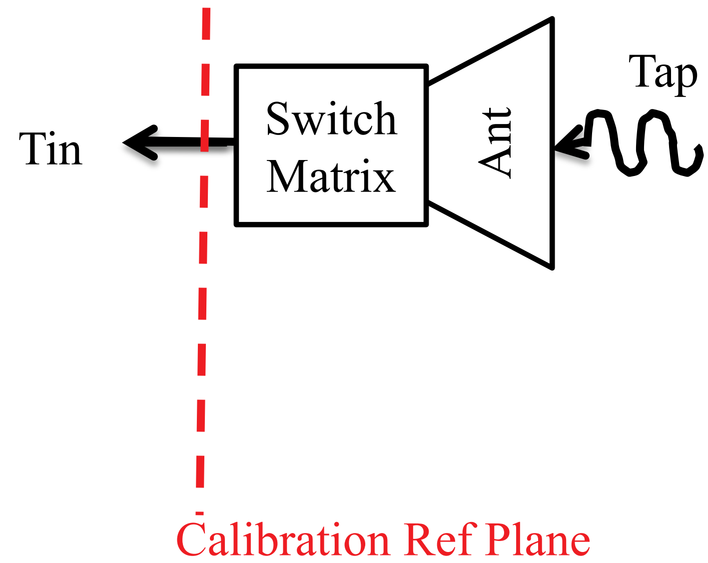
$$T_n = (C_{c+n} - C_c)/G$$



T_n (K)		
K H pol	Ka V pol	Ka Hpol
390	274	270

Antenna Switch Matrix Calibration

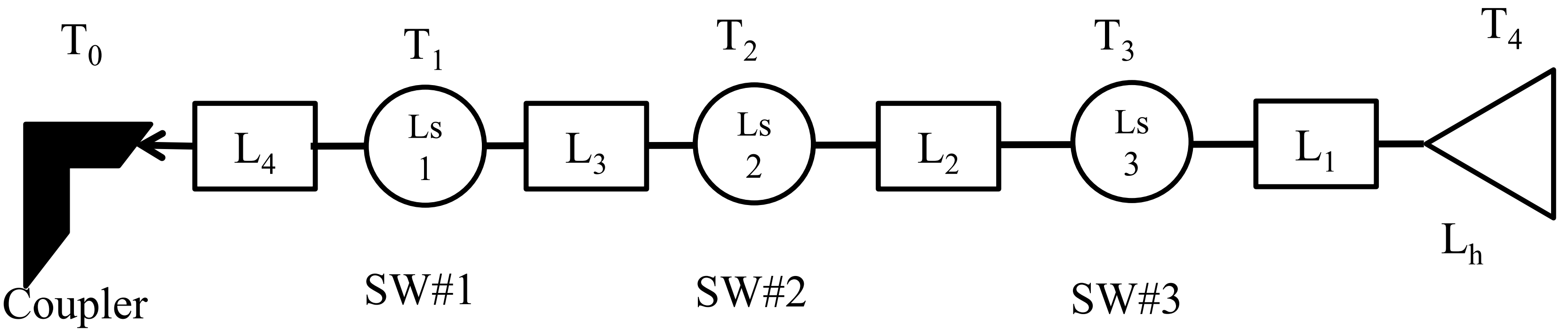
- Goal: Establish a relation between T_{ap} and T_{in}

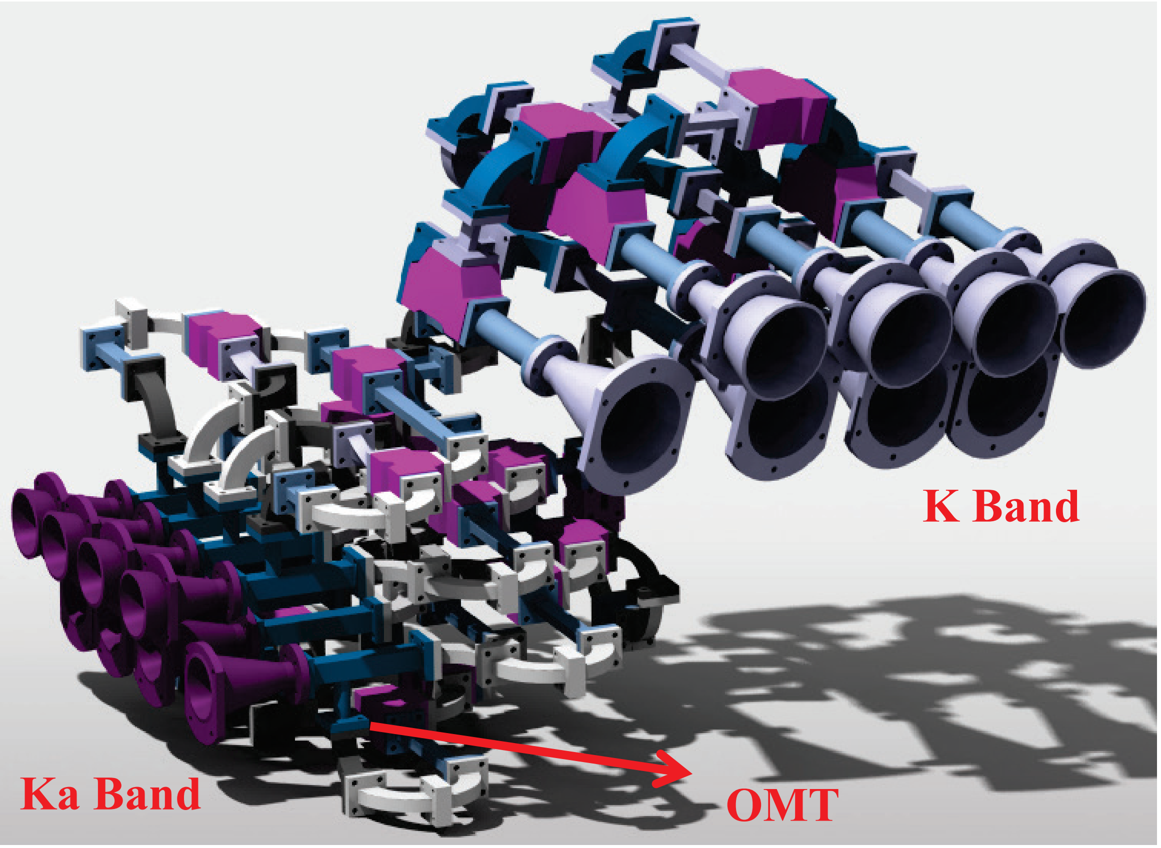


- Radiative transfer model for the switch matrix
  - Waveguide lengths from CAD
  - Silver WG loss/unit length
  - Other losses from component data sheets

- Model evaluation using Thermal Vacuum (TV) test

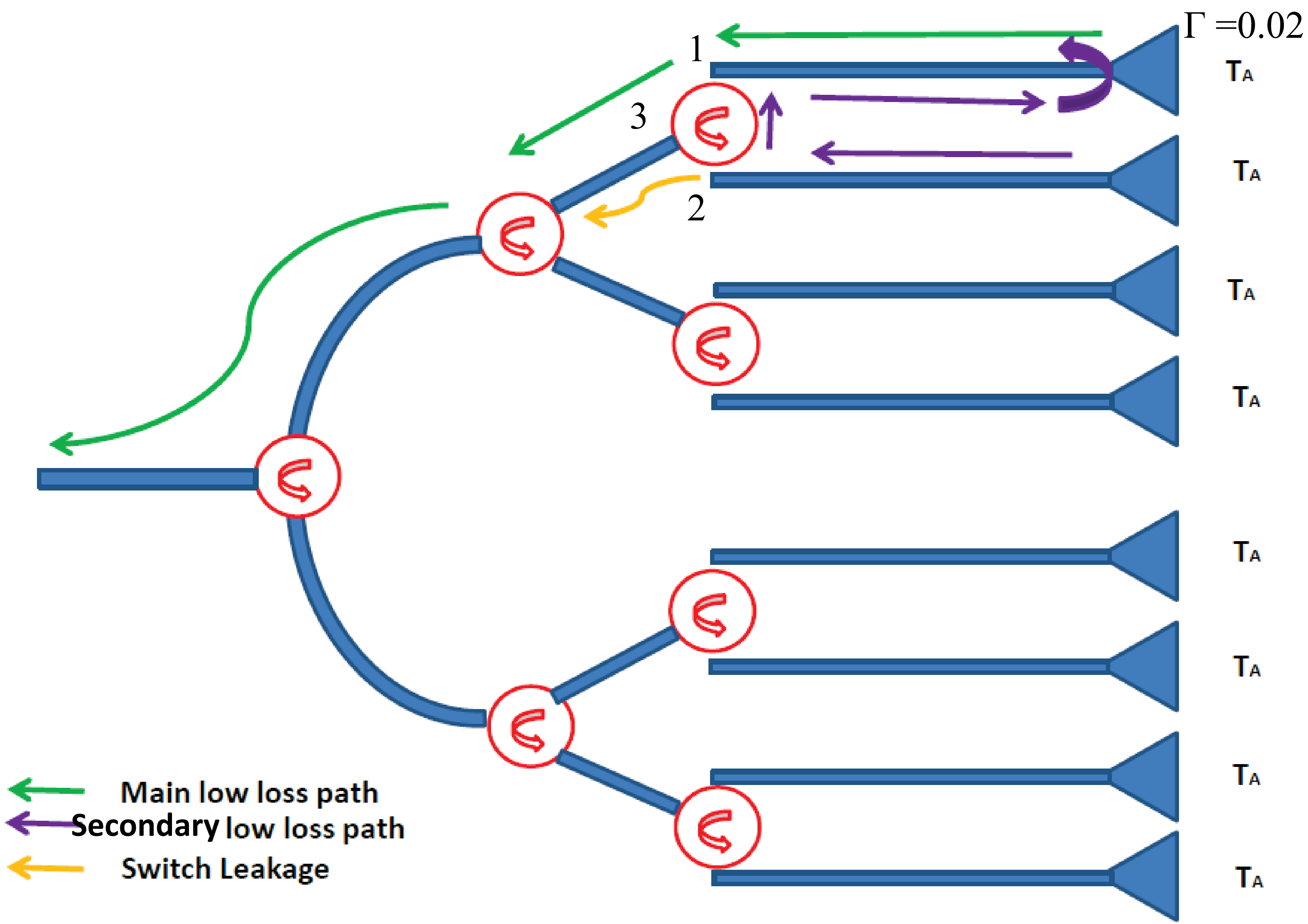
SW Matrix Cal : Simplified block diagram



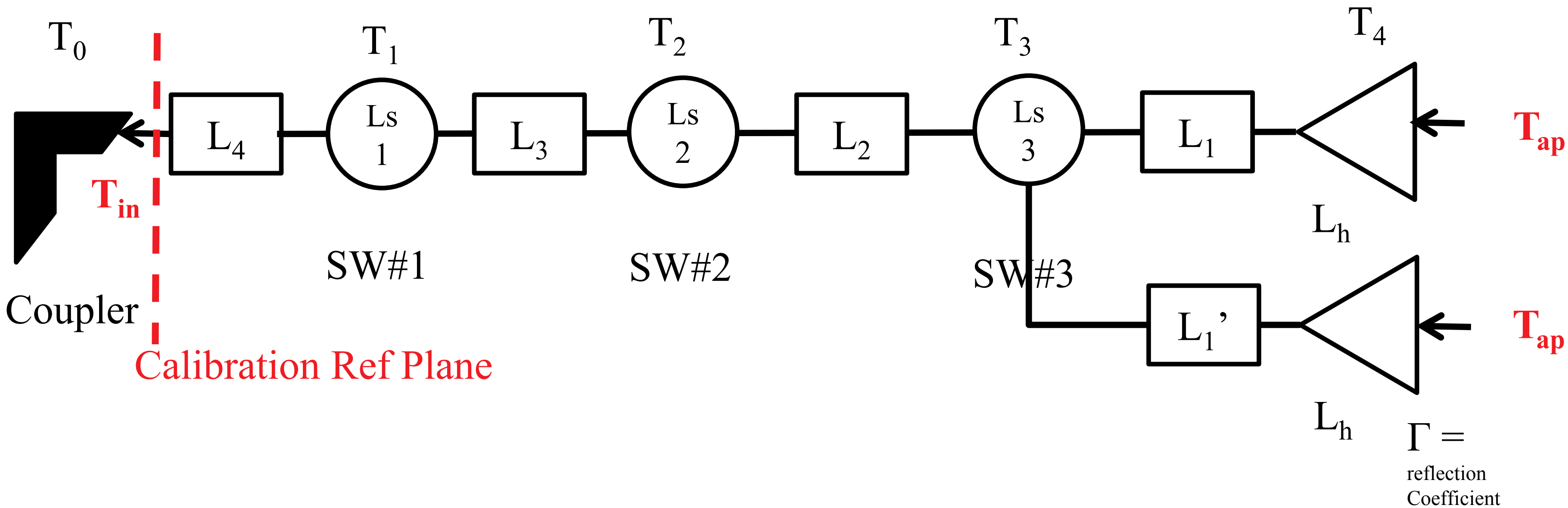


- OMT for Ka band horns
- 8 feed horns connects to a single receiver
- 3 layers of switch (4-2-1)
- For a single feed horn path
  - 4 waveguide loss sections
  - 3 switch losses
  - 1 feed horn, OMT loss

SW Matrix Cal: Primary & Secondary Path



SW Matrix Cal: MWR SW Matrix Model



- Simplified FORWARD MODEL

$$T_{in} = gT_{ap} + a_0T_0 + a_1T_1 + a_2T_2 + a_3T_3 + a_4T_4$$

- INVERSION MODEL

$$T_{ap} = \{ T_{in} - (a_0T_0 + a_1T_1 + a_2T_2 + a_3T_3 + a_4T_4)\}/g$$

$$\begin{aligned} a_4 = \; & 0.5(1-L_1)(L_2L_3L_4)L_s^3 \\ & + (1-L_h)(L_1L_2L_3L_4)L_s^3 \\ & + \Gamma(1-L_h)(L_1L_2L_3L_4)L_hL_s^3 \\ & \quad + 0.5\Gamma(1-L_1)(L_1L_2L_3L_4)L_h^2L_s^3 \\ & + 0.5\Gamma(1-L_1)(L_1^2L_2L_3L_4)L_h^2L_s^4 \\ & + \Gamma(1-L_h)(L_1^3L_2L_3L_4)L_h^2L_s^4 \end{aligned}$$

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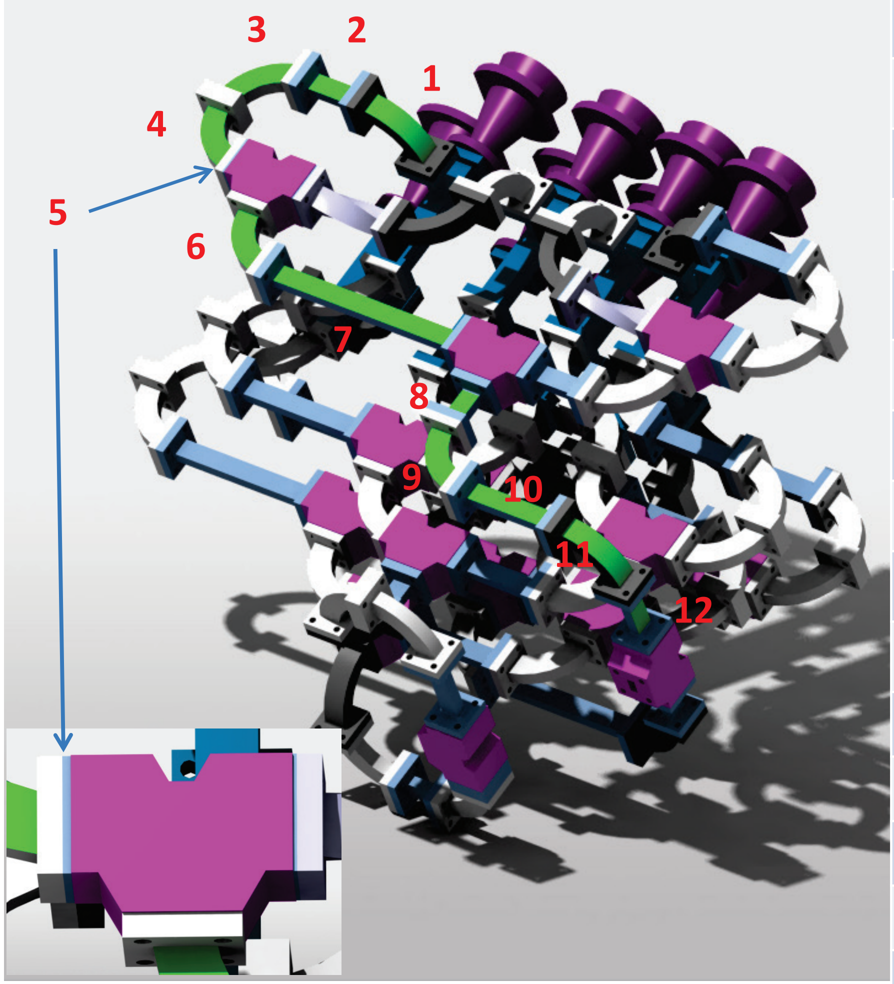
SW Matrix Cal: Computation of WG Loss

Feed Horn 8 – OMT Horizontal path (green)



241.483mm + 4*CH90+2*CE90

WG	L (mm)	Code
1	39.898	CE90
2	30.308	TGAM30.31-36
3	39.898	CH90
4	39.898	CH90
5	1.366	TGAM1.37-36
SW1		Dickie Switch
6	39.898	CH90
7	102.540	TGAM102.54-36
SW2		Dickie Switch
8	23.272	TGAM23.27-36
9	39.898	CH90
10	50.652	TGAM50.65-36
11	39.898	CE90
12	33.345	TGAM33.34-36
SW3		Dickie Switch

WG Length computation Example (horn#8, Ka Band-H pol)

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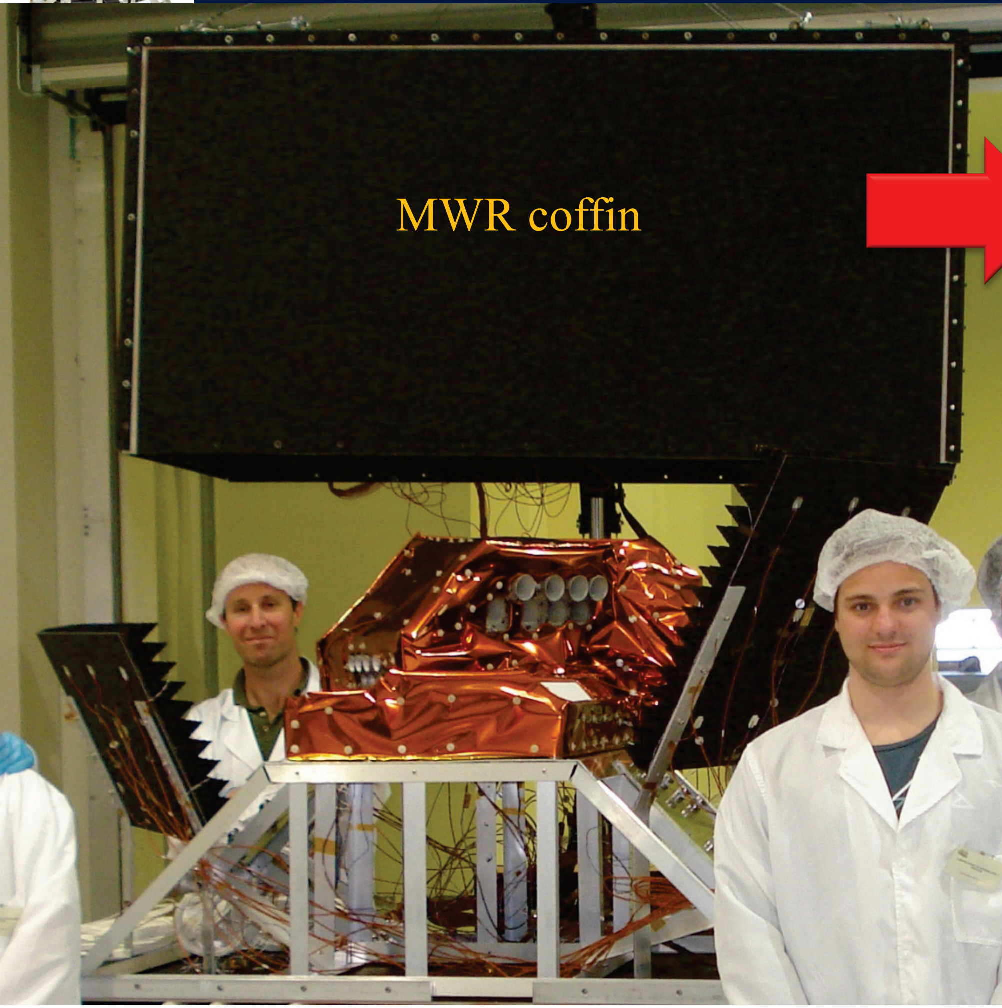
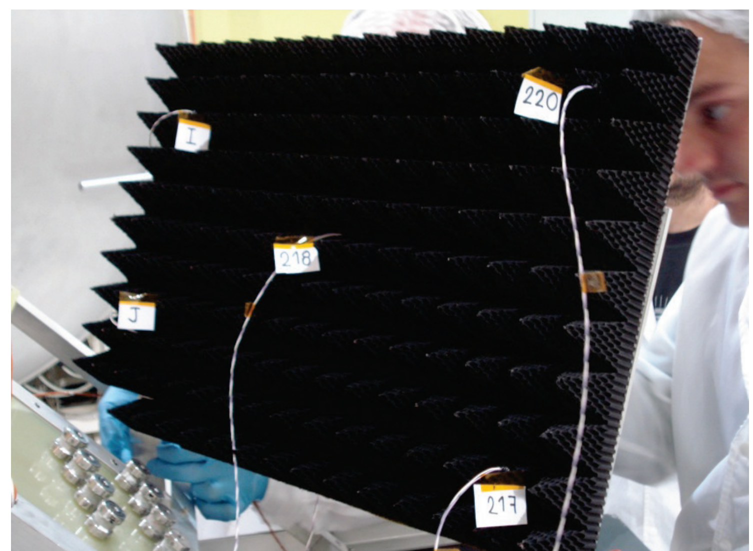
SW Mat Cal : Description of The TV Test





- The thermal vacuum (TV) test for MWR was performed in September 2009. (09/06 – 09/09)
- The flight reflectors were replaced by Black Body Absorbers

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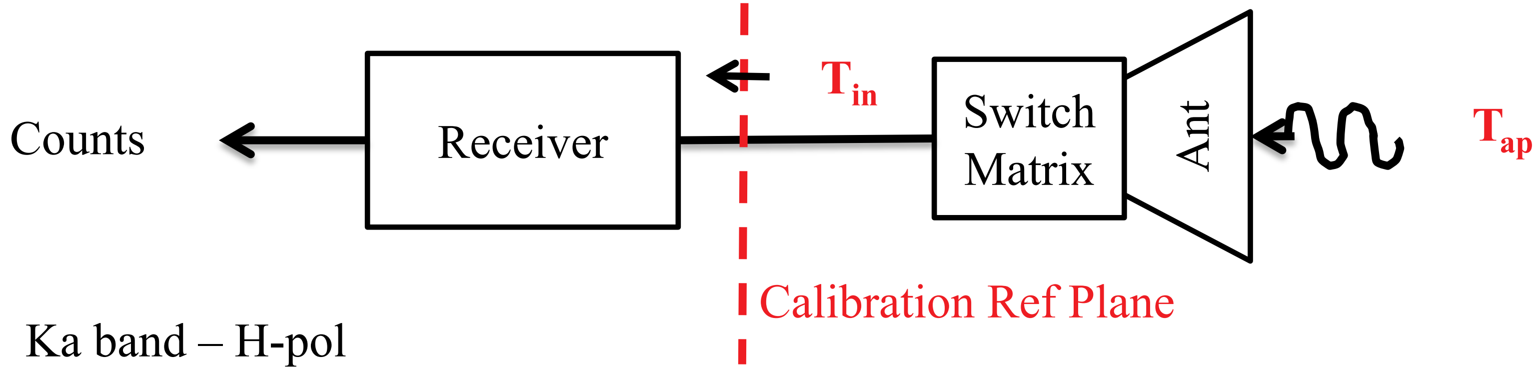
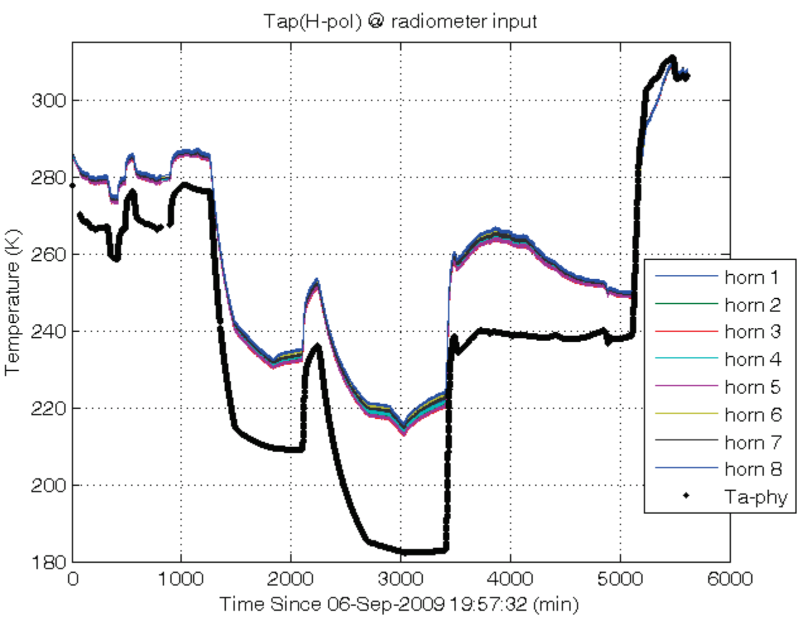
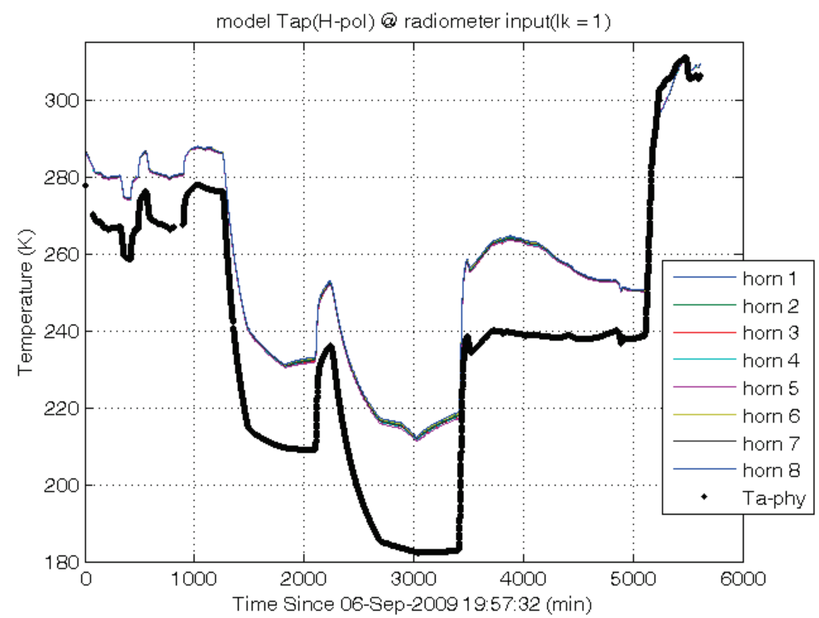
SW Matrix Cal : Measured vs. Model



Ka band – H-pol





Tin From Rad counts

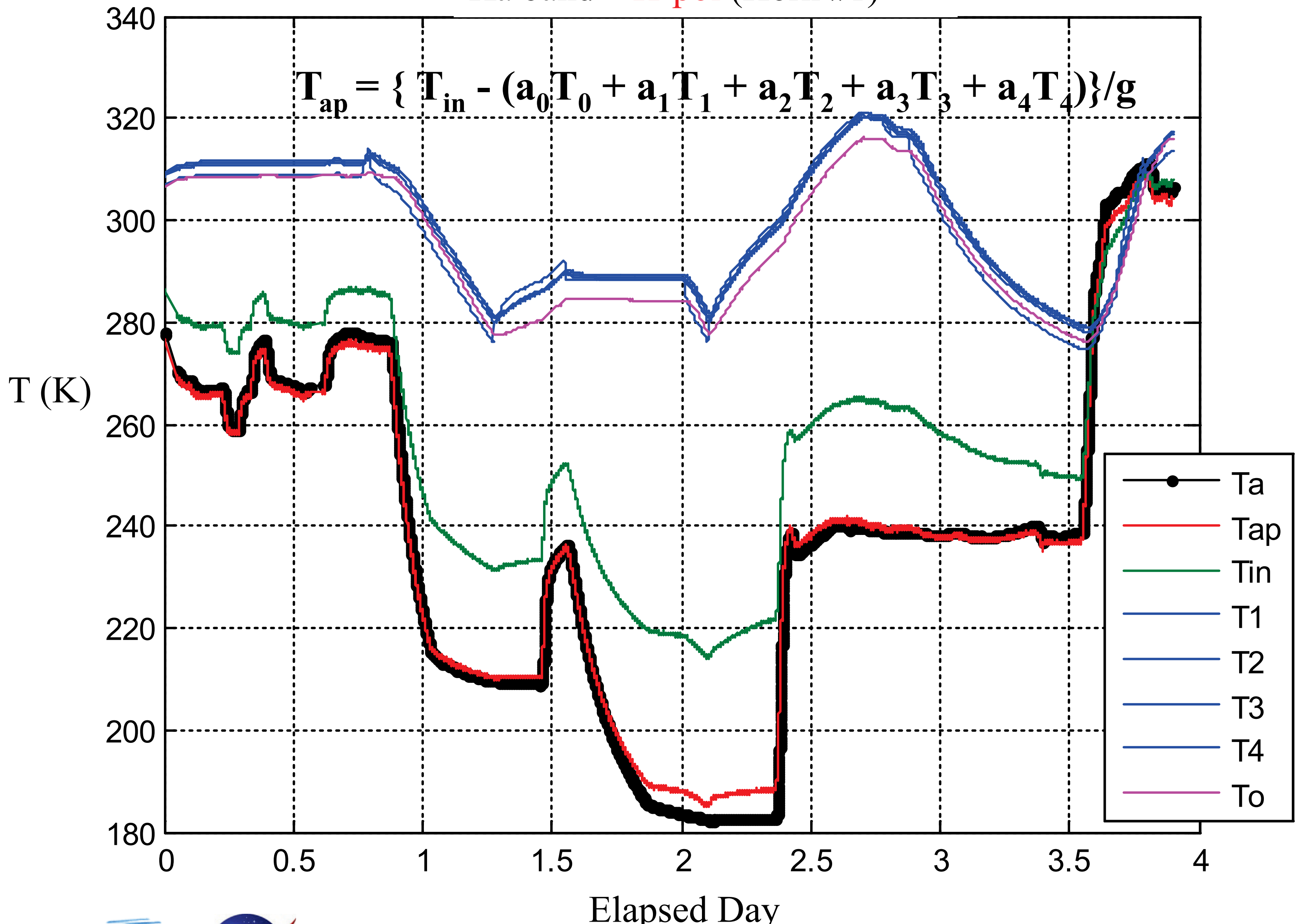
$$T_{in} = \{(C_{in} - C_o)/(C_{in+n} - C_{in})\} * T_n + T_o$$

Tin From Model

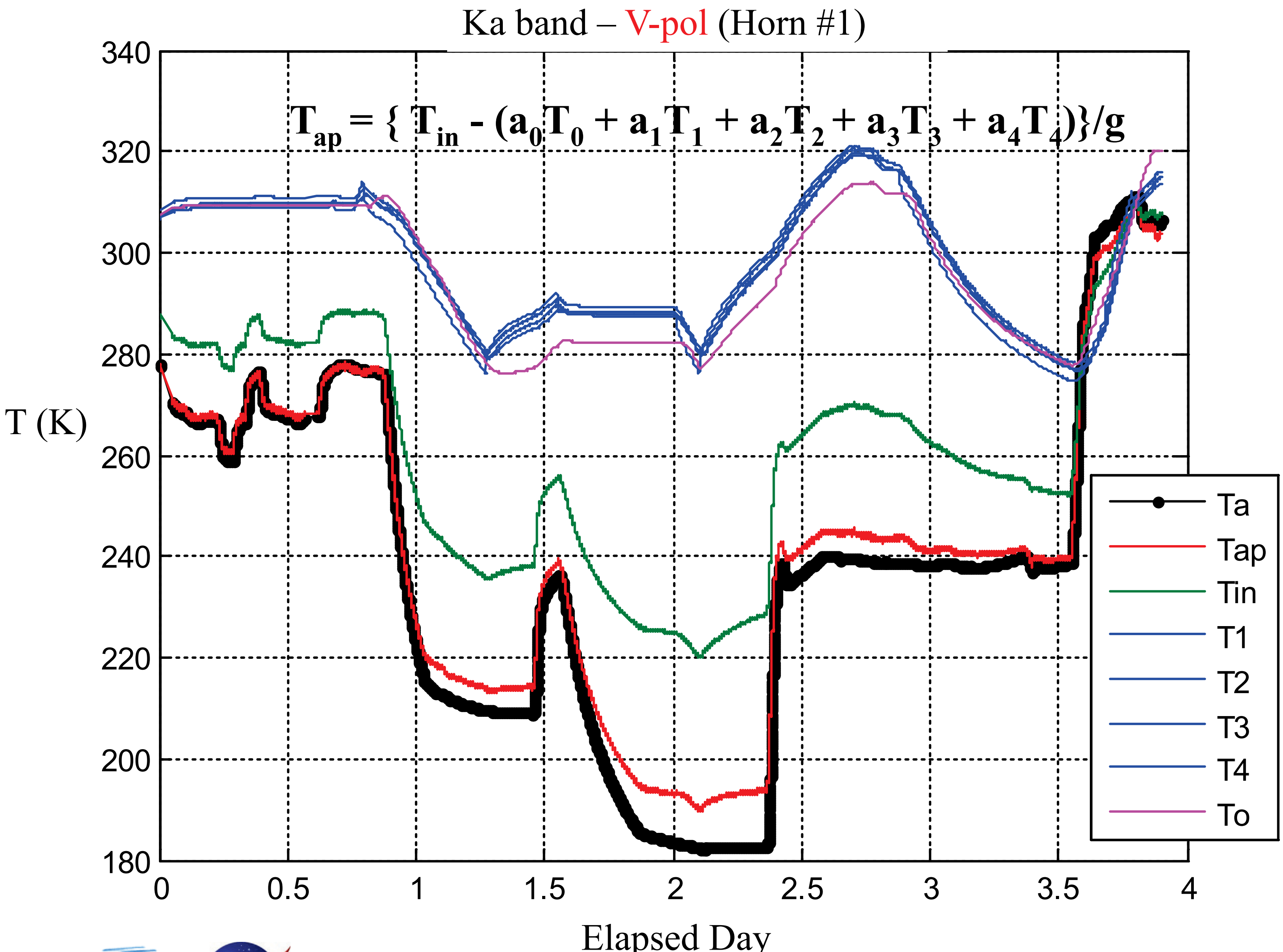
$$T_{in} = gT_{ap} + a_0T_0 + a_1T_1 + a_2T_2 + a_3T_3 + a_4T_4$$

SW Matrix Cal : Model Inversion

Ka band – H-pol (Horn #1)



SW Matrix Cal : Model Inversion



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SW Mat Cal: Need for Regression Model

- The 'a' coefficients used in the forward model based on too many assumptions
  - Standard (theoretical) silver WG loss
  - Nominal switch S – pars from manufacturer data sheet
  - Antenna aperture reflection coefficient (Γ) computed based on VSWR from the OMT data sheet (NOT individual horn measurements)
- Unfortunately no reliable end-to-end insertion loss measurement for 24 horn paths were available
- Therefore, model coefficients were derived based on only available TV test data

SW Matrix Cal: Regression Model

$$T_{ap} = b_1 + b_2T_{in} + b_3T_{in}^2 + b_4T_o + b_5T_{av}$$

$$\text{Where, } T_{av} = (T_1+T_2+T_3+T_4)/4$$

- ❑ Motivation for first 3-terms is to account for possible receiver non-linearity

  Then the real $T_{in}' = (T_{in} - a)^2$

- ❑ Since the MWR has active thermal control, the switches and horn plate temperatures are represented by uniform temperature, T_{av}

- ❑ Measured Absorber temperature (Ta) is assumed to be the horn apparent temp and is used to train the model

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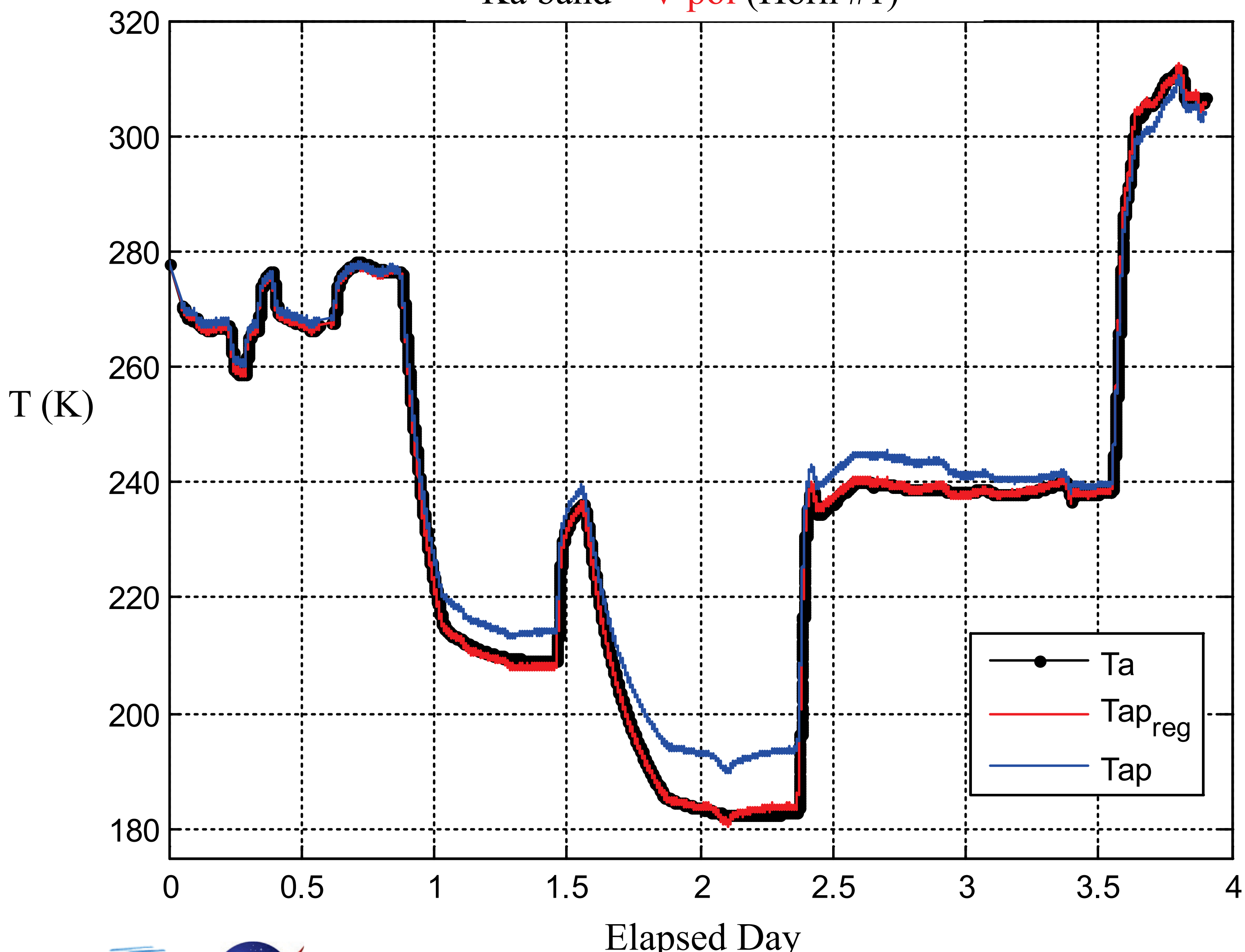
Regression Model Result

Ka band – V-pol (Horn #1)



Limitations of Pre-Launch Algorithm

- Assumption of antenna temperature (Ta) in the regression
  - Unknown emissivity of the absorber (assumed 1.0)
  - Effects of feed-horn spill-over in the TV chamber
- No Antenna Pattern Correction (APC) applied
  - No end-to-end Tb calibration using flight reflectors
  - Reflector antenna patterns limited to ± 40° about boresight (desired over ± 180°)
  - Inability to simulate effects of spacecraft on the antenna far-out sidelobes and feed spill-over

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Outline

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- Pre-Launch Calibration
  - Receiver Calibration
  - Antenna Switch Matrix Calibration
- On-orbit Calibration
- Summary & Conclusions

On-Orbit Calib Goal & Methodology

- Goal
  - Obtain an effective antenna pattern correction
    - To convert antenna temperature (Ta) to main beam brightness temperature (Tb)
  - Correct for residual radiometric calibration biases
- Method
  - Model based Tb inter-comparison with Windsat Radiometer
    - Adopted from Global Precipitation Measurement (GPM) Missions inter-satellite working group (XCAL) cross-calibration techniques
  - Double difference technique

    $MWR_{bias} = (T_a(obs) – T_b(sim))_{MWR} - (T_b(obs) – T_b(sim))_{Windsat}$

  - Bias modeled as linear function of observed T_a

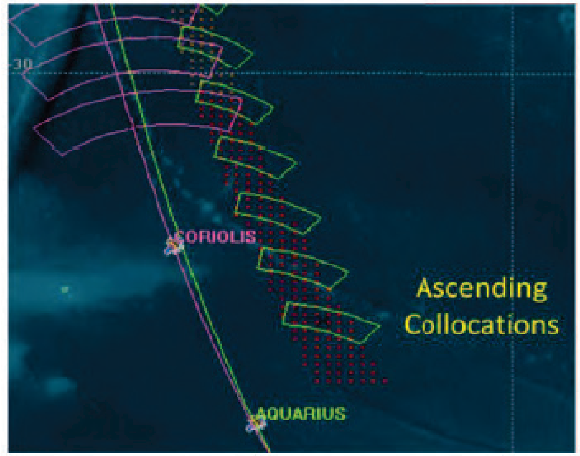
    $MWRbias = A*T_a\,(obs)_{MWR} + B$ (effective APC correction)

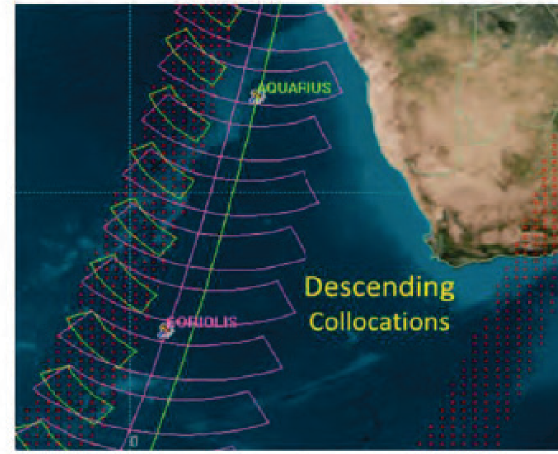
Choice of Windsat

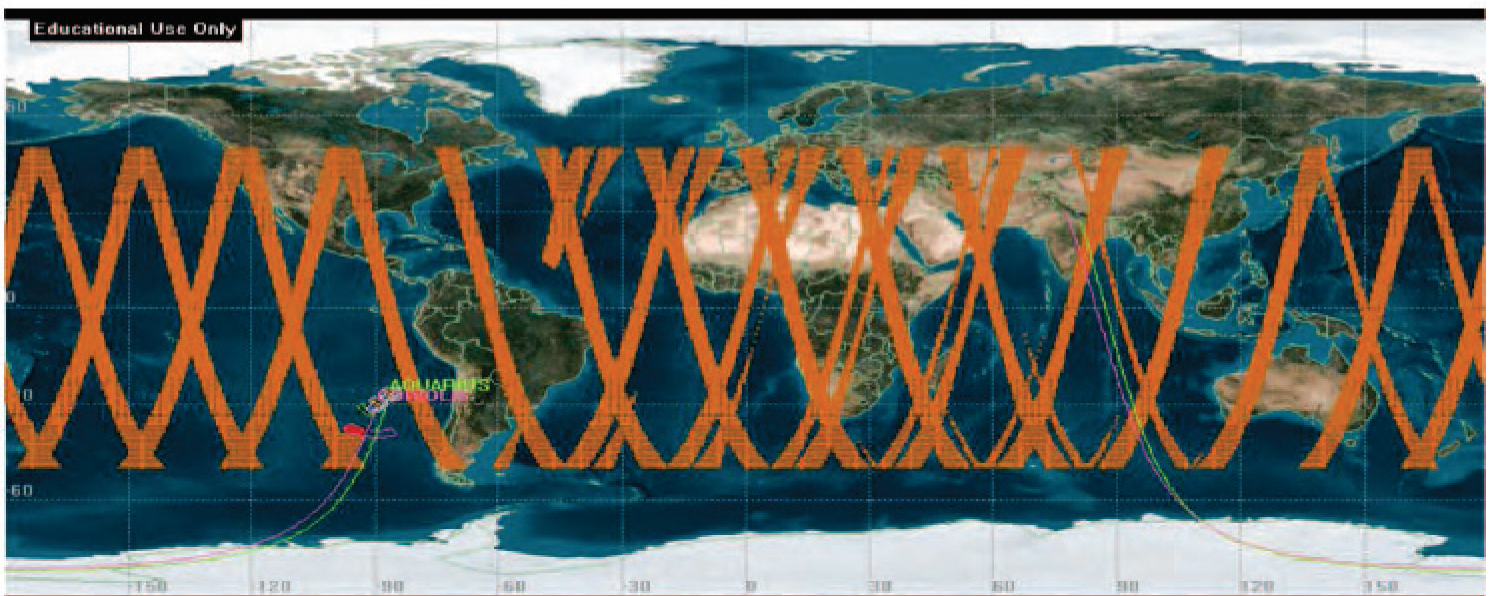
Similarities

Parameter	WindSat	MWR
Altitude	840 Km	657 Km
Eccentricity	0.00134	0.00120
Orbit Inclination	98.7°	98.01°
Ascending Node	6 p.m.	6 p.m.
Channels	6.5, 10.7, 18.7, 23.8 & 37 GHz (V,H)	23.8 GHz (H) & 36.5 GHz (V,H)
Swath Width	∼ 950 Km	∼ 380 Km
Earth Incidence Angle	53°	52° & 58°

Geometry







MWR and Windsat collocations swath in 45 hours

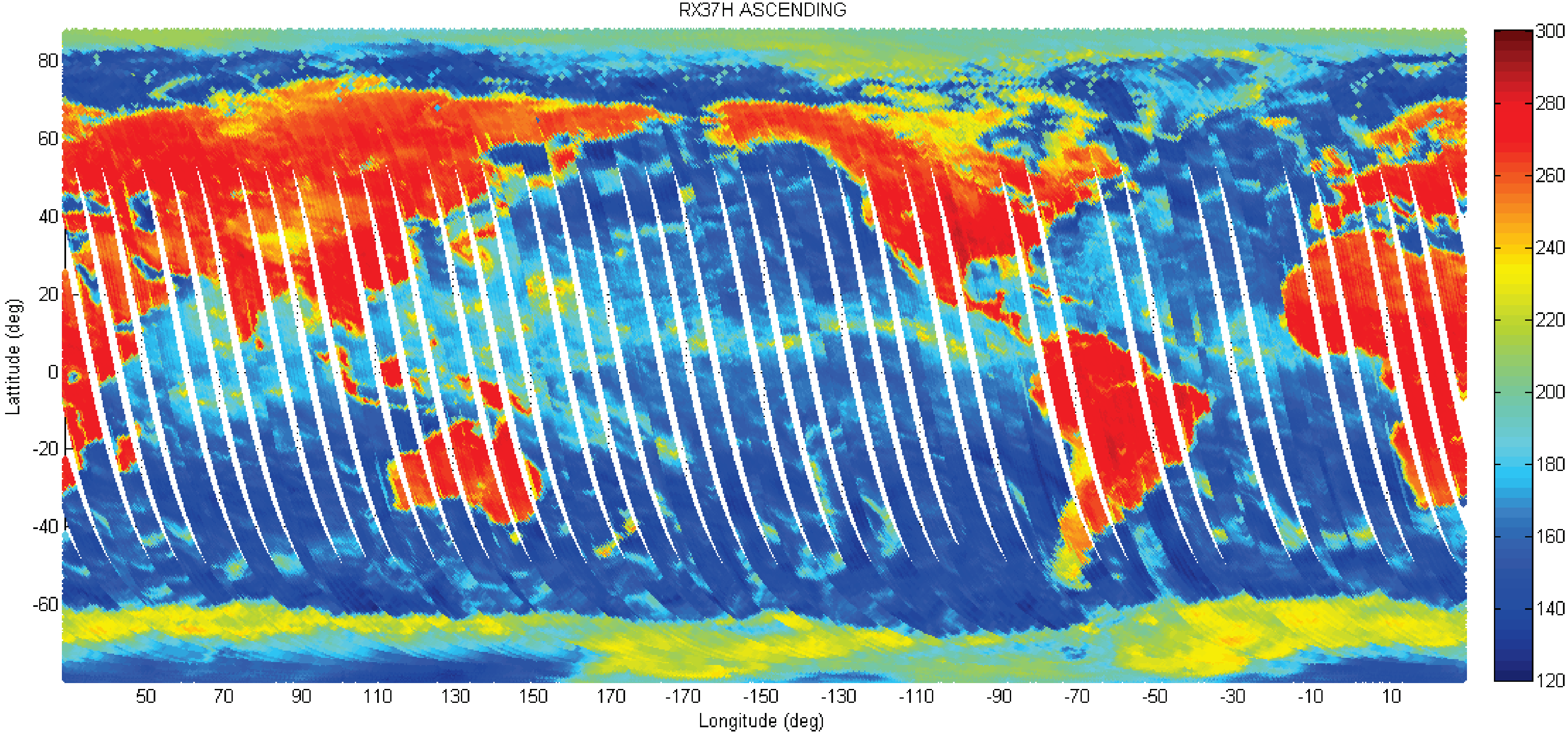
MWR OOCO Summary

OOCO – On Orbit Check Out

- MWR turn-on evening Aug 30th, 2011
- First Tb images were produced ~ 6 hours after data reception on Wed Aug 31st
- Preliminary inter-satellite Tb calibration with WindSat completed on Sunday Sept 4th
- First geophysical retrieval on Tues Sept 6th

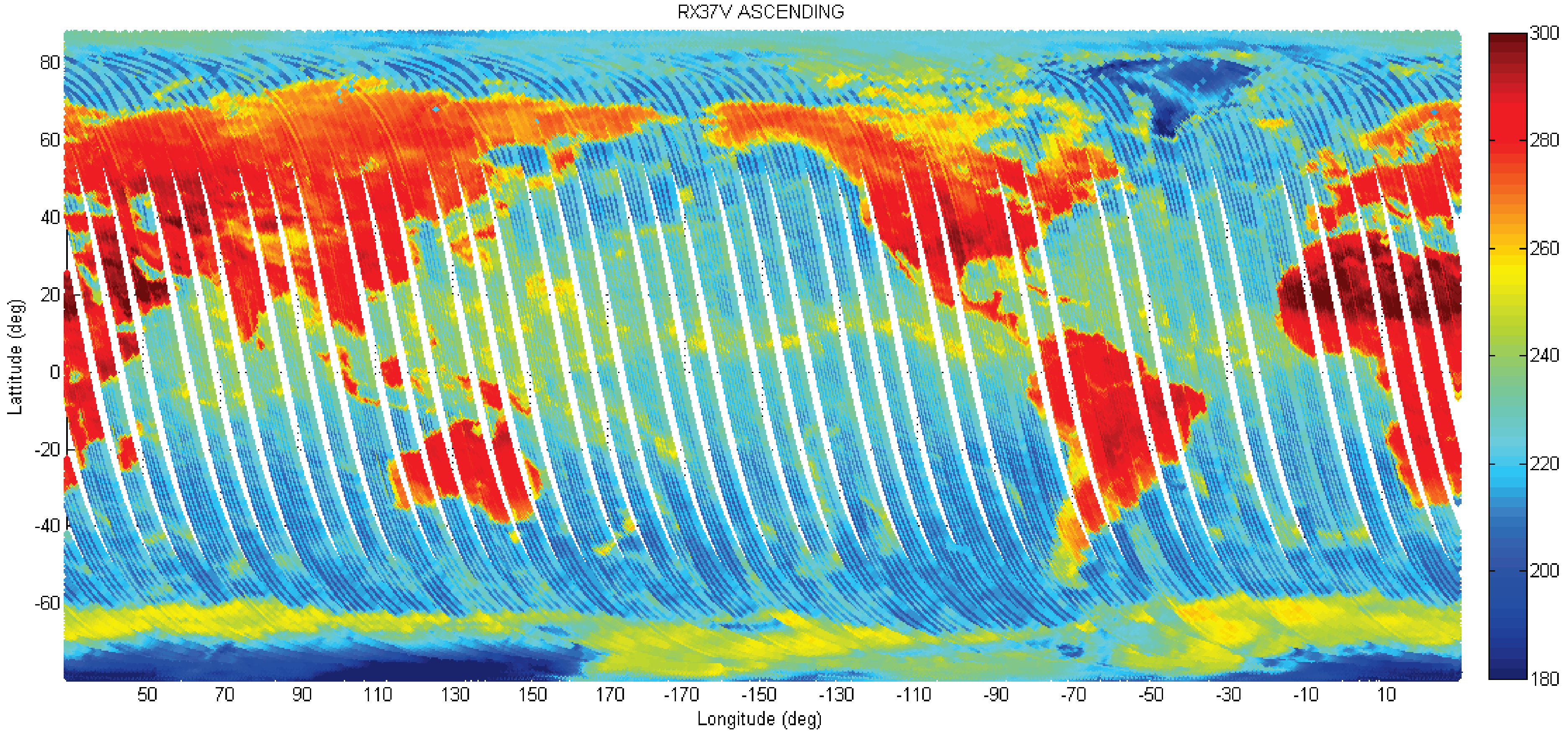
36.5 GHz H-pol T_b

First 5 days (only ascending passses)



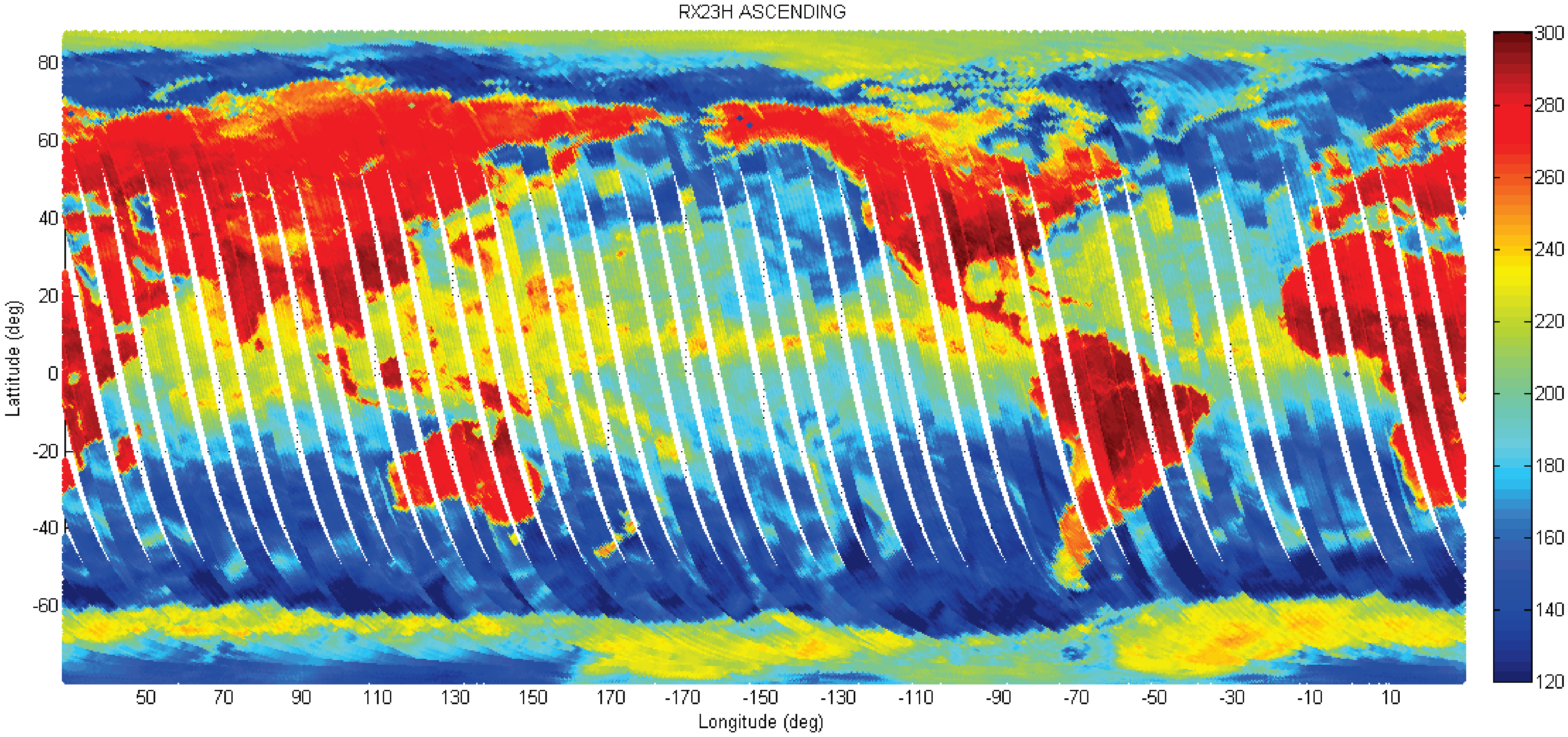
36.5 GHz V-pol T_b

First 5 days (only ascending passses)



23.8 GHz H-pol T_b

First 5 days (only ascending passses)



Inter-Satellite Radiometric Calibration

- Inter-satellite radiometric calibration(X-Cal) was performed using the WindSat radiometer

- Near simultaneous, collocated comparisons between MWR and WindSat ocean T_b's
  - Initially 65 revs of MWR T_b's used
  - MWR T_b s converted to 53° Earth Incidence Angle (Using Radiative Transfer Model) before WindSat comparison
  - Collocation cells were 1° x 1° Lat-Lon boxes
  - Comparisons performed per beam basis (24 total)

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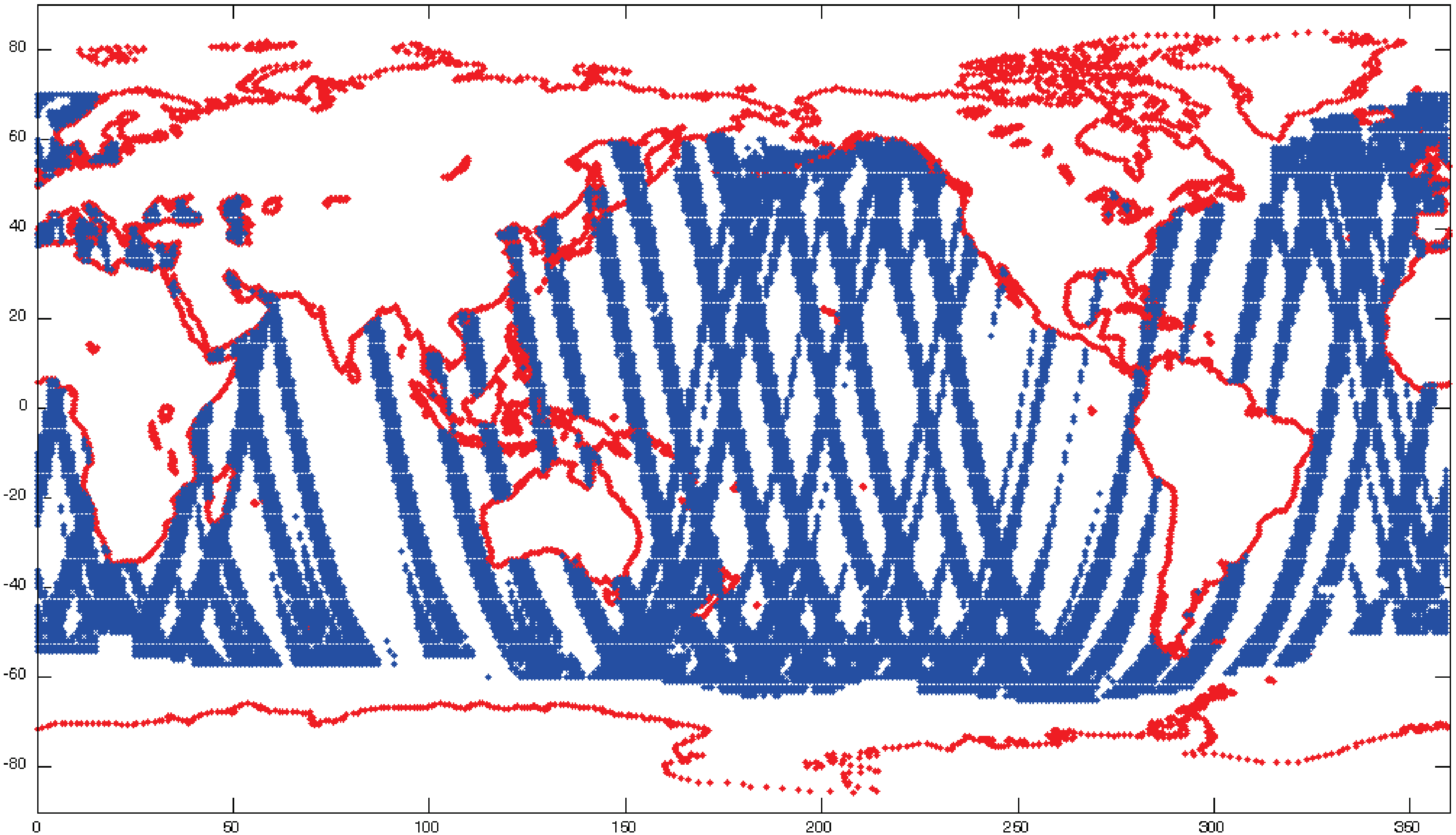
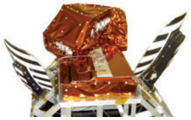
MWR-Windsat Collocations



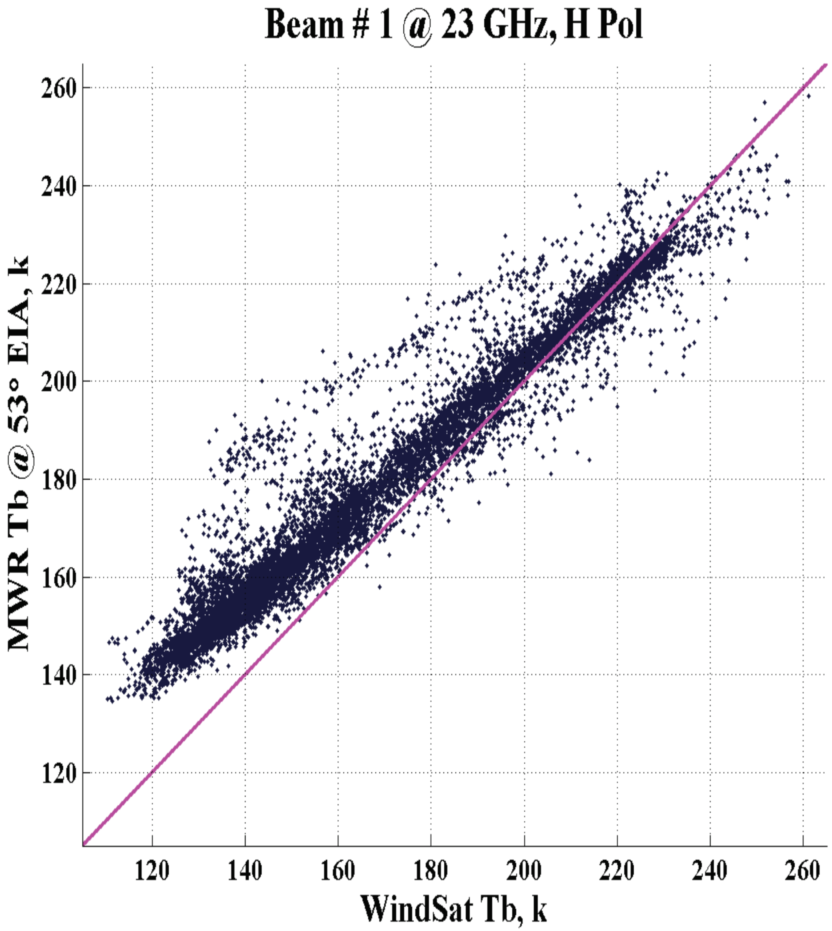
1° x 1° collocations for 65 revs of MWR T_bs used



Example Beam # 1, 23 GHz H-pol

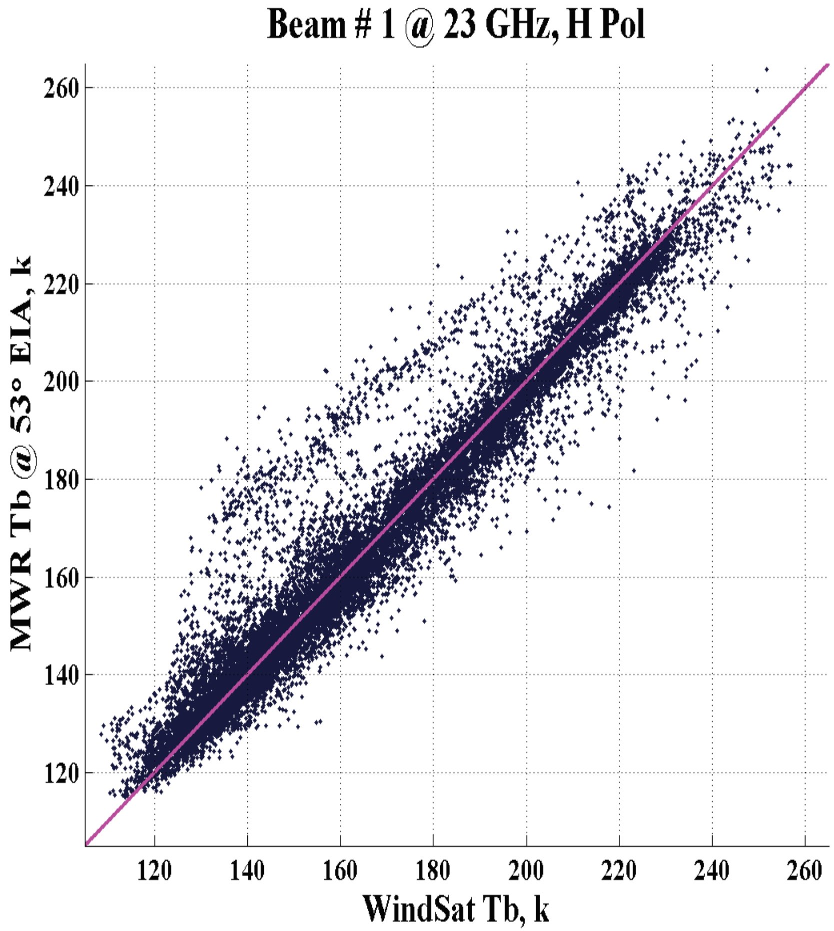
Pre-Launch

T_b v2.0



Post-Launch

T_b v2.1



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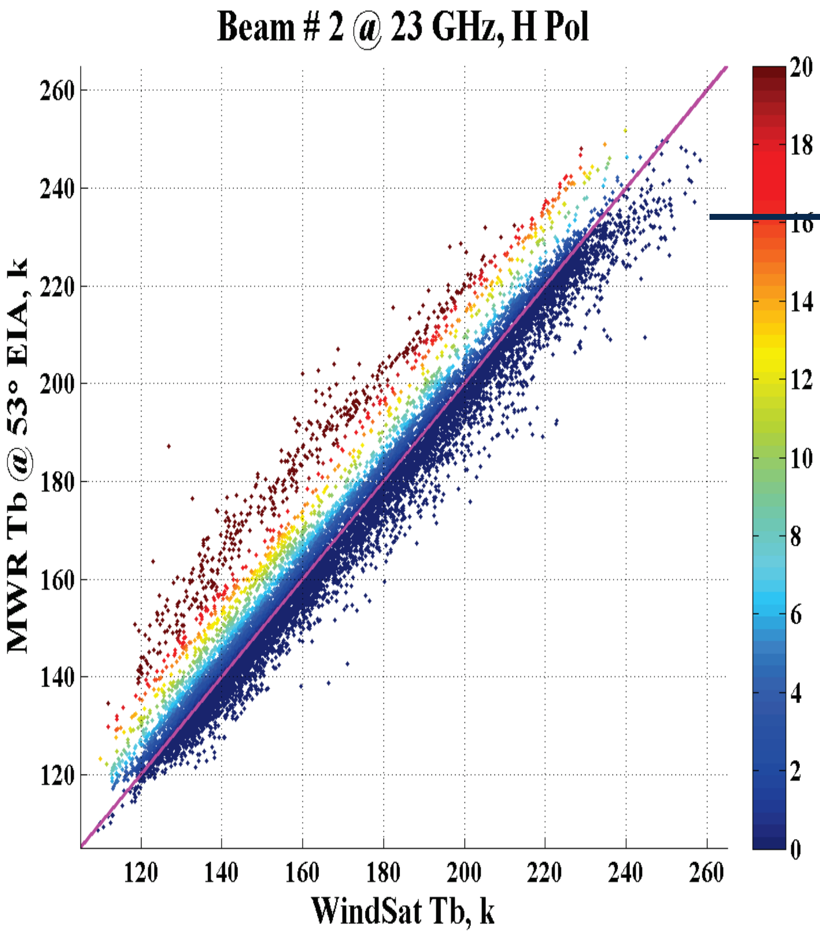
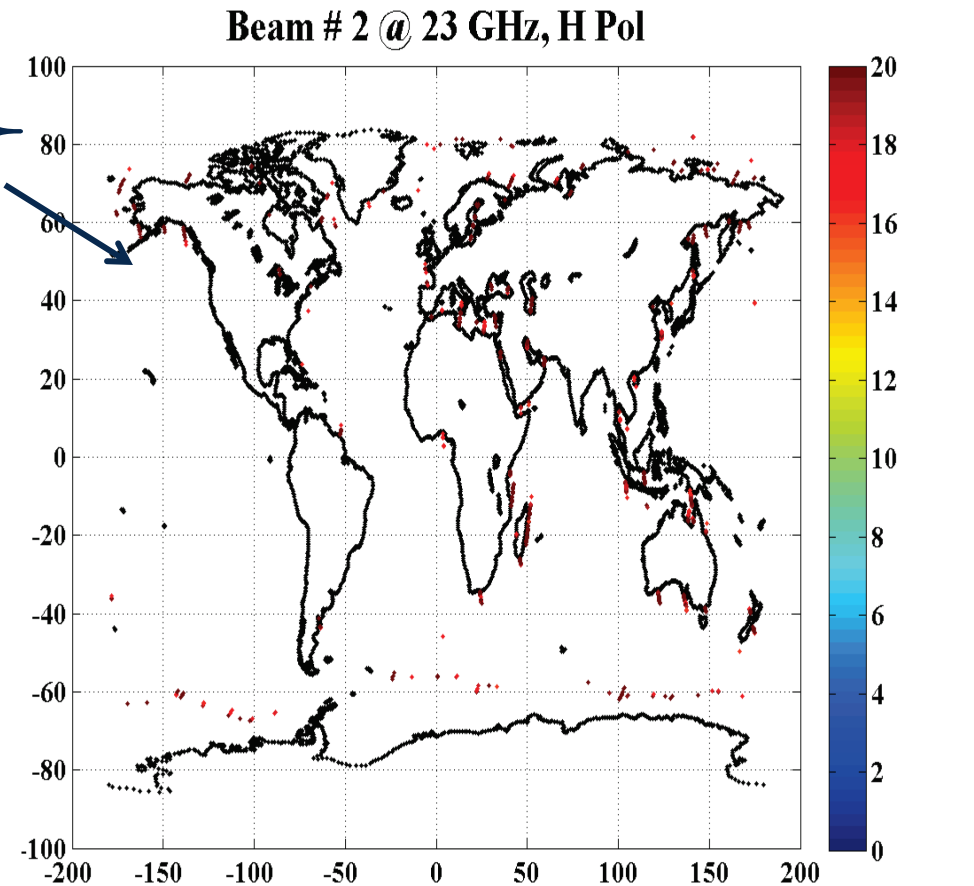
Beam # 2, 23 GHz H-pol

Locations of outlier points are associated with land masses and sea ice and therefore should be deleted from ocean calibration





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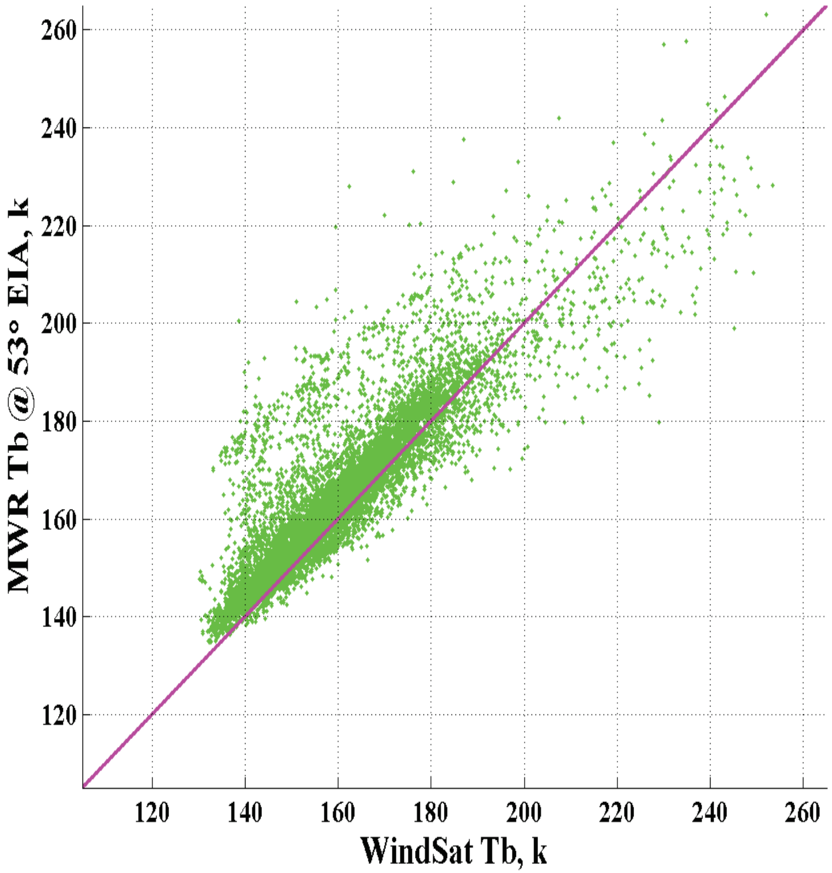
Beam # 1, 37 GHz H-pol

Pre-Launch

T_b v2.0

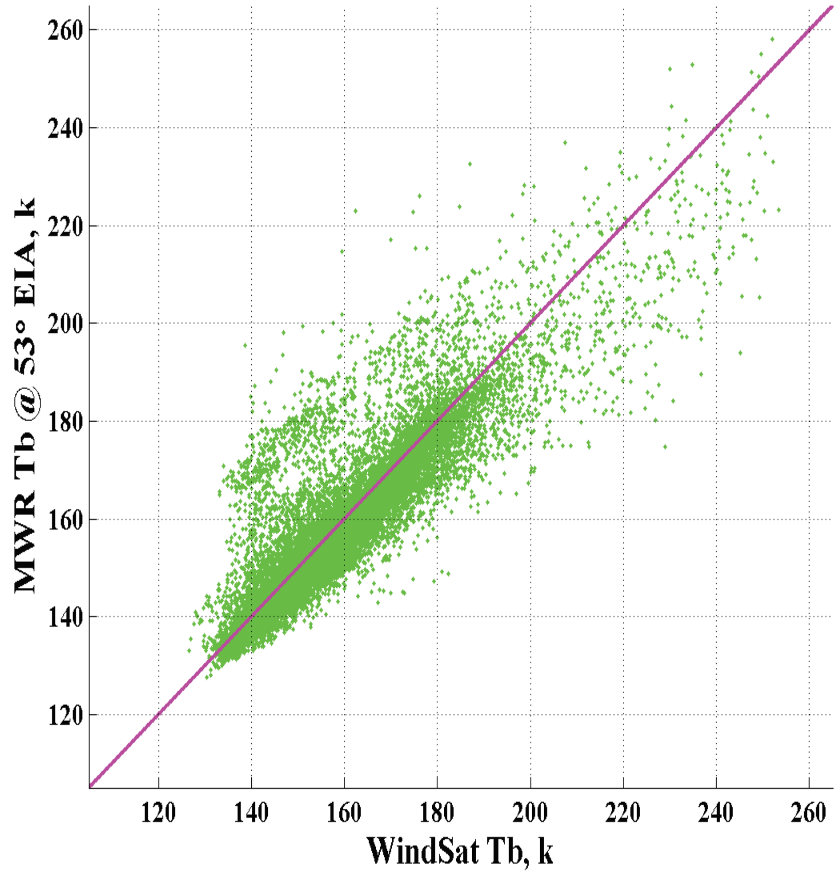
Beam # 1 @ 37 GHz, H Pol



Post-Launch

T_b v2.1

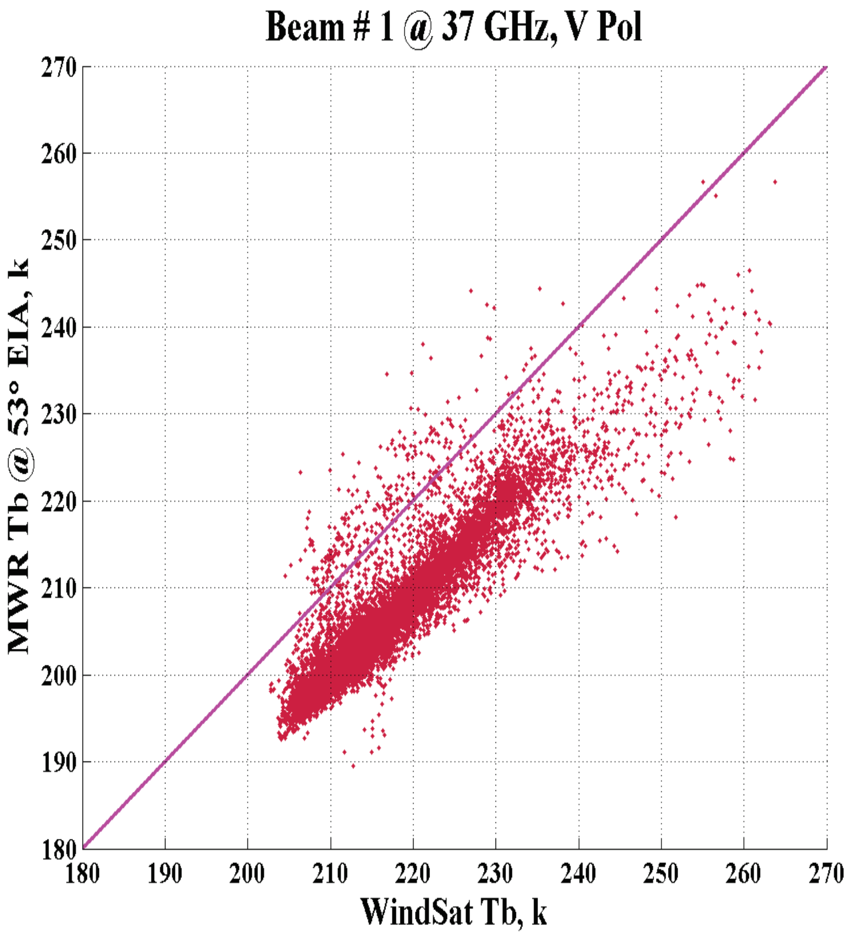
Beam # 1 @ 37 GHz, H Pol



Beam # 1, 37 GHz V-pol

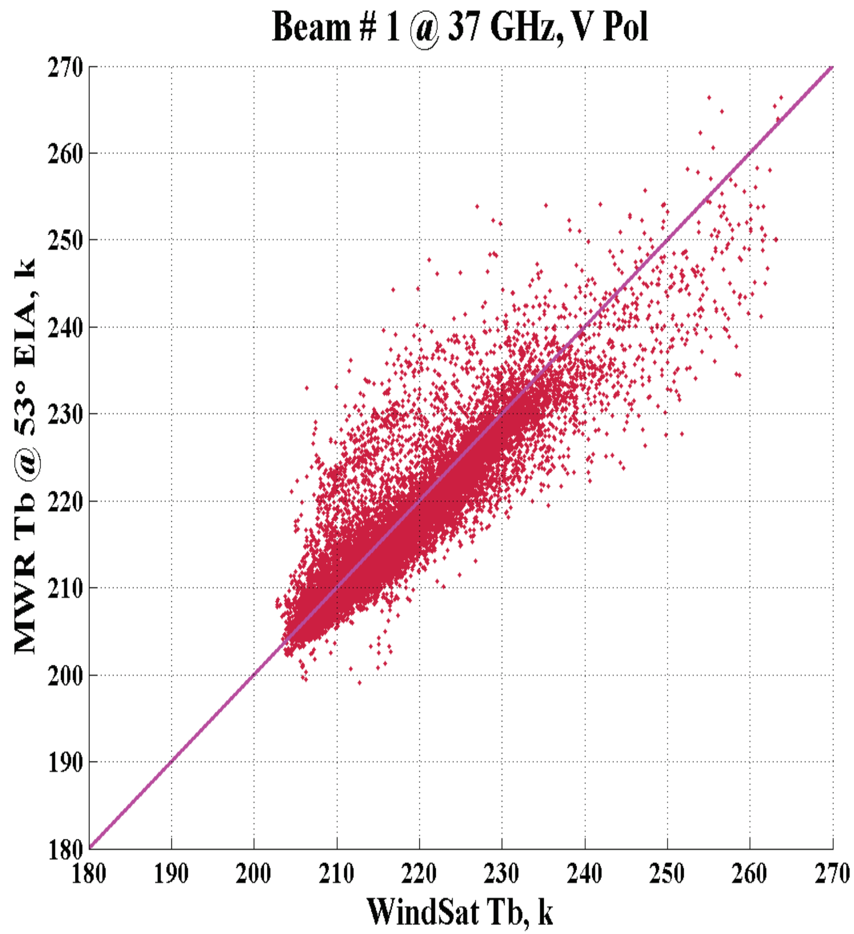
Pre-Launch

T_b v2.0



Post-Launch

T_b v2.1



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Calibration Algorithm v2.2

- The slope-offset correction coefficients from the v2.1 algorithm was further tuned after obtaining 127 orbits of MWR/WindSat collocations

- Final APC with correct beam balancing (v2.2)

- The following charts compare orbital average histograms of MWR biases
  - Pre-launch (v2.0) algorithm and the final post-launch algorithm (v2.2)

$$MWR_{bias} = (T_a(obs) - T_b(sim))_{MWR} - (T_b(obs) - T_b(sim))_{Windsat}$$

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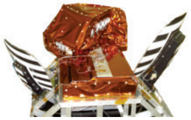
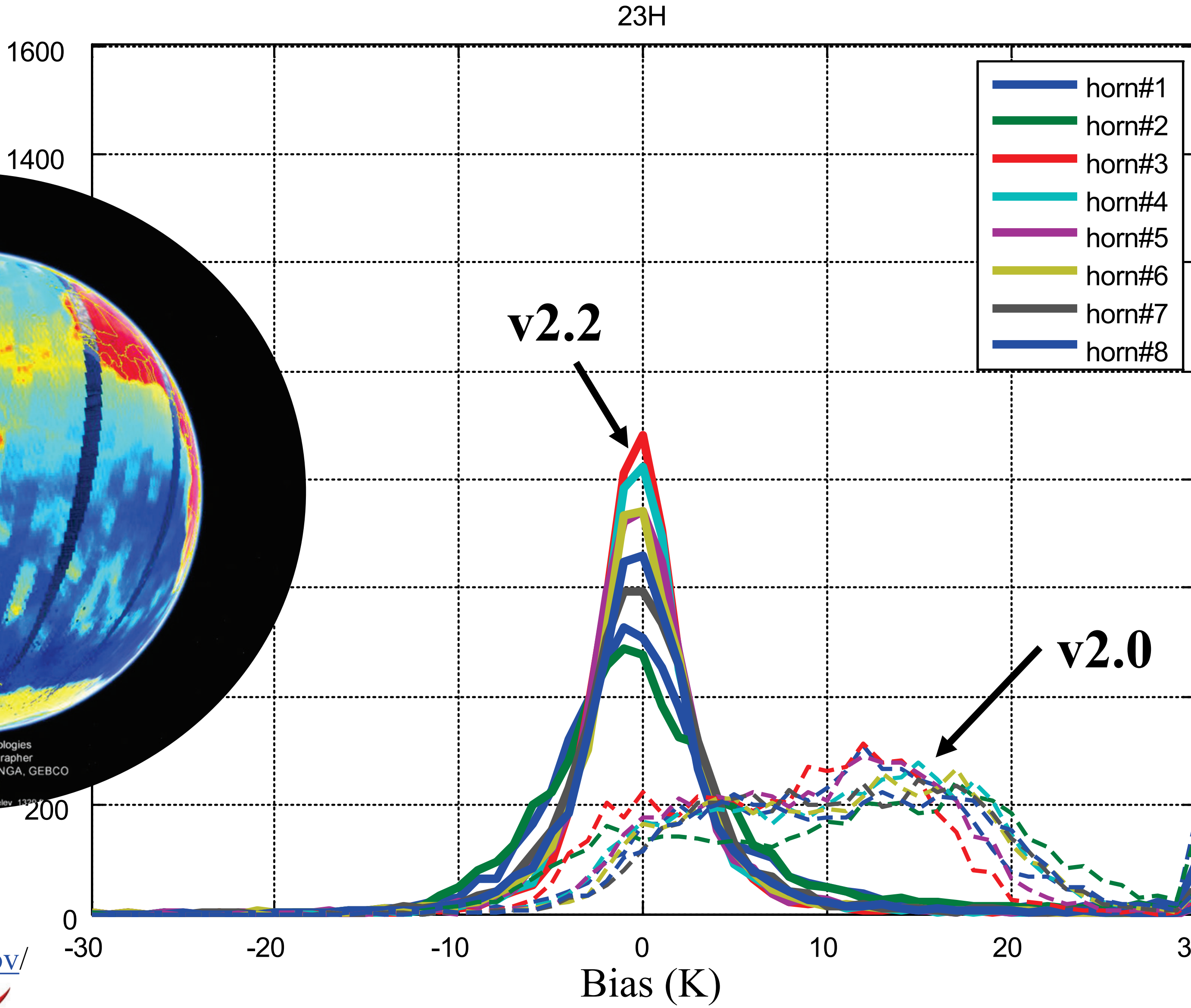
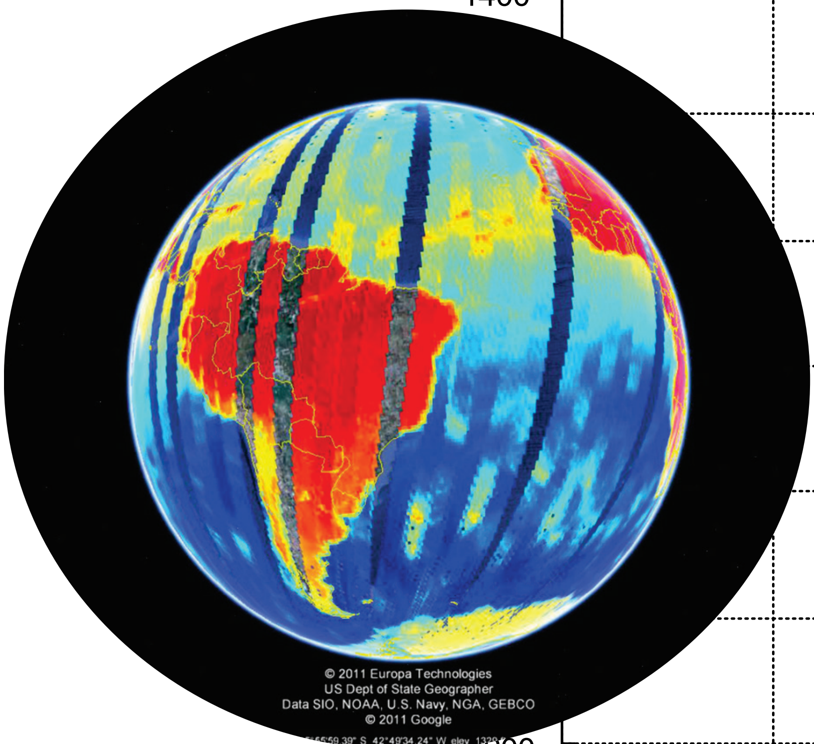


23.8 GHz H-pol Bias Histogram





v2.2

v2.2 MWR T_b Data

ftp://aqst@podaac.jpl.nasa.gov/

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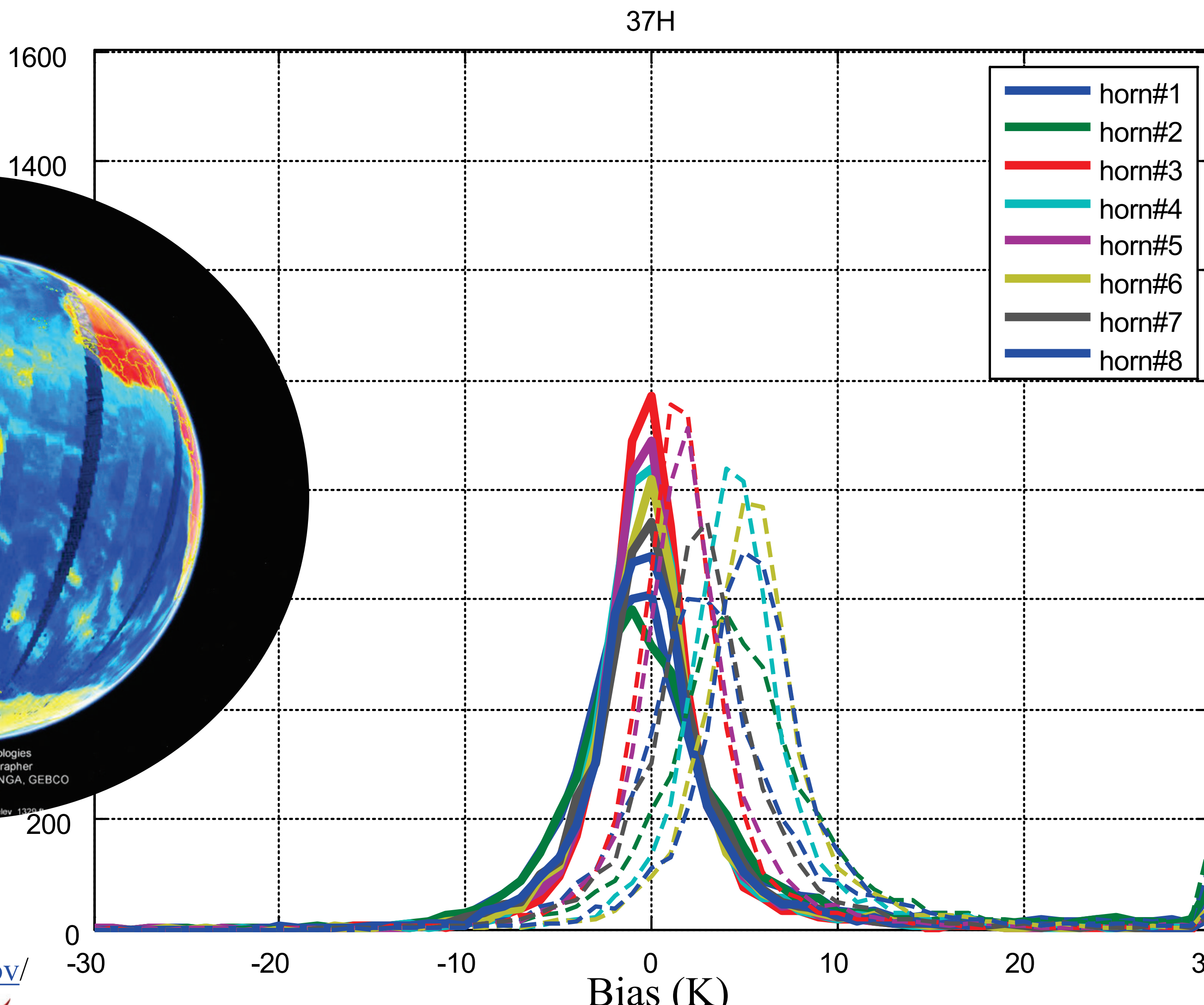
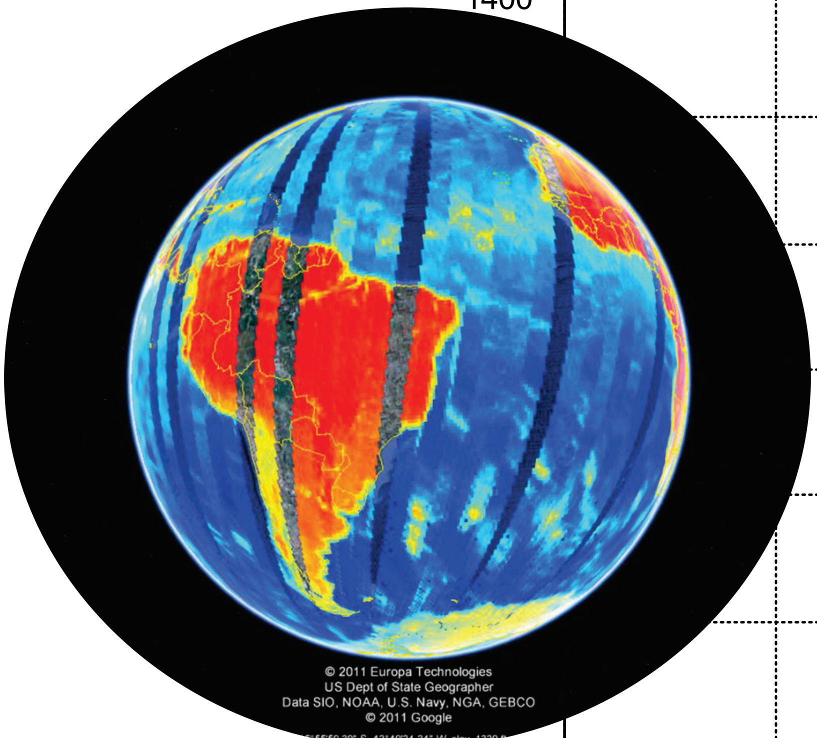
36.5 GHz H-pol Bias Histogram





v2.2

v2.2 MWR T_b Data

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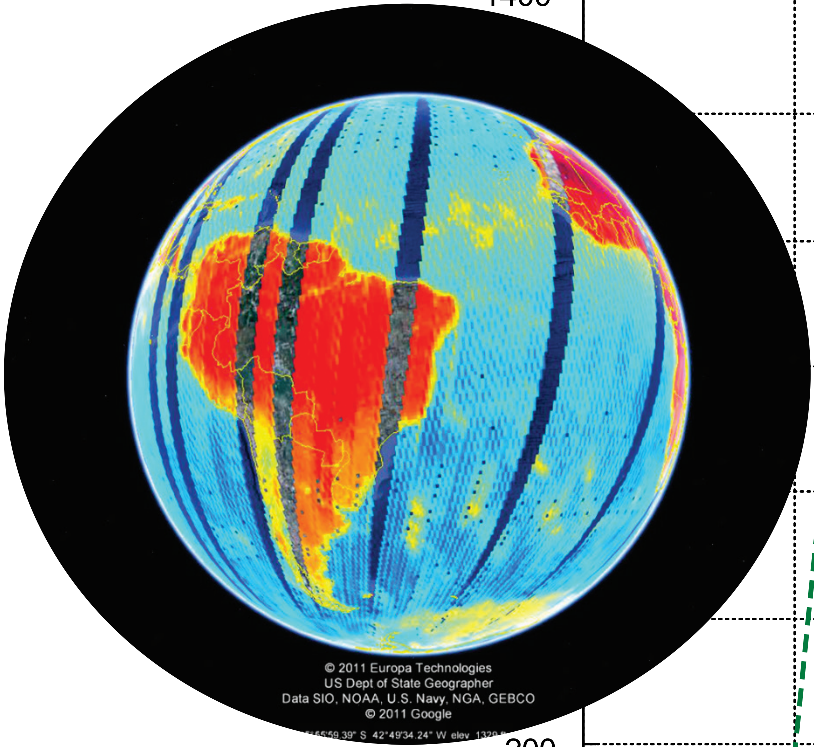
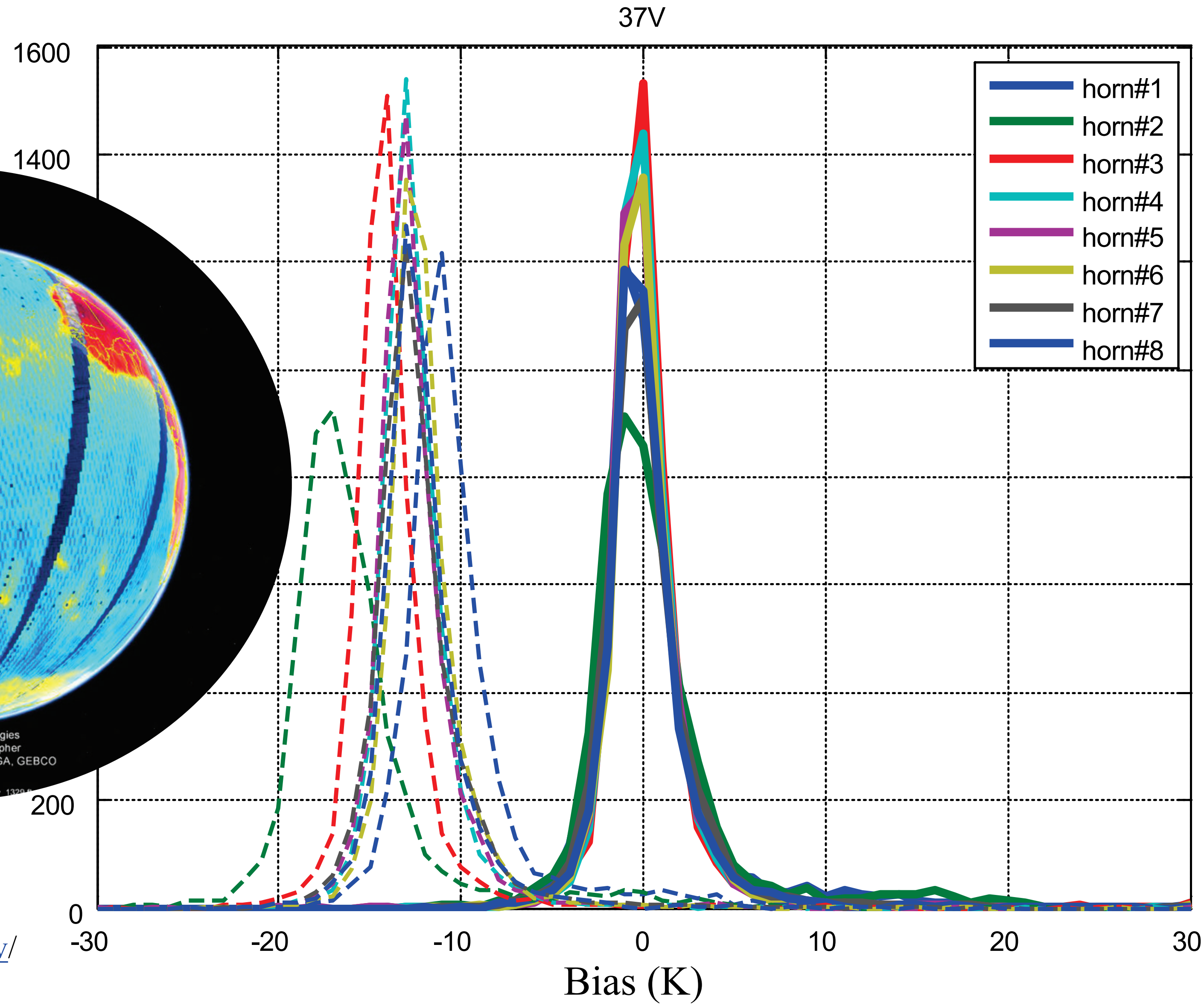
36.5 GHz V-pol Bias Histogram





v2.2

v2.2 MWR T_b Data

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Summary & Conclusions

Pre-Launch Calibration

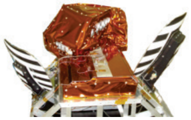
- ❑ Simplified radiometric calibration model developed
- ❑ Receiver transfer function calibration (Lab test)
- ❑ Theoretical transfer function for antenna switch matrix
  - Coefficients based on nominal losses
  - Model evaluation using TV test data
- ❑ Regression based model development

On-orbit Calibration

- ❑ APC and residual bias correction
- ❑ Removal of inter-beam biases (normalize beam T_b's)

Future Work

- Monitor trends in T_b bias over 1 year Cal/Val period
  - Characterize seasonal and annual T_b bias variation
- Establish a more accurate radiative transfer model for the MWR antenna switching matrix
  - Accurate determination of transmission losses of 24 feed-horn paths using detailed analysis of on-orbit deep space calib data
- Derivation of accurate APC and separation of other biases
  - Strong biases due to land contamination are present in some of the horns
- Calibration of the +45° & -45° polarization channel for the Ka band system



Publications

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[1] **Sayak Biswas**, Kaushik Gopalan, Linwood Jones and Steve Bilanow, “Correction of Time-Varying Radiometric Errors in Version 7 of TRMM Microwave Imager Calibrated Brightness Temperature Product,” *IEEE Geosci. And Rem. Sens. Letters*, vol. 7, NO 4. Oct 2010.

[2] Kaushik Gopalan, Linwood Jones, **Sayak Biswas**, Steve Bilanow, Thomas Wilheit and Takis Kasparis, “A Time-Varying Radiometric Bias Correction for the TRMM Microwave Imager”, *IEEE Trans. GeoSci. Rem. Sens*, vol. 47, NO. 11, Nov 2009.

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[3] Gopalan,Kaushik, **Sayak Biswas**, Linwood Jones, Stephen Bilanow and Thomas Wilheit, "A Time-Varying Radiometric Bias Correction for the TRMM Microwave Imager and Inter-Satellite Radiometric Calibration with WindSat and SSMI", *Proc. of MicroRad2010*, March 1-4, 2010, Washington DC.

[4] **Biswas,Sayak**, Linwood Jones, Salman Khan, Juan-Cruz Gallo and Daniel Rocca, "MWR and WindSat Inter-Satellite Radiometric Calibration Plan", *Proc. of MicroRad2010*, March 1-4, 2010, Washington DC.

[5] El-Nimri S, Jones W L, Crofton S and **Biswas S**, "An improved wide band ocean emissivity radiative transfer model", *in the proceedings of Geoscience and Remote Sensing Symposium(IGARSS)*, July 25 30, 2010, Honolulu, HI.

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[6] Timothy L. Miller, NASA/MSFC, Huntsville, AL; and M. W. James, L. Jones, C. S. Ruf, E. W. Uhlhorn, M. C. Bailey, C. D. Buckley, D. E. Simmons, S. Johnstone, A. Peterson, L. A. Schultz, **S. Biswas**, J. W. Johnson, G. Shah, D. Fenigstein, W. H. Cleveland, J. Johnson, and R. E. Hood, "Observations during GRIP from HIRAD: Ocean surface wind speed and rain rate", *91st Annual Meeting of American Metereological Society (AMS)*, Jan. 23-27, 2011, Seattle, Washington.

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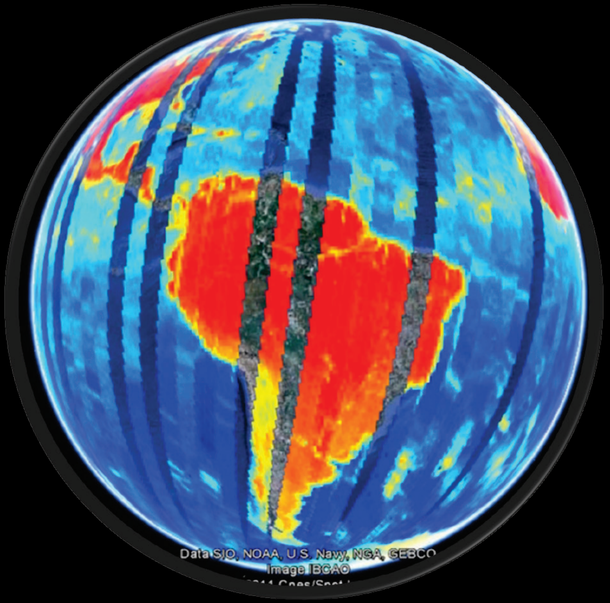
[7] Kaushik Gopalan, **Sayak Biswas**, W. Linwood Jones, Takis Kasparis and"Inter-Satellite Radiometric Calibration of WindSat, TMI and SSMI", *PMM Internat. Sci. Team meeting*, Aug. 4 - 7, 2008, Fort Colins, CO.

[8] W. Linwood Jones, **Sayak Biswas**, Juan Cruz Gallo and Daniel Rocca, "Post-Launch Radiometric Calibration for the Microwave Radiometer (MWR)", *4th Aquarius/SAC-D Internat. Sci Workshop*, Dec. 3-6, 2008 Puerto Madryn, Chubut, Argentina.

[9] Juan Cruz Gallo, Daniel Omar Rocca, Linwood Jones and **Sayak Biswas**, "MWR Calibration, Pre-launch and Post-launch", *6th Aquarius/SAC-D International Science Symposium*, Jul. 19-21, 2010, Seattle, WA.

THANK

Y  U !