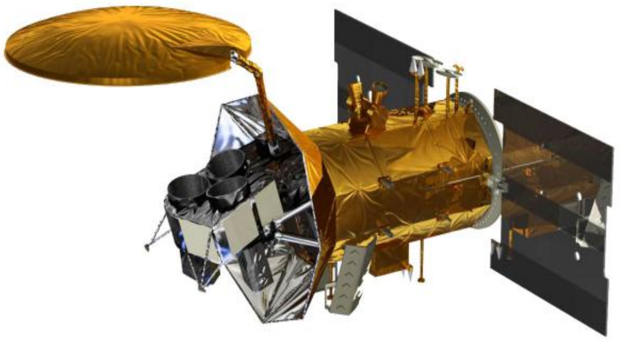
Microwave Radiometer (MWR) Counts to Tb (Brightness Temperature) Algorithm Development (Version 6.0) and On-Orbit Validation



Zoubair Ghazi

CFRSL –Central Florida Remote Sensing Lab

Dissertation Defense
October 24, 2014

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Dissertation Objective

- To develop an improved counts to brightness temp (Tb) algorithm for the CONAE Microwave Radiometer on the Aquarius/SAC-D satellite
- Validation of Tb measurements using inter-satellite radiometric comparisons (X-CAL)
- Produce an Algorithm Theoretical Basis Document (ATBD) and deliver prototype MatLab code to CONAE

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MWR Counts-to-Tb Algorithm History

- Post-launch CFRSL & CONAE evaluated MWR counts-to-Tb algorithm V5.0
  - Used 6 mo of MWR on-orbit collocation with WindSat
    - Ocean Tb's exhibited small and acceptable Tb biases
    - Land Tb's exhibited anomalous behavior
      - Land/water Tb transitions were "Smeared"
      - Step function changes of noise diode deflections
- Based upon on-orbit evaluation, it was concluded that:
  - V5.0 was unacceptable for producing MWR science data
  - An improved counts-to-Tb algorithm must be developed to address the anomalous Tb effects
- Further, CONAE developed a revised Counts-to-Tb algo V5.0S that included a smear correction

- **This was the starting point for my dissertation research**

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My Research Approach

1. Evaluated the MWR counts-to-Tb algorithm V5.0S
   - On-orbit X-CAL with WindSat indicated that
     - Smear effects at land/water boundaries were removed
     - However, anomalous effect of noise diode deflections remained
   - Determined that MWR system gain varied with scene Tb
2. Developed a forward model for MWR system Counts-to-Tb
   - Empirically derived coefficients to match on-orbit observations, including deep space calibrations
   - Characterized model coefficients versus scene Tb
3. Developed a gain non-linearity correction
4. Implemented a new inverse model Counts-to-Tb algorithm V6.0
5. Validated algorithm using X-CAL with WindSat

Introduction to Aquarius/SAC-D and MWR

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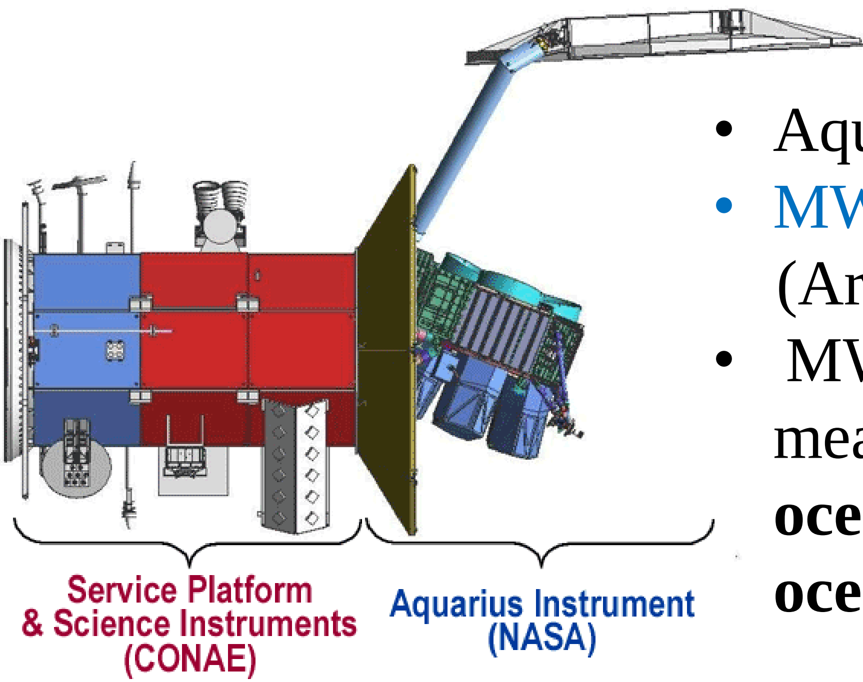
Aquarius/SAC-D Mission

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 instrument - NASA
- MWR - CONAE
  (Argentinian Space Agency)
- MWR provides auxiliary environ measurements: **water vapor, ocean surface wind speed, and oceanic rain rate**

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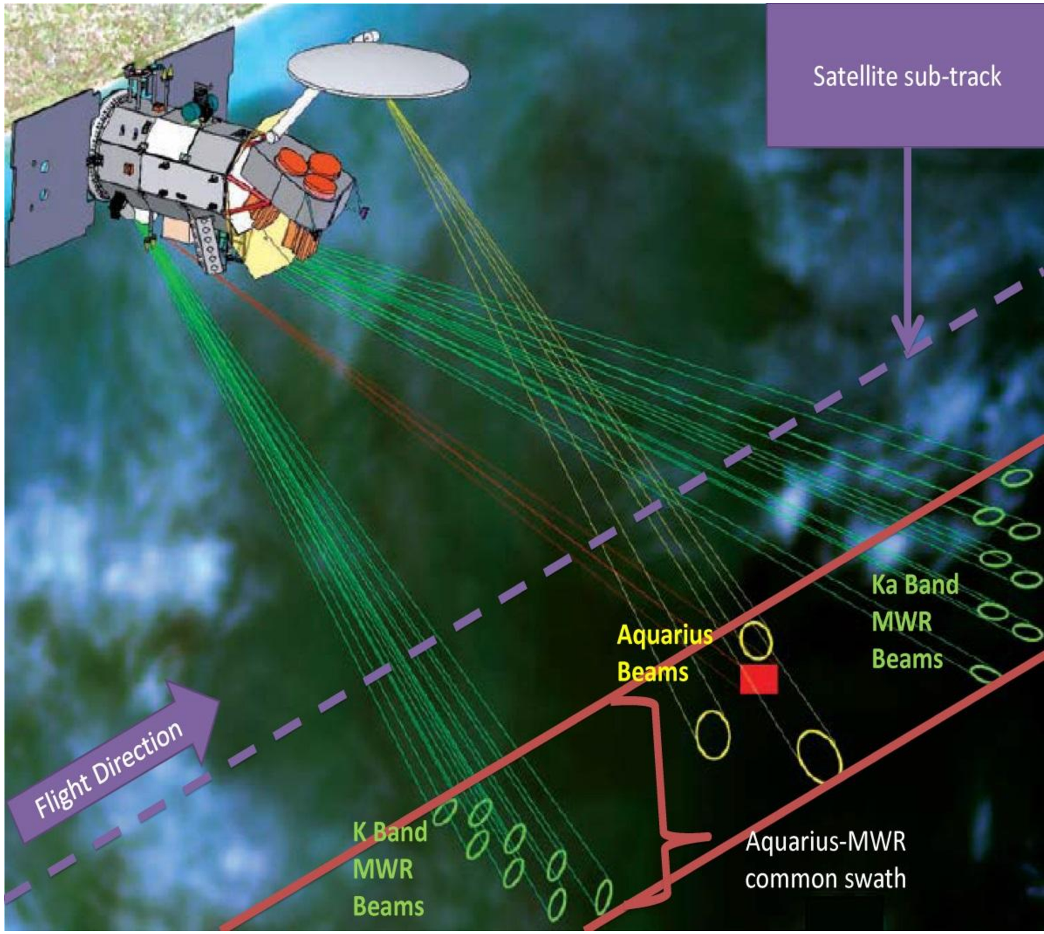
Microwave Radiometer - MWR

MWR supports AQ science by measuring simultaneous & collocated ocean brightness temperatures *(Tb)*

- 3 channel push-broom Dicke radiometer:
  - 36.5 GHz H- & V-Pol (forward-look)
  - 23.8 GHz H-Pol (aft-look)
- Earth Incidence angle
  - 52^{o} for odd beams
  - 58^{o} for even beams
- Matches the AQ swath width of 380 km



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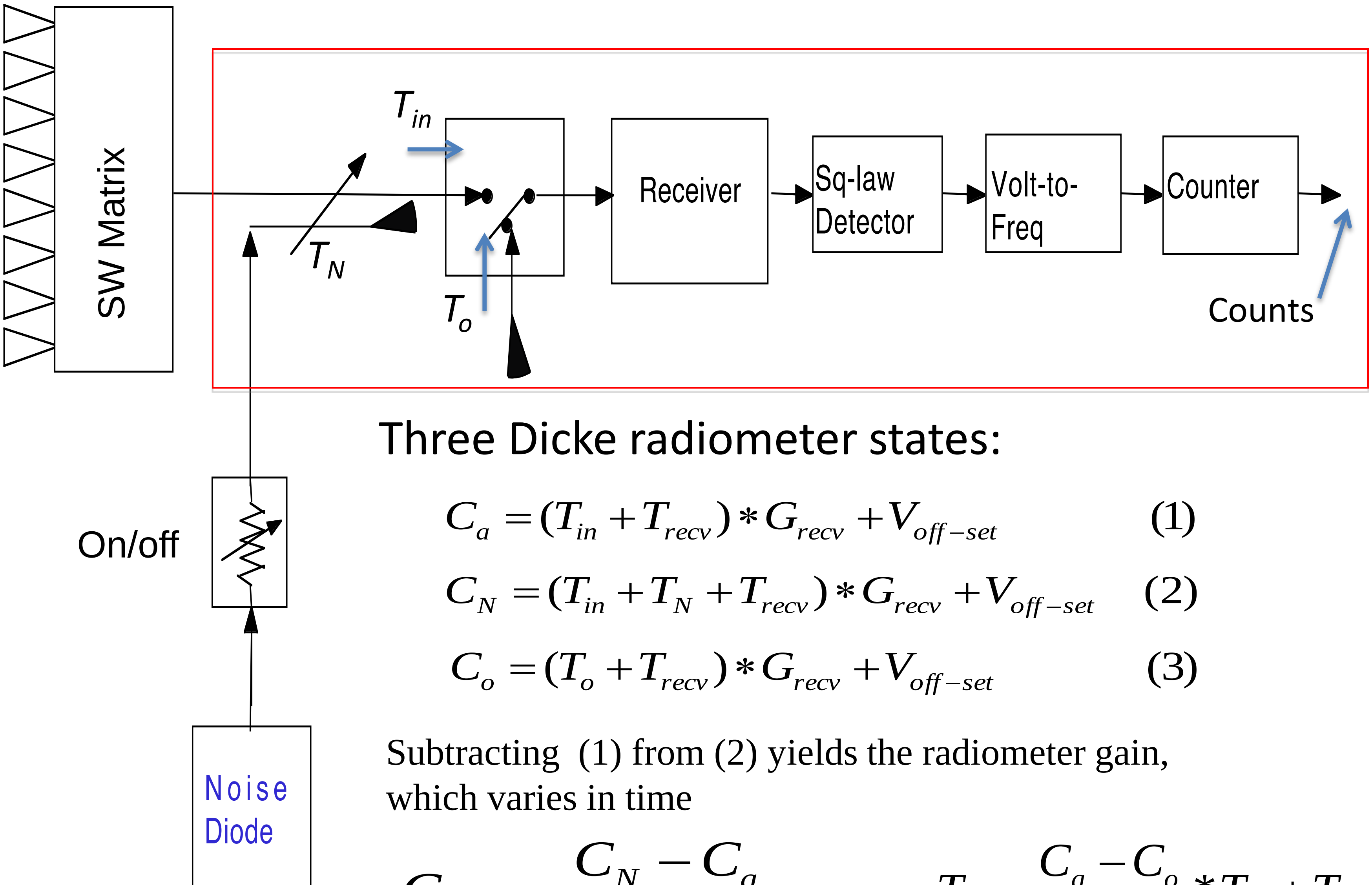
MWR Single Channel Block Diagram



Three Dicke radiometer states:

$$C_a = (T_{in} + T_{recv}) * G_{recv} + V_{off-set} \quad (1)$$

$$C_N = (T_{in} + T_N + T_{recv}) * G_{recv} + V_{off-set} \quad (2)$$

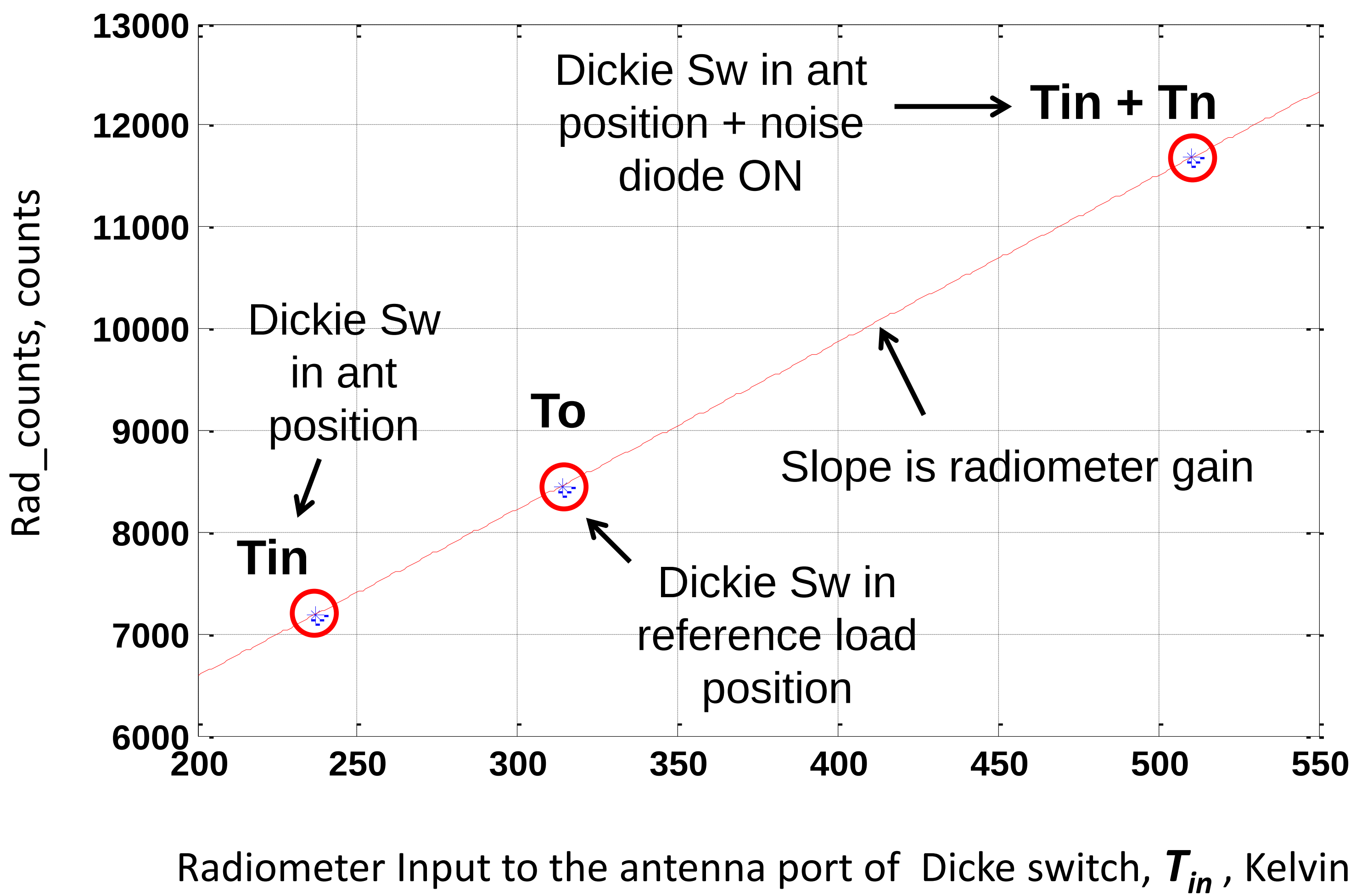
$$C_o = (T_o + T_{recv}) * G_{recv} + V_{off-set} \quad (3)$$

Subtracting (1) from (2) yields the radiometer gain, which varies in time

$$G_{recv} = \frac{C_N - C_a}{T_N}$$

$$T_{in} = \frac{C_a - C_o}{C_n - C_a} * T_N + T_o$$

Example: Dicke Radiometer Transfer Function (for constant gain)



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On-Orbit MWR Transfer Function

- Our objective was to determine the MWR transfer function based upon on-orbit measurements
- However, under typical on-orbit condition, the radiometer system gain will vary cyclically (once/orbit) due to the receiver physical temperature changes
- Therefore, a procedure was developed to synthesize **rad_counts @ constant system gain** from MWR measurements

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Counts Normalization Procedure to Remove Variable Receiver Gain

- Time variable gain was removed and all counts were normalized using the following equation:

$$Co_{norm_i} = Co_i * \frac{< Gain >}{Gain_i}$$

$$Co_i = (To_i + < Trec >) * Gain_i$$

To_i	is the instantaneous reference load physical temperature, Kelvin
$<Trec>$	is the orbit average receiver noise temperature
$Gain_i$	is the instantaneous system gain
$<Gain>$	is the orbit average gain

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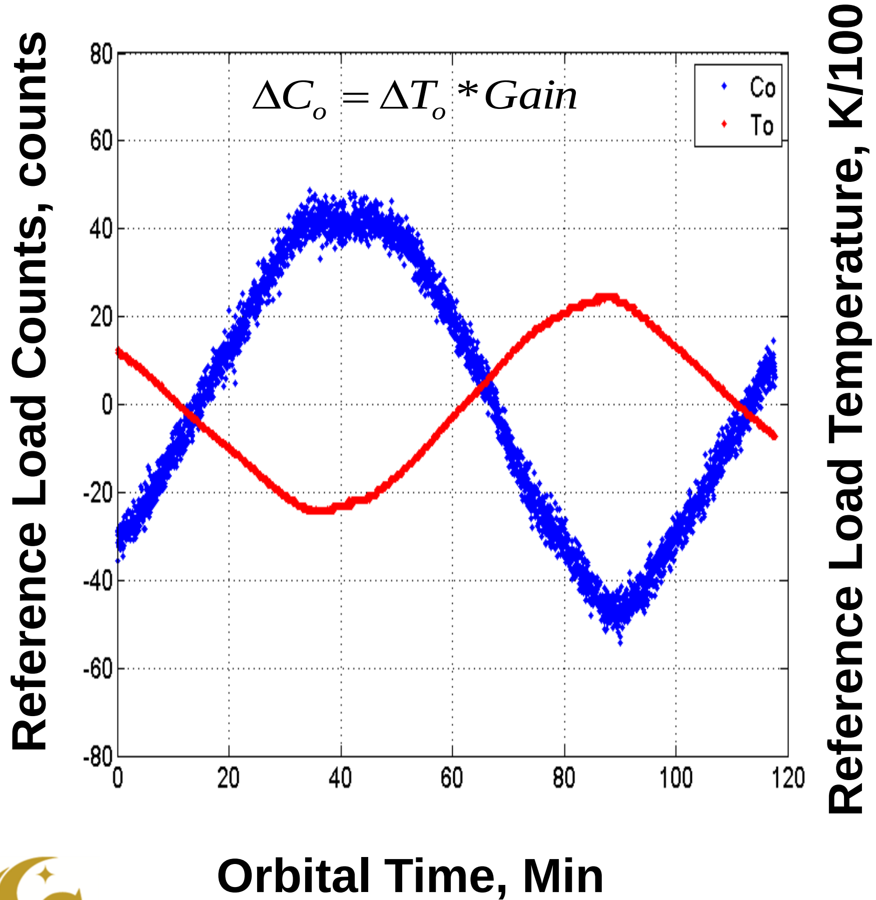
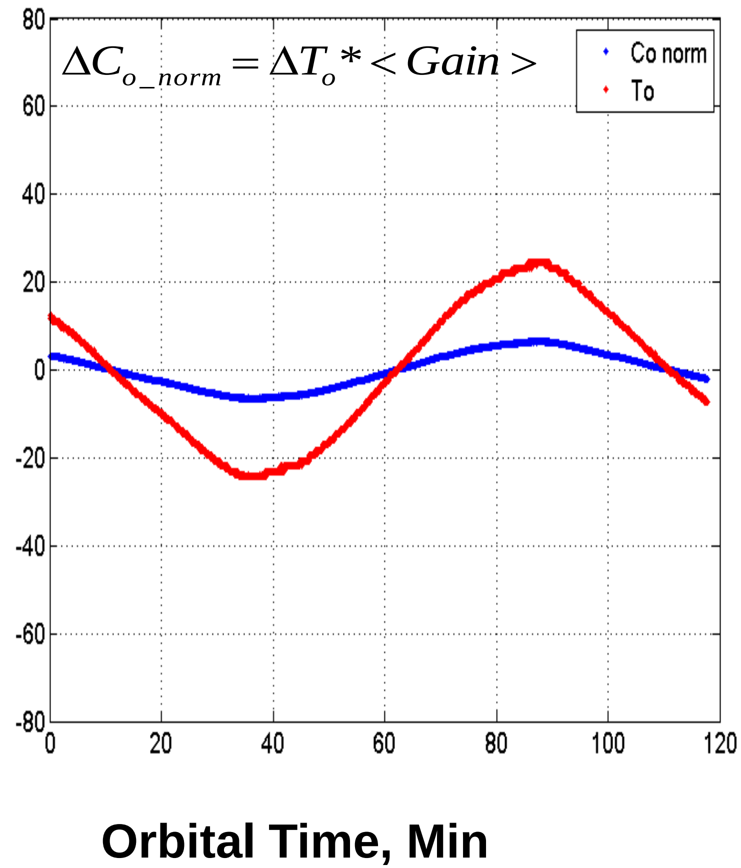
Example Gain Normalization

Before Normalization



After Normalization



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Measurement of MWR System Gain (Noise Diode Deflection)

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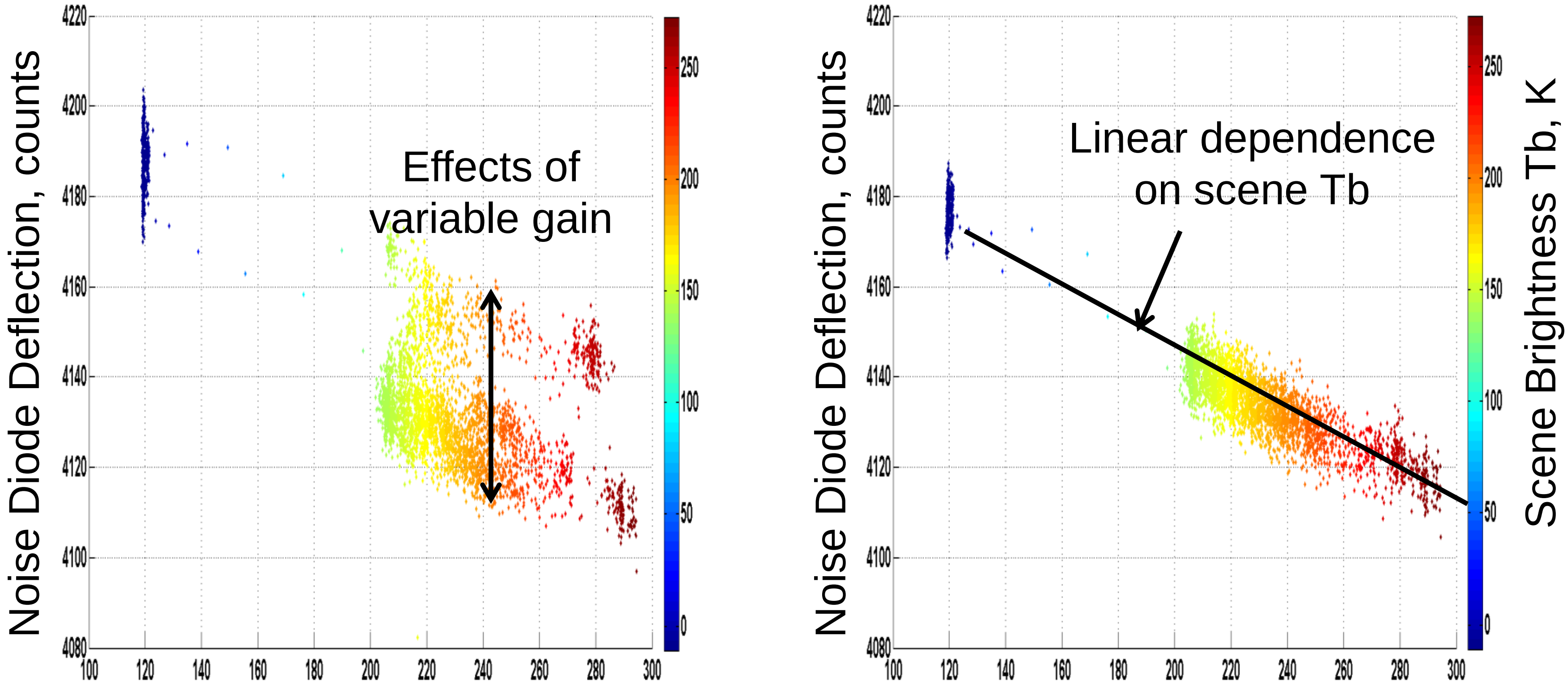
37GHz V-pol, Comparison of V5.0S Noise Diode Deflection = $(C_n - C_a)$

Before Count (gain) Normalization

After Count (gain) Normalization



Radiometer Input to the antenna port of Dicke switch, T_{in} (Kelvin)

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MWR Signal Processing with non-linear system gain compression

$$C_a = (T_{ant} + T_{recv}) * G_{recv-1} + V_{off-set} \quad (1)$$

$$C_N = (T_{ant} + T_N + T_{recv}) * G_{recv-3} + V_{off-set} \quad (2)$$

$$C_{ref} = (T_{ref} + T_{recv}) * G_{recv-2} + V_{off-set} \quad (3)$$

$$(T_{ant} + T_N + T_{recv}) > (T_{ref} + T_{recv}) > (T_{ant} + T_{recv})$$

therefore,

$$G_{recv-3} < G_{recv-2} < G_{recv-1}$$

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MWR Slightly Non-linear Gain Model

$$G_{recv\_1} = G_o g(T_{ref}) h_1(T_{in})$$

$$G_{recv\_2} = G_o g(T_{ref}) h_2(T_{in})$$

$$G_{recv\_3} = G_o g(T_{ref}) h_3(T_{in})$$

G_o is the mean "long term gain"

$g(T_{ref})$ is the orbital gain change due to phy temp (T_{ref})

$h(T_{in})$ is the gain compression due to variable scene brightness temp (and injected noise diode)

These parameters are estimated during a single orbit where a deep-space calibration is performed

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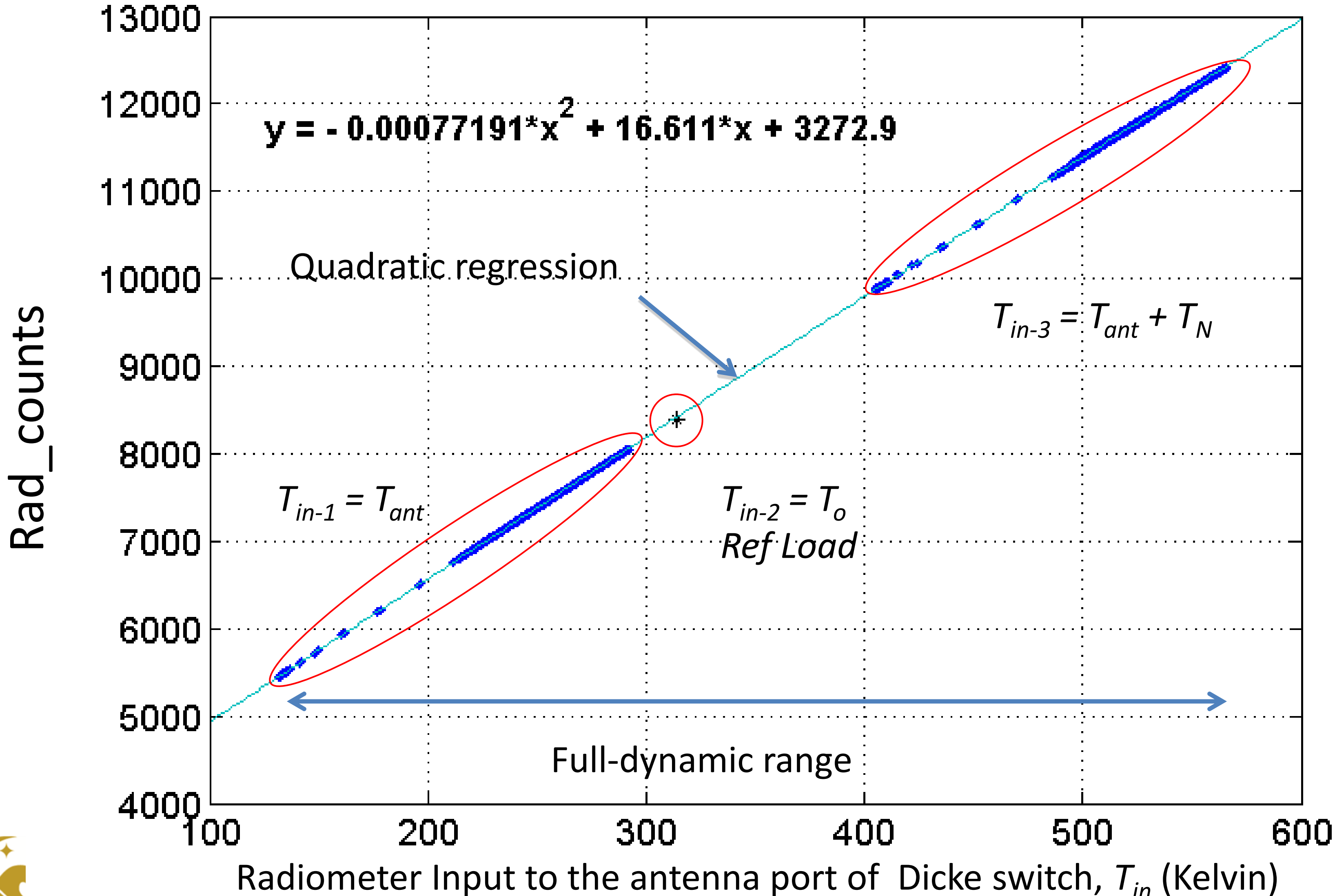
MWR Radiometer Transfer Function for One Orbit



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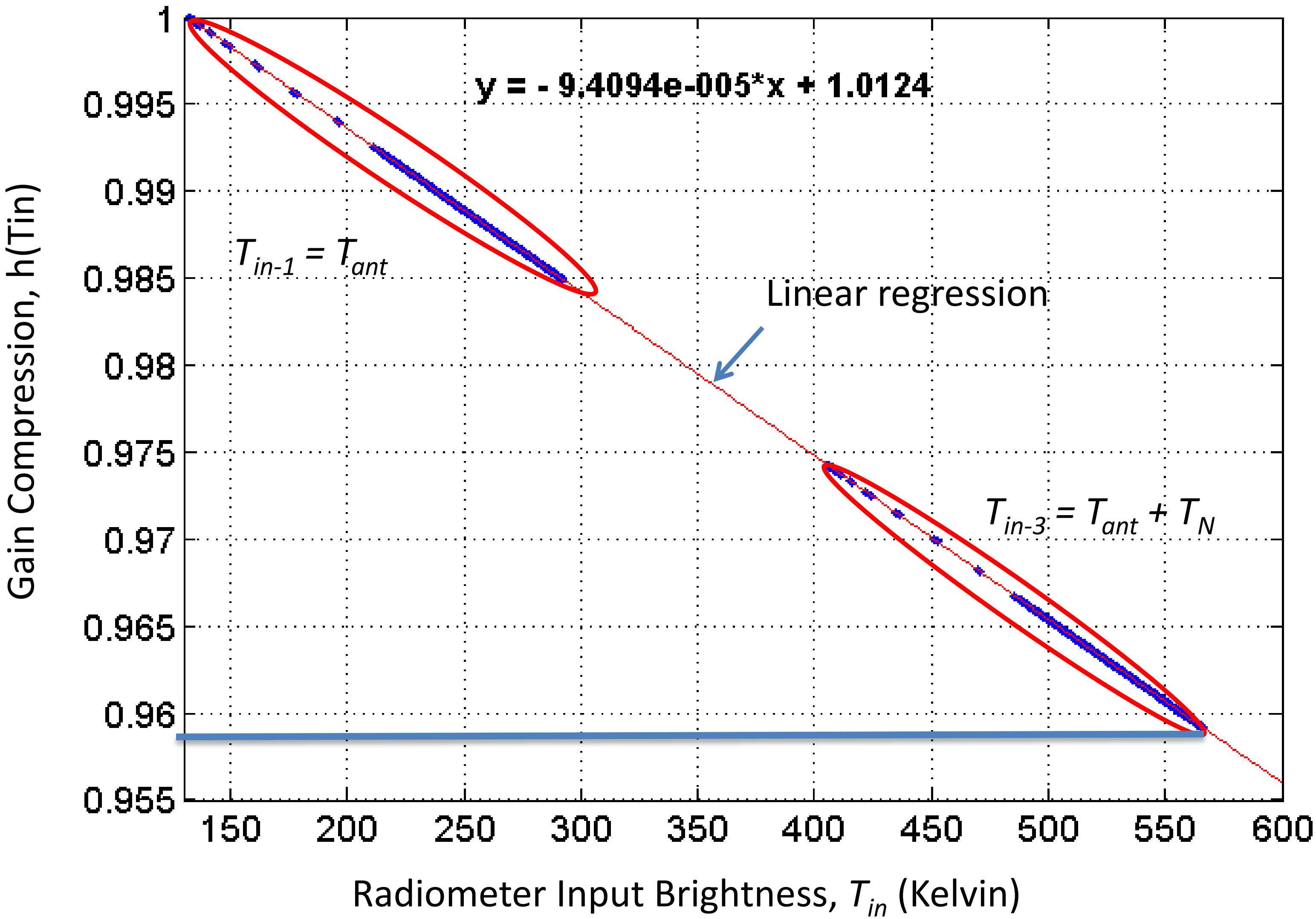
Gain Compression Function, $h(T_{in})$



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Non-Linearity Correction, Radiometer Transfer Function (V5.0S)

- Seven Deep Space Calibration (DSC) orbits that included, space, ocean, and land observations were used to cover wide range of scene Tb's
- After counts (gain) normalization, the radiometer transfer function was established
  - $Rad\_counts = f(T_{in})$
- Quadratic regression for 37V channel yielded the following

$$Rad\_counts = -7.5x10^{-4}(T_{in})^2 + 16.58\,(T_{in}) + 3270$$

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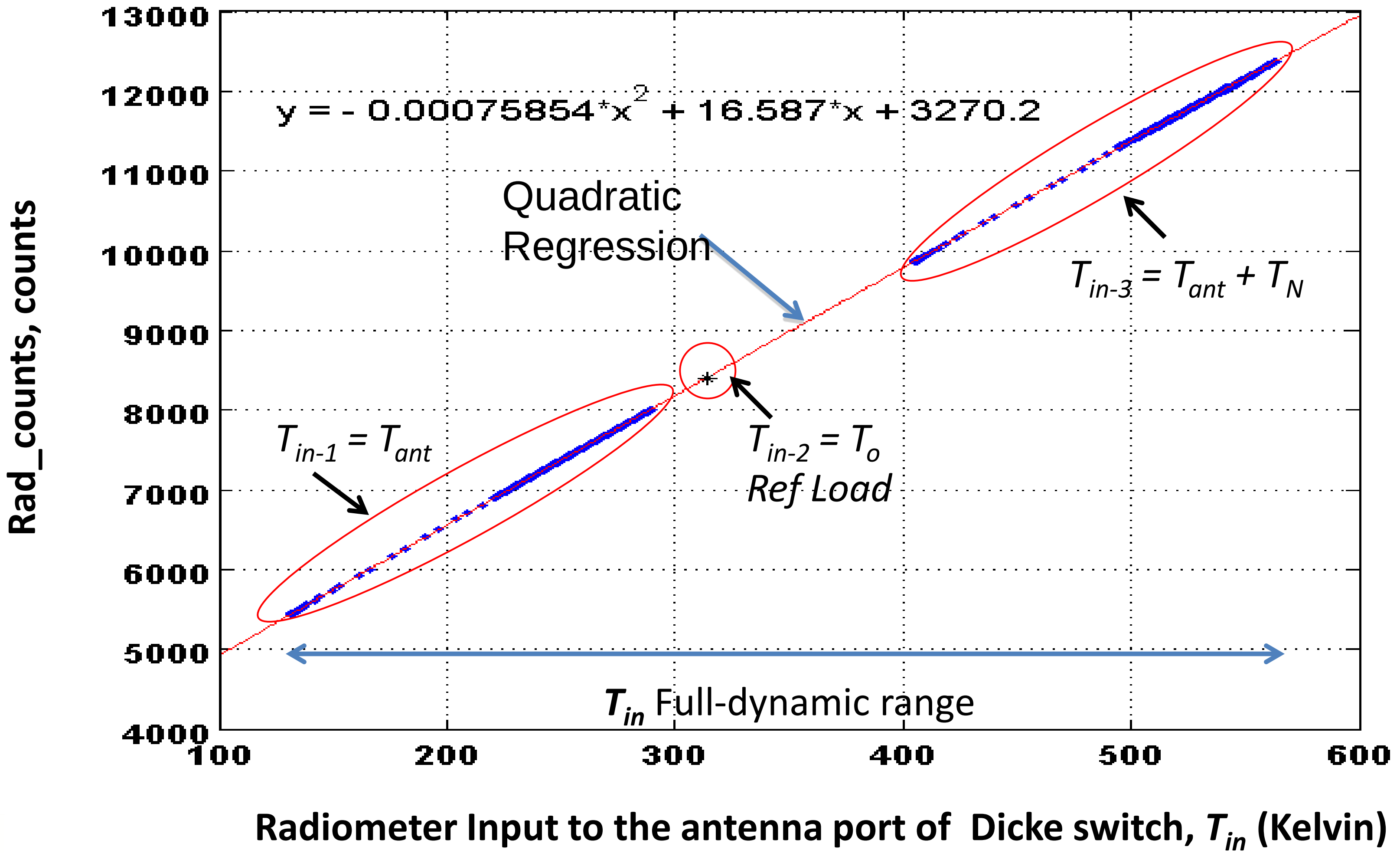
MWR Radiometer Transfer Function for 37V V5.0S (constant gain) for One Orbit



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V6.0 Radiometer Transfer Function Linearization

- Averaging 2nd order regression coeff's from 7 DSC orbits, the instantaneous counts linearization equation is:
  - For 37 V

$$C_{x\_linear} = C_x - (\text{-}7.4677\text{e-}004) * T_{in}^{\ 2}$$

  - For 37 H

$$C_{x\_linear} = C_x - (\text{-}6.9064\text{e-}004) * T_{in}^{\ 2}$$

  - For 23 H

$$C_{x\_linear} = C_x - (\text{-}2.1708\text{e-}004) * T_{in}^{\ 2}$$

Where *x = ant, N, and ref*

Tin is the input *Tb* to the Dicke switch, which is estimated using non-linear counts

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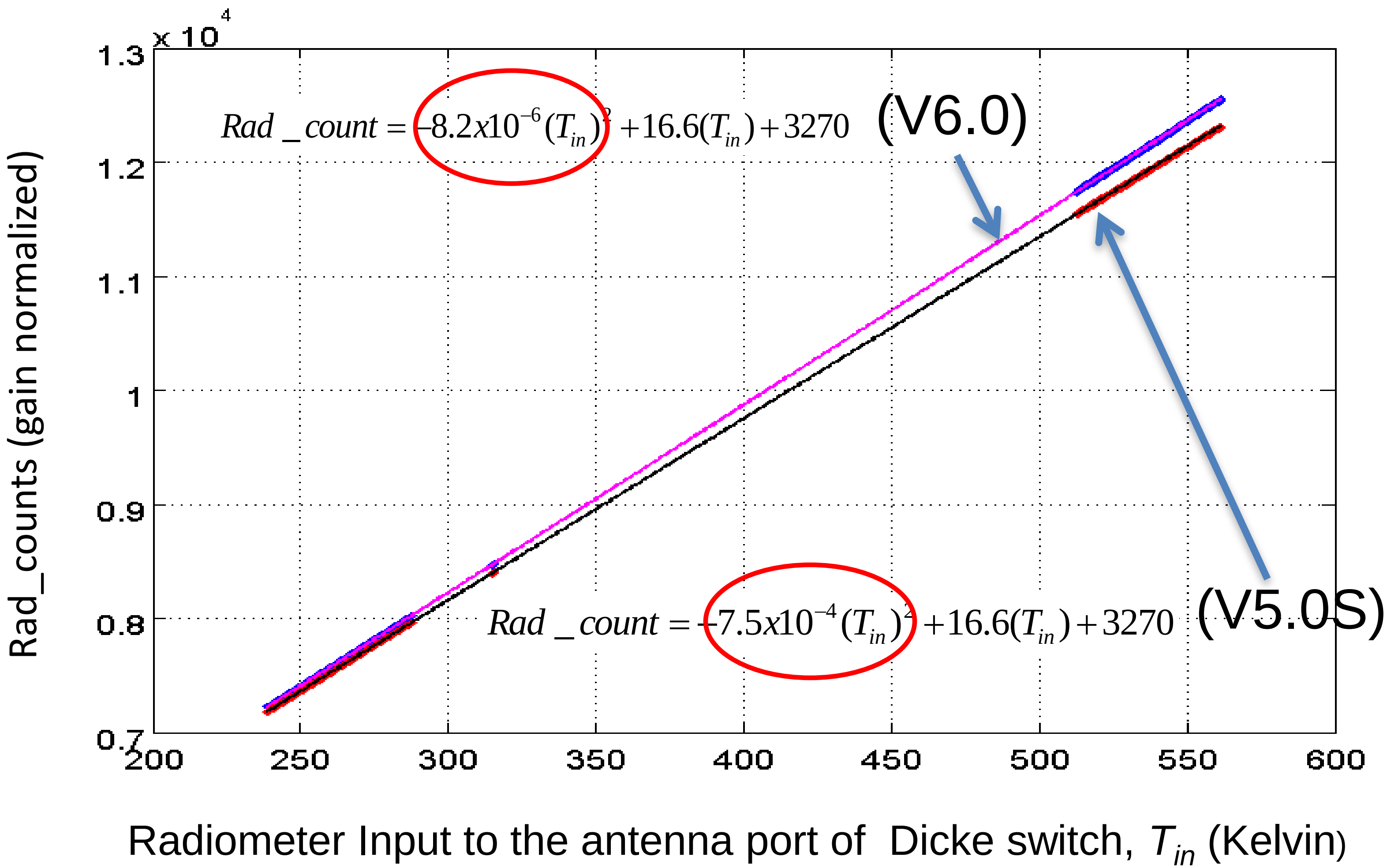
Radiometer Transfer Function 37V (constant gain) V5.0S and V6.0



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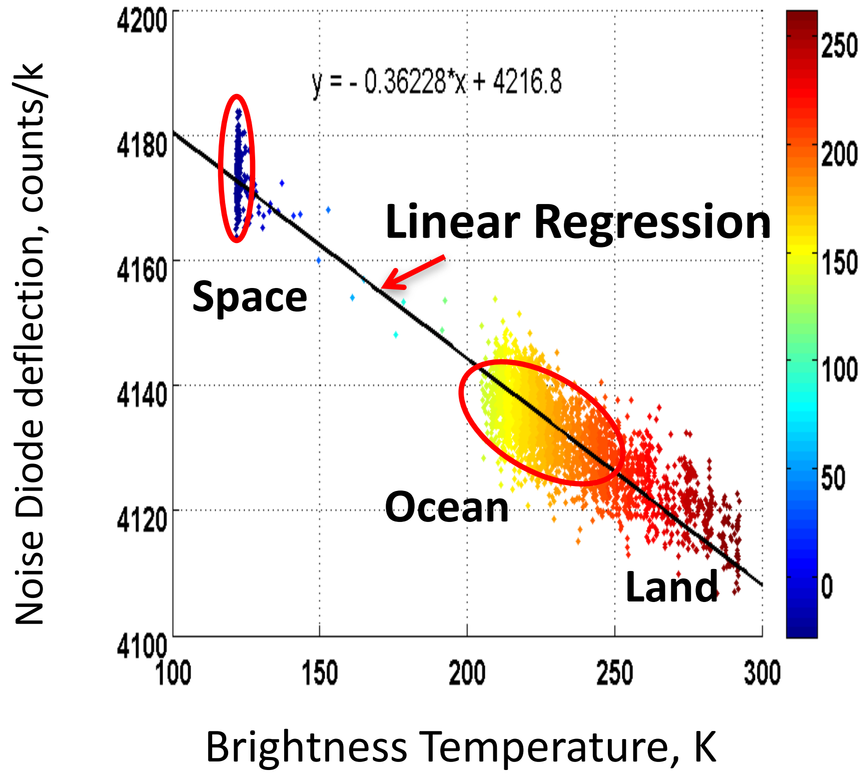
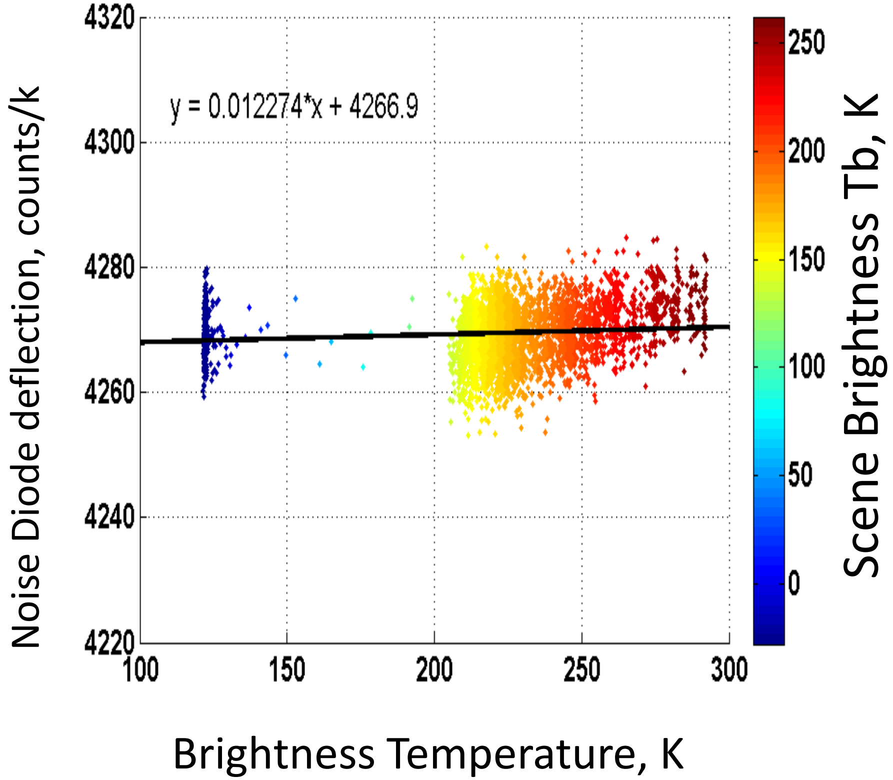
37GHz V-pol , One Orbit Noise Diode Deflection $= (C_n - C_a)$

V5.0S
(Without counts linearization)



V6.0
(With counts linearization)



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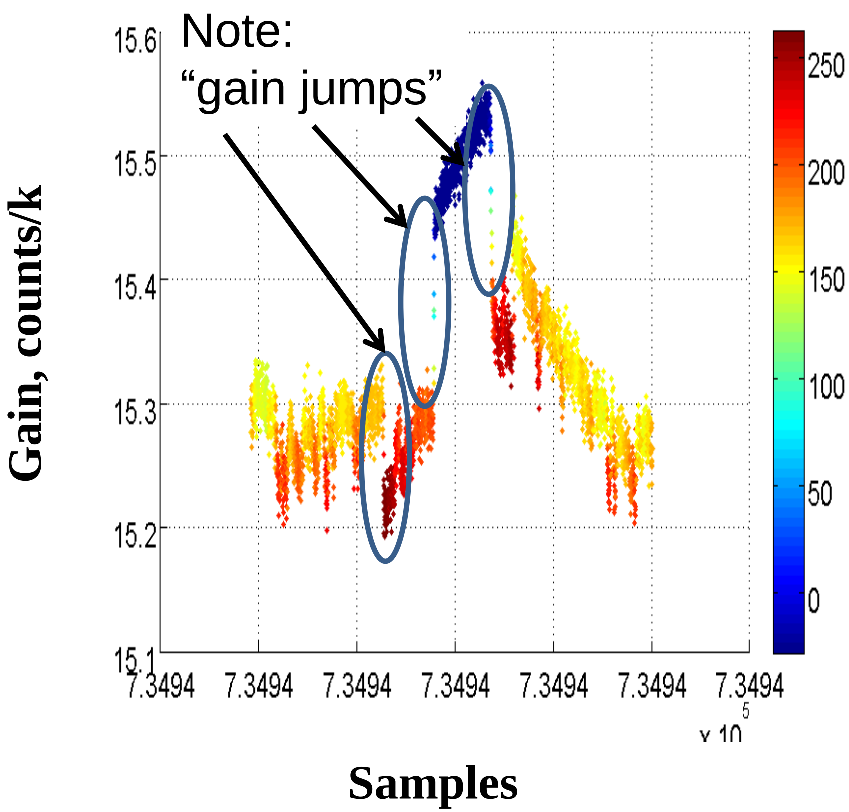
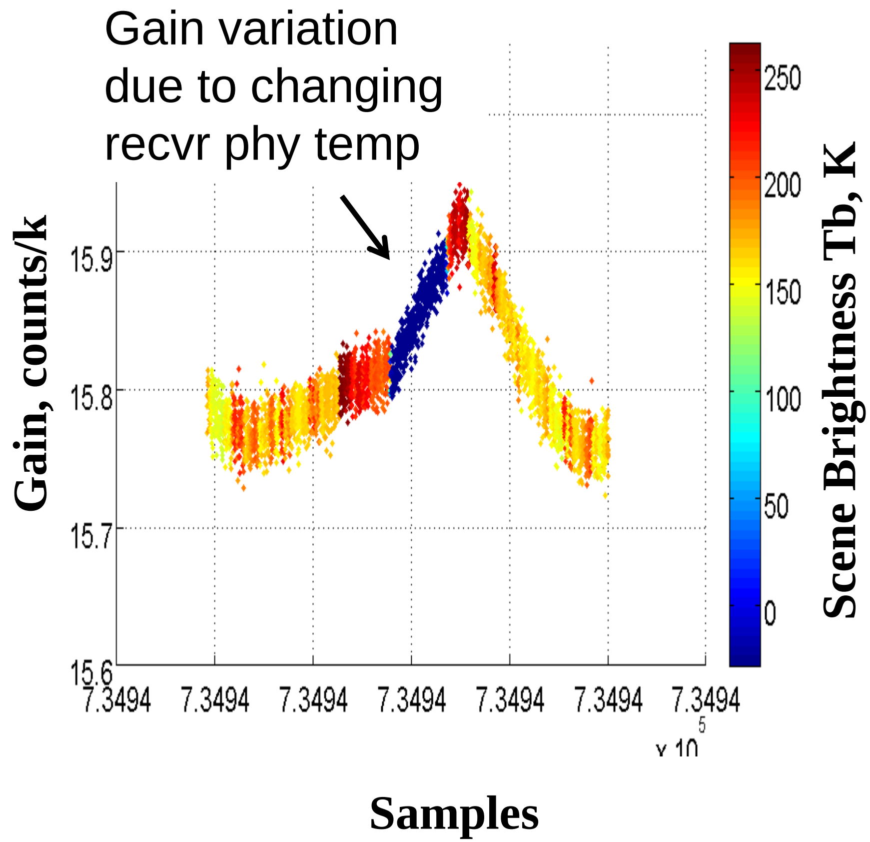
37GHz V-pol , One Orbit Radiometer Gain

V5.0S



V6.0



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Reanalysis of Prelaunch TV Calibration Test using Linearized Counts

Pre-launch Data Analysis Objectives for V6.0 (using Linearized Counts)

- Characterization of injected noise diode temperature (T_N) over physical temperature
- Retrieve **antenna switch matrix** loss coefficients
  - Empirical method (regression model) was applied
  - Assumption: All transmission and reflection coeff's are constant and are NOT expected to change during MWR's mission life time

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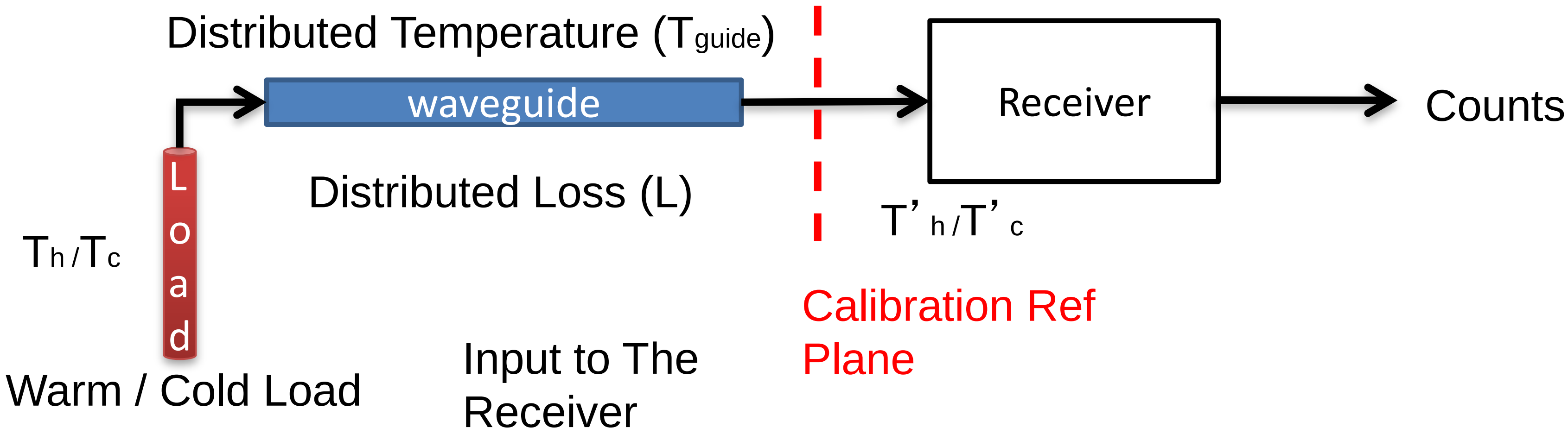
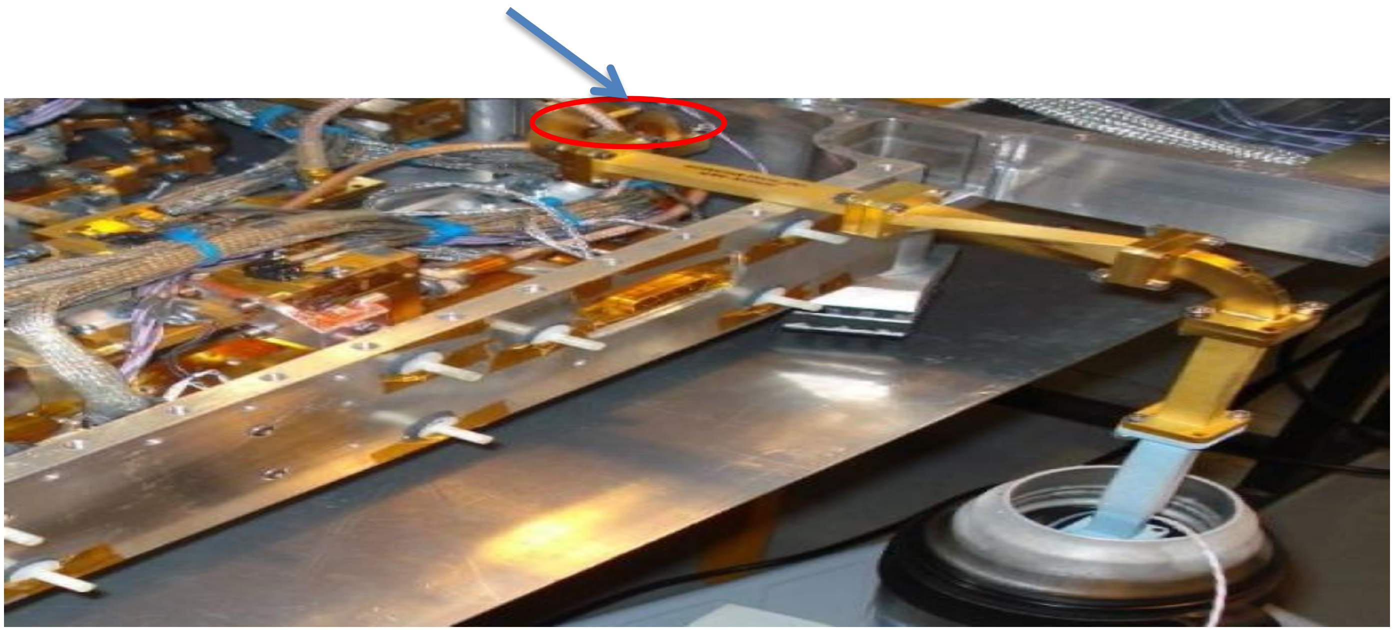
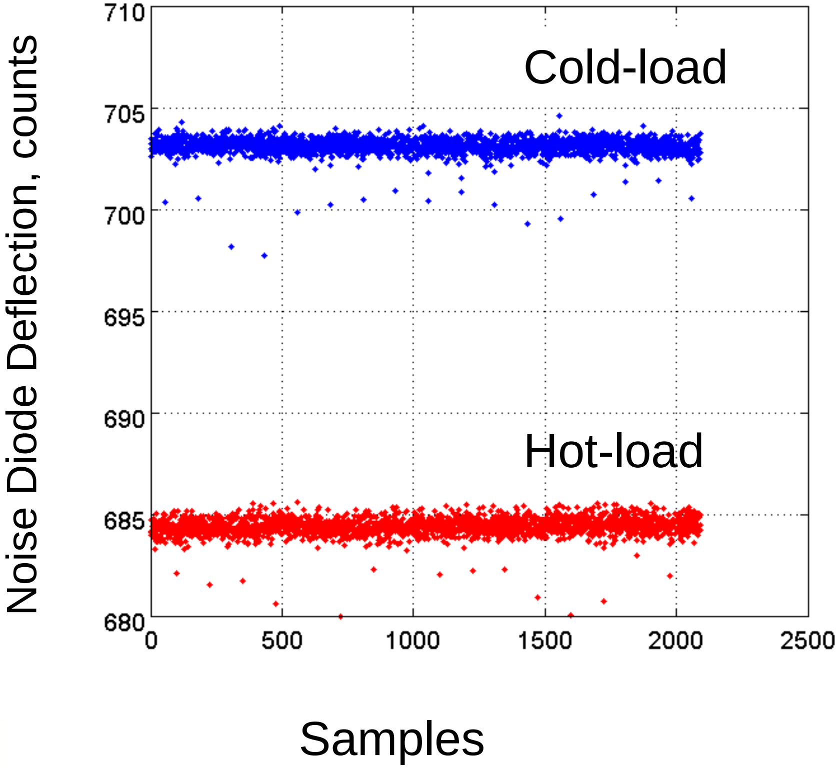
Pre-TV test Block Diagram



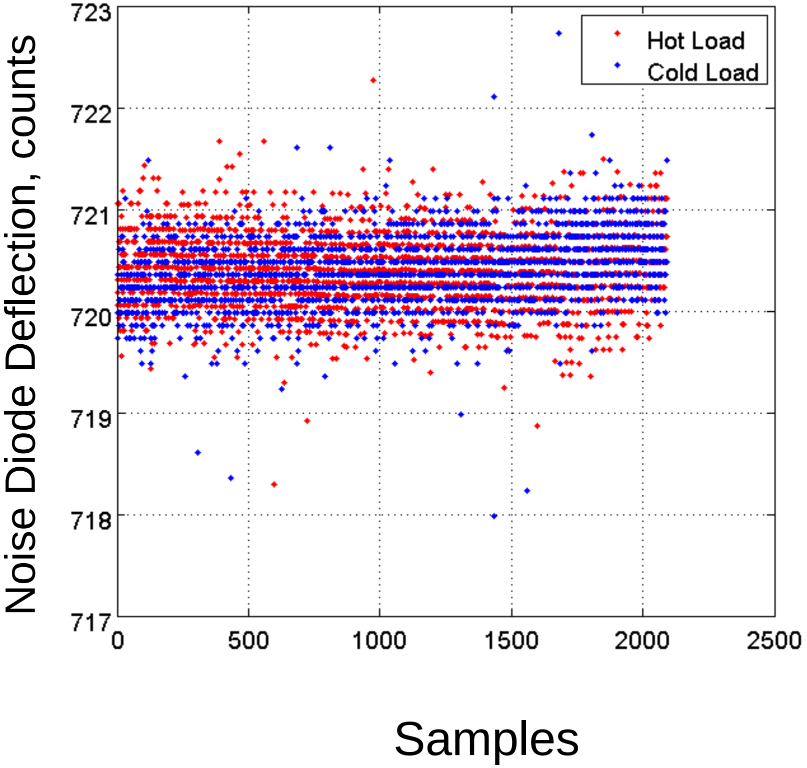


Pre-TV test, Comparison of the Noise Diode Deflection V2.0 and V6.0

SAYAK BISWAS
V2.0



V6.0



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Inversion Model for Apparent Brightness Temperature (T_{ap})

$$T_{ap}=[T_{in}-(b_2*T_o+b_3*T_1+b_4*T_2+b_5*T_3+b_6*T_4)]/b_1$$

- where
  - T_{ap} is the scene brightness temp at horn aperture
  - T_{in} is the input brightness temperature to antenna port of Dicke switch
  - T_o , T_1 , T_2 , T_3 ,& T_4 are MWR physical temps
  - b_1, b_2, b_3, b_4, b_5 and b_6 are **antenna switch matrix** loss coefficients derived using the regression model

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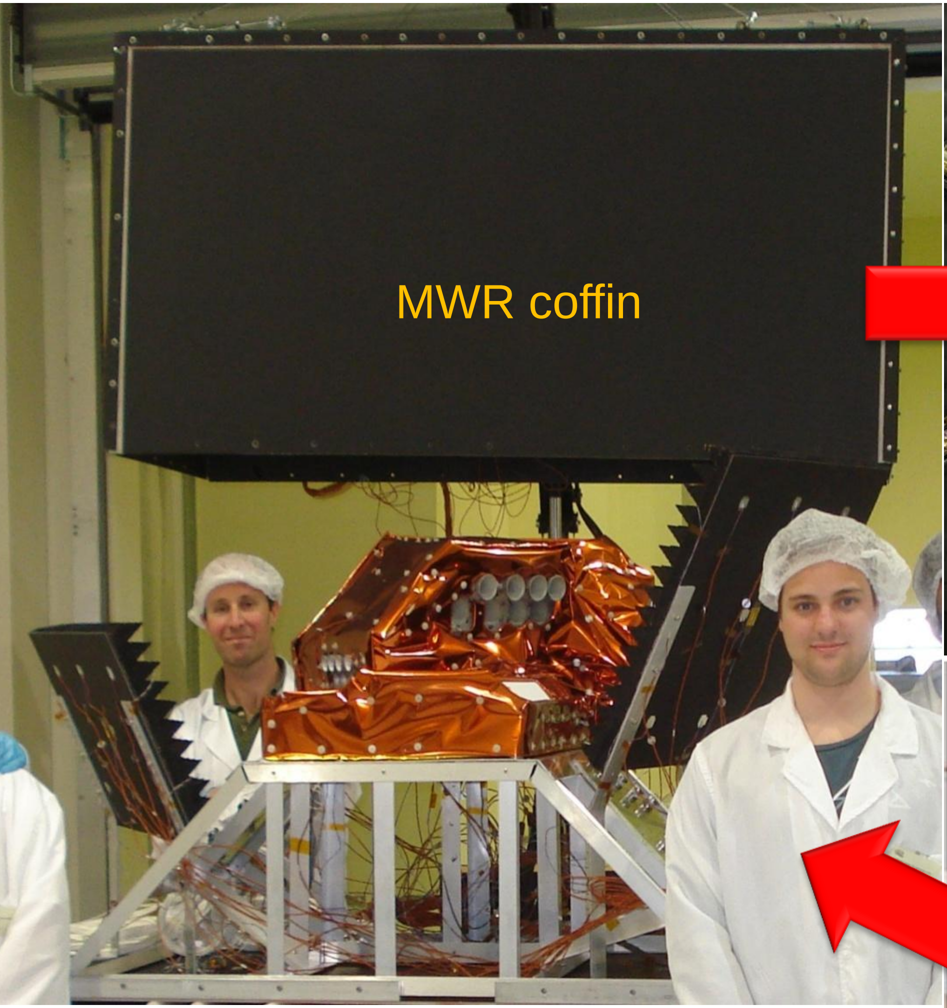
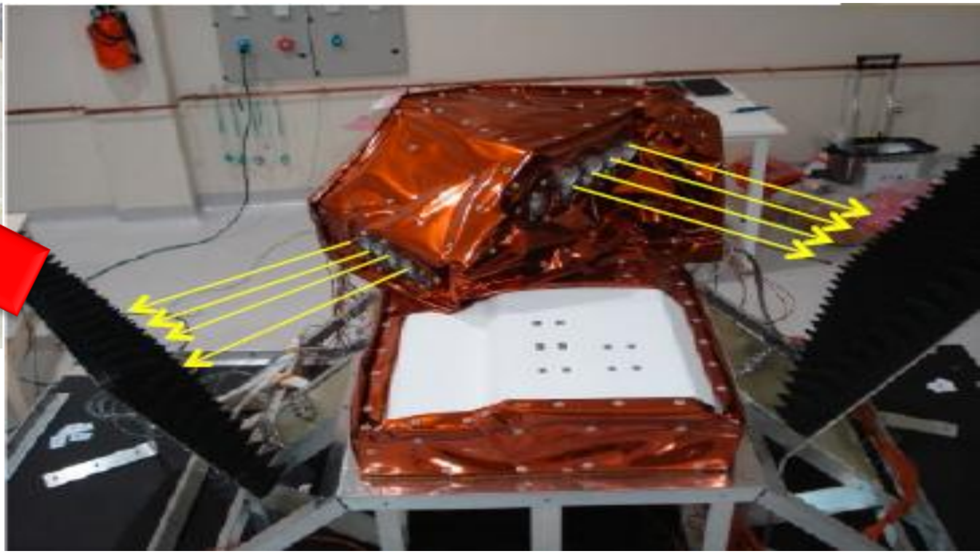
Thermal Vacuum Test





- The thermal vacuum (TV) test for MWR was performed in September 2009. (09/06 – 09/09)
- Performance of the SW matrix losses coefficients

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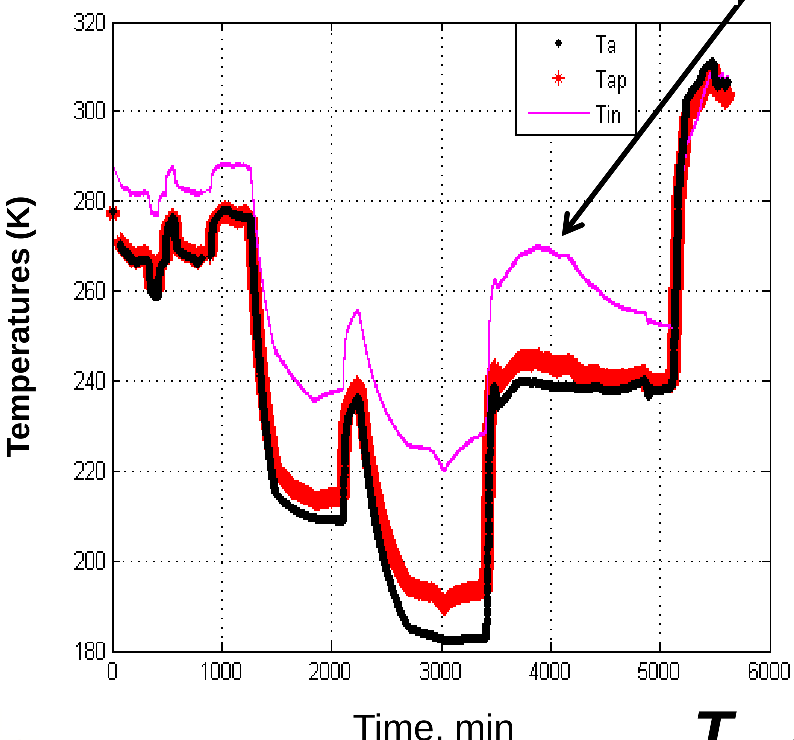
37GHz V-pol, Computed Apparent Temp based on: SWM losses and reflection (V2.0), regression model (V6.0)

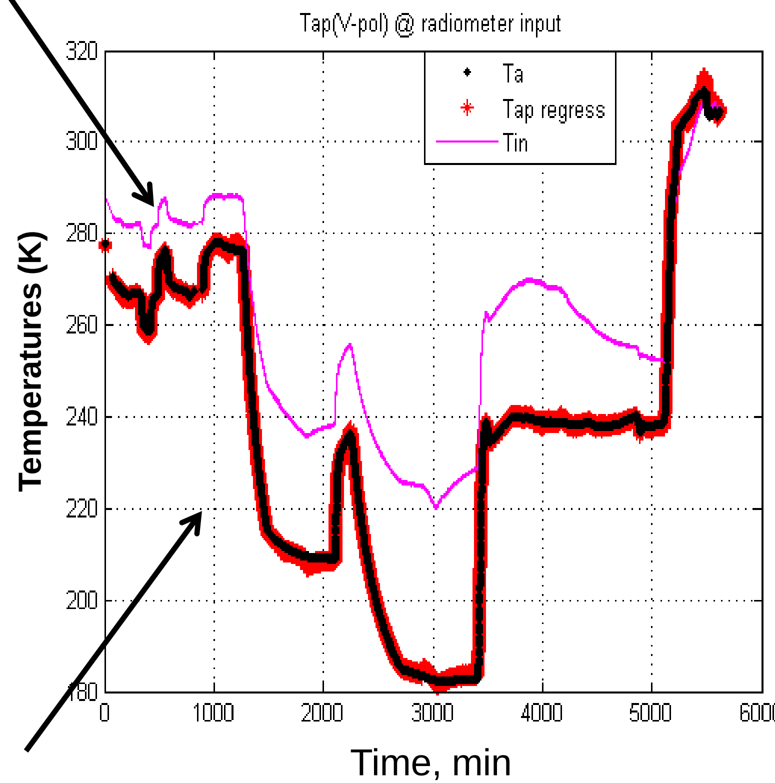
$$T_{ap}=[T_{in}-(b_2*T_o+b_3*T_1+b_4*T_2+b_5*T_3+b_6*T_4)]/b_1$$

T_{in} calc from rad_counts

SWM Model, RMS=3.94



Regression Model ,RMS= 0.75



T_{ap} & $T_{ap\_regress}$

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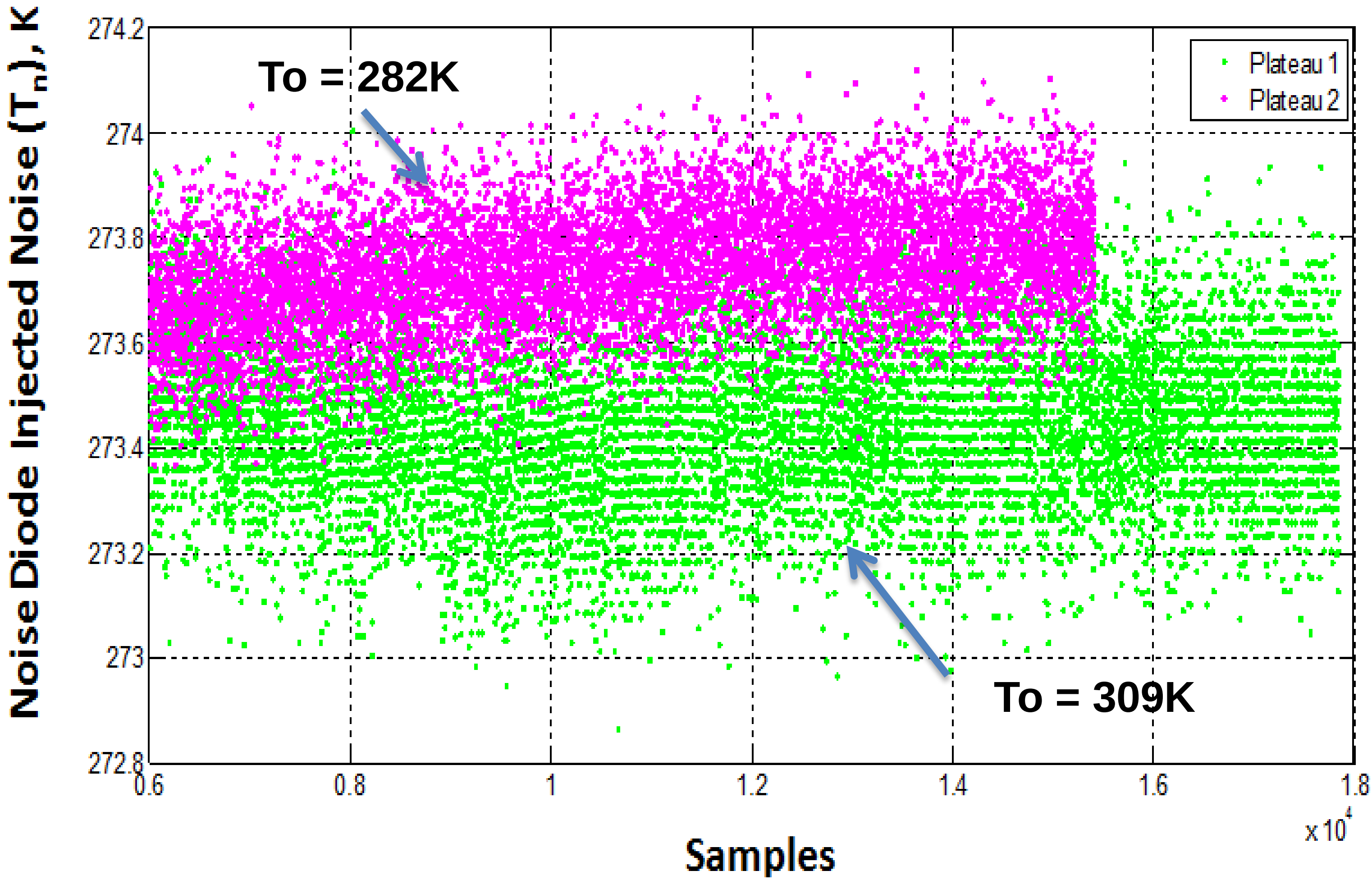
Calculated Noise Diode Injection Noise (T_N) for Two Different TV Plateaus



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- Post-Launch MWR Calibration Analysis
  - Deep Space Calibration
  - WindSat X-CAL

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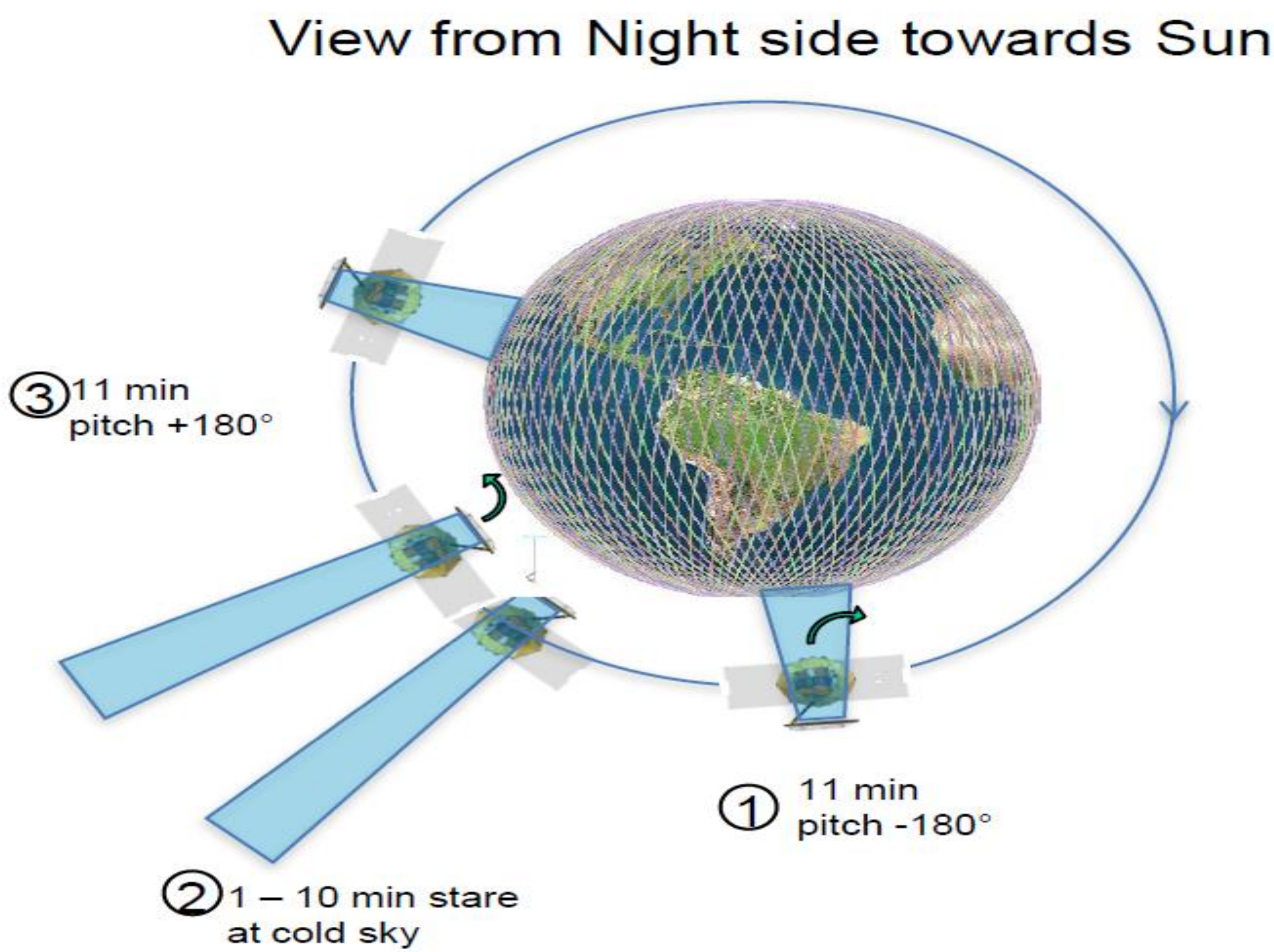
Deep Space Calibration cause MWR Antenna Beams to view Homogeneous Scene = 2.7 K



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Post Launch X-CAL Analysis

- APC and residual bias correction were applied by inter-satellite XCAL
  - MWR = target & WindSat = reference
- MWR and WindSat have different incident angles, therefore, Tbs were adjusted using theoretical radiative transfer model values for both satellites (MWR_{sim} and WS_{sim})

$$\boldsymbol{WS_{adj} = WS_{obs} + (MWR_{sim} - WS_{sim})}$$

- Double Difference Technique

$$\boldsymbol{DD = MWR_{obs} - WS_{adj}}$$

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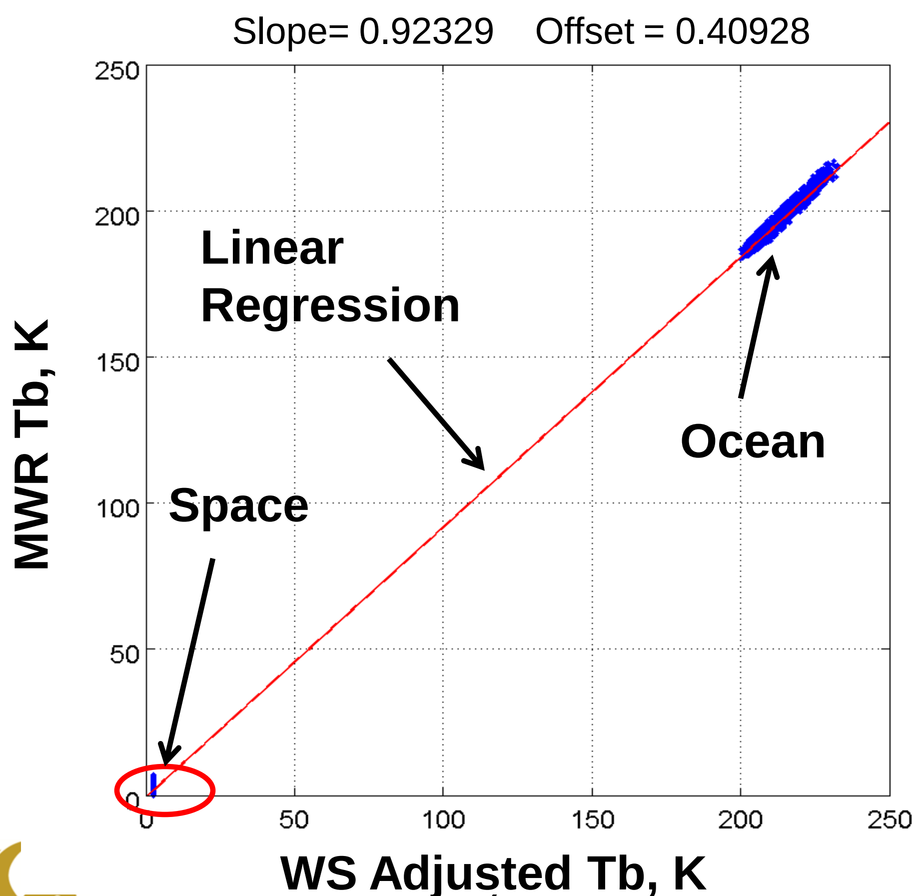
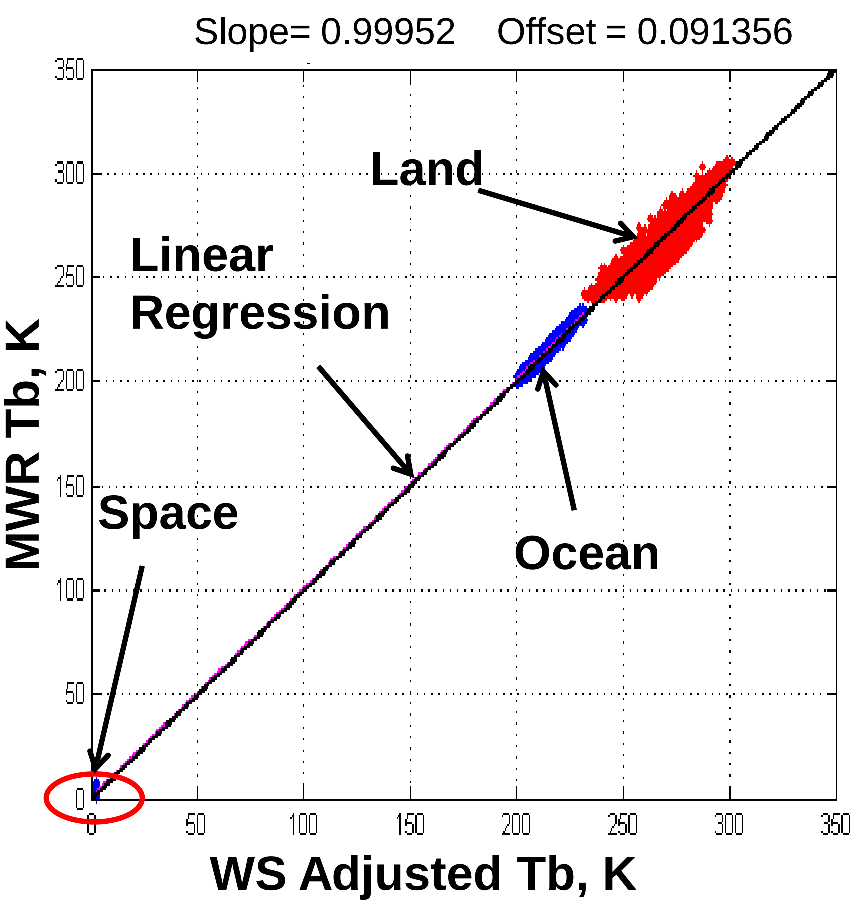
37GHz V-pol Beam-1: X-CAL of MWR V6.0 and WindSat

Before Correction



After Correction



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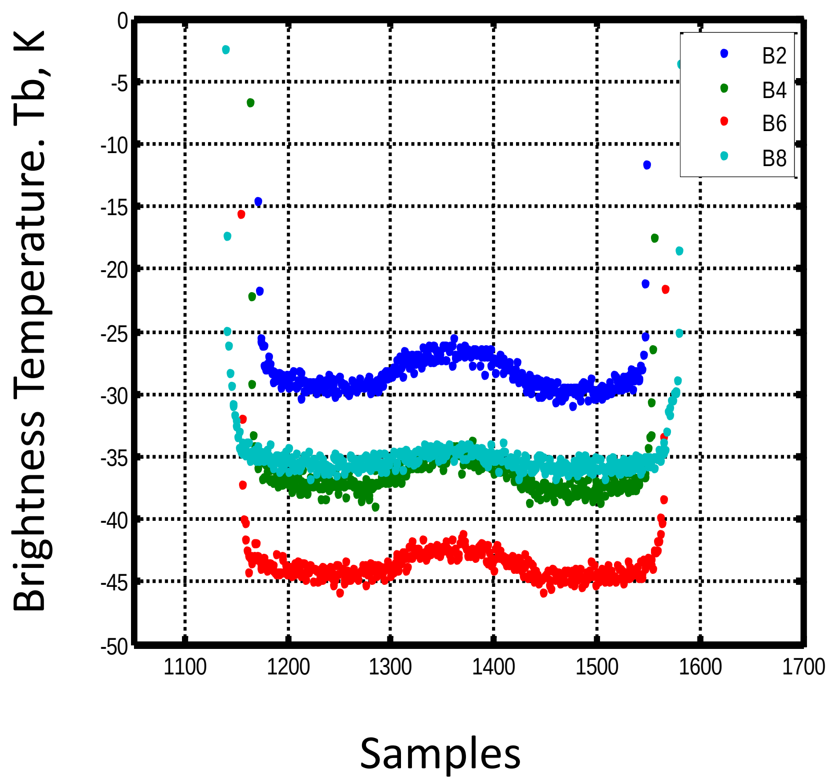
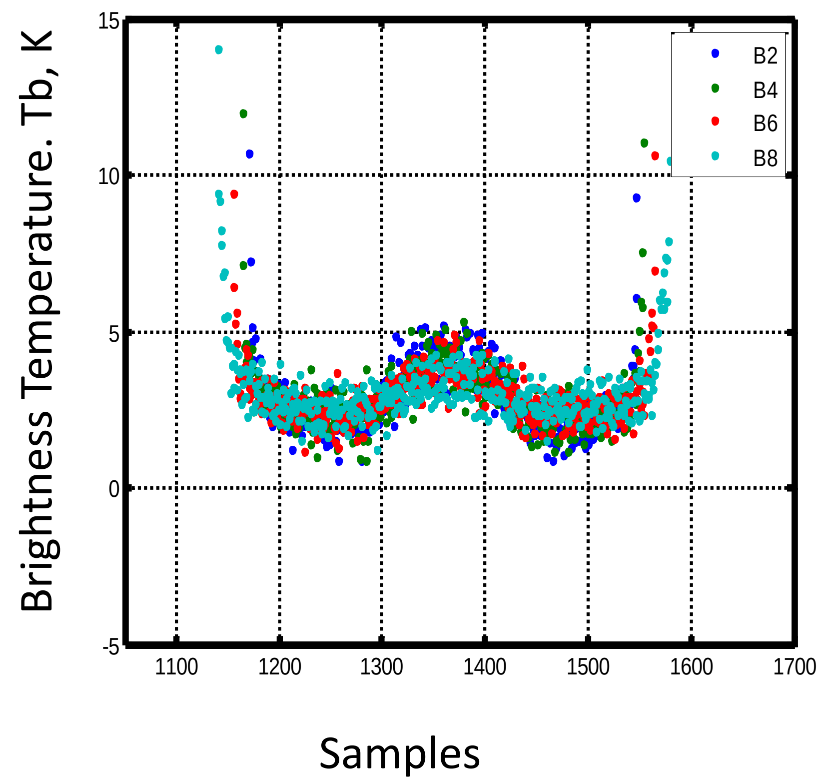
37V, Cold Sky Calibration Measurements Even Beams

Version 5.0S



Version 6.0



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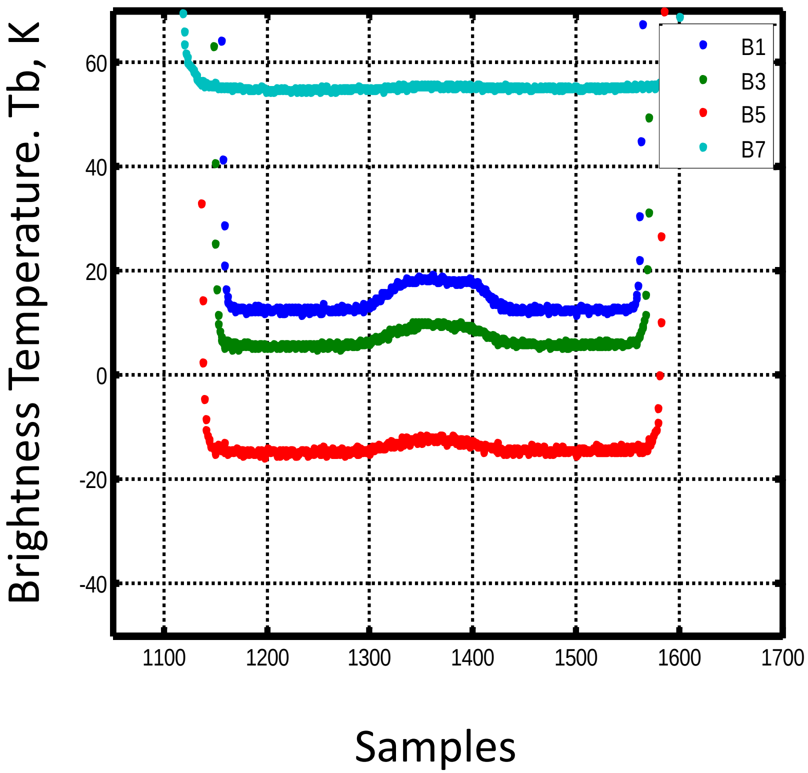
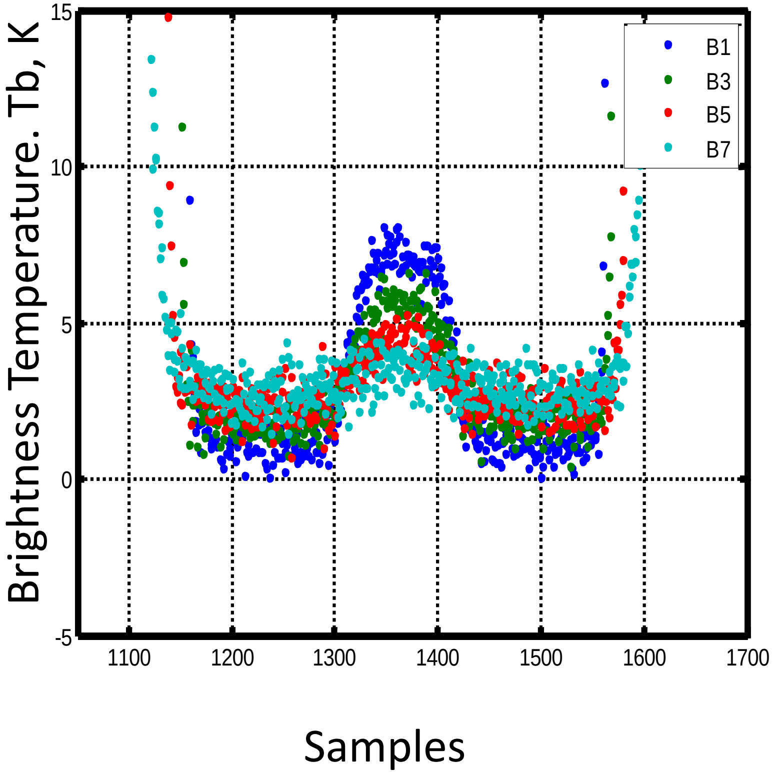
37V, Cold Sky Calibration Measurements Odd Beams

Version 5.0S



Version 6.0



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Double Difference Radiometric Biases
MWR/WindSat
(Five Days Average)
Jan 01, 2012 – Dec 31, 2012

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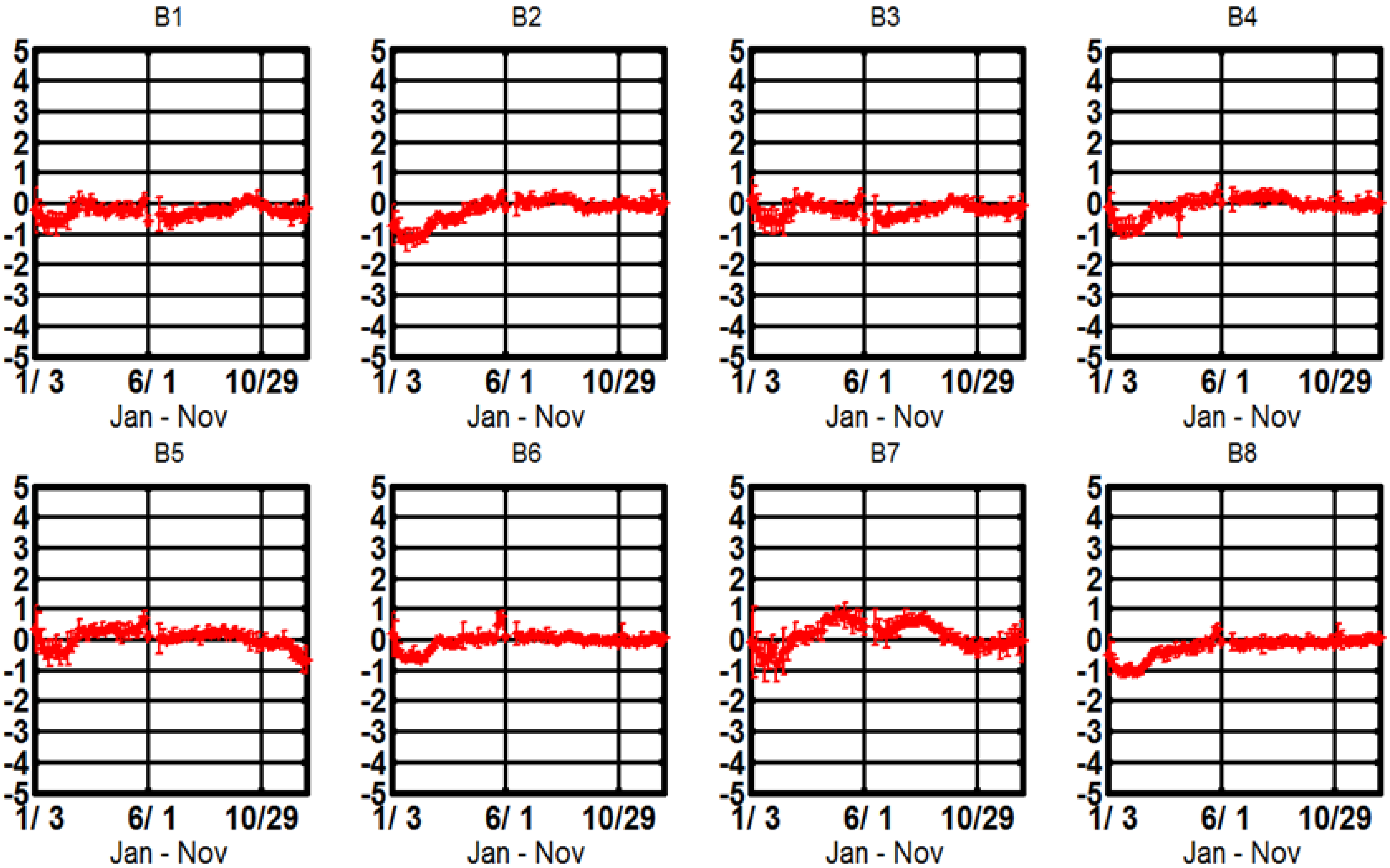
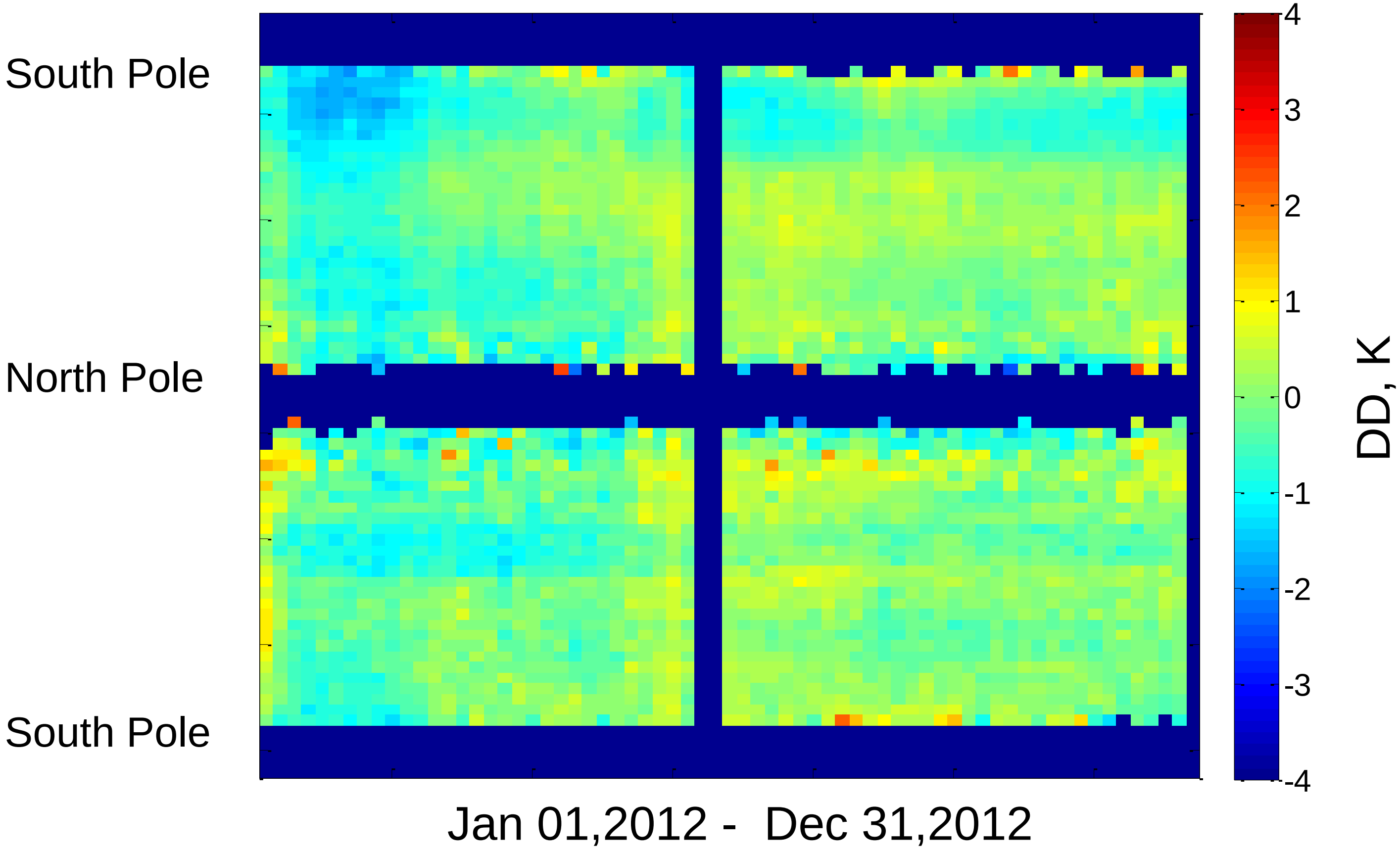
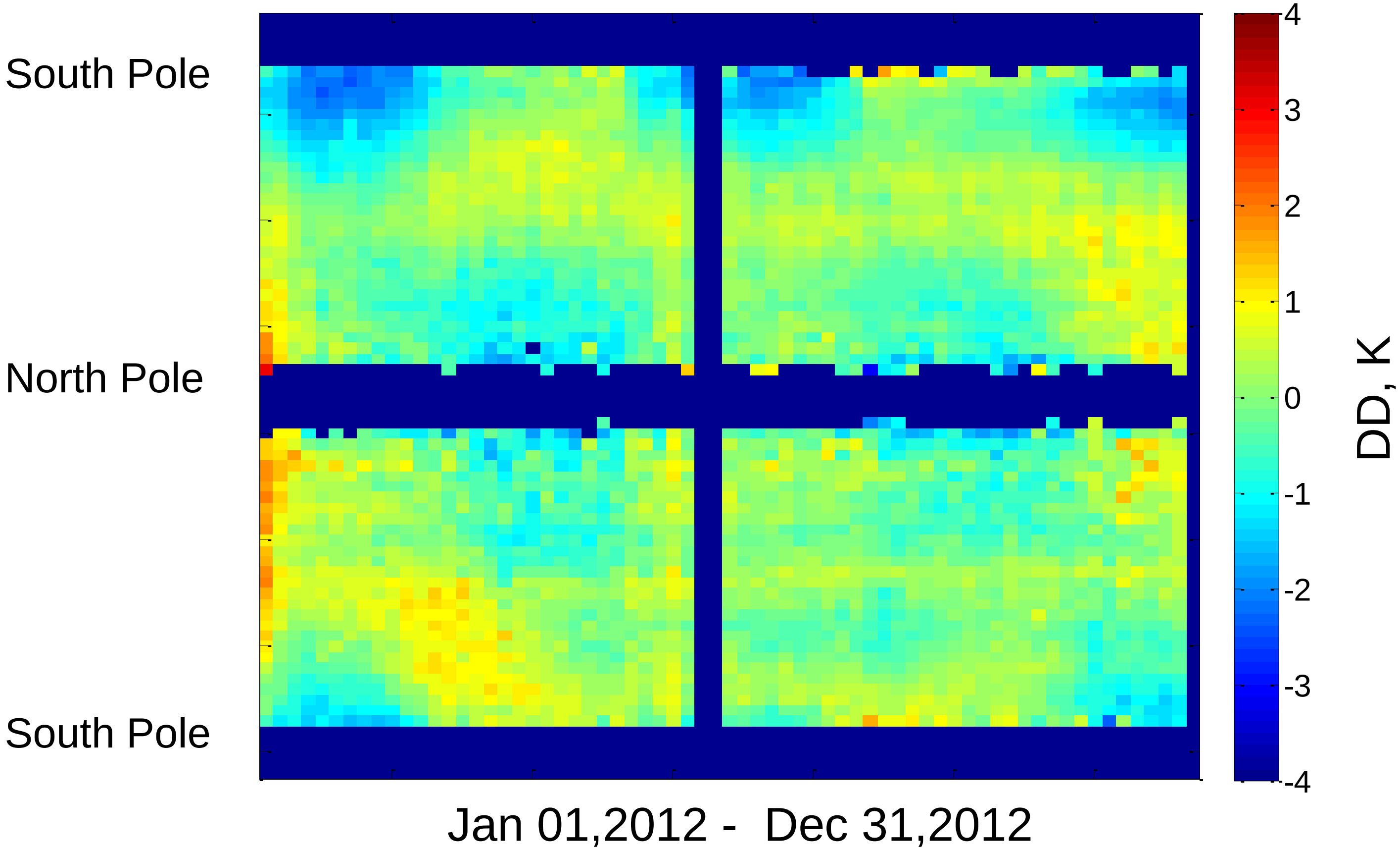
Double Difference Biases 37V (K), 2012



Five days Average in 5° Lat Zones 37V, Even Beams for 2012



Five days Average in 5° Lat Zones
37V, Odd Beams for 2012



Conclusion

- MWR Counts-to-Tb algorithm V6.0 has been developed and distributed to the AQ Cal/Val Team
  - MWR transfer function non-linearity in V5.0S has been characterized and corrected in V6.0
  - Antenna switch matrix loss coefficients were derived using re-analysis of MWR pre-launch TV calib test
- Validation of V6.0 performed using 2 years of on-orbit measurements
  - On-orbit X-CAL, between MWR and WindSat, have produced the antenna pattern correction (APC) and removed small Tb biases
- V6.0 Algorithm Theoretical Basis Document and MatLab code delivered to CONAE for science data processing

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Publications

- **Conferences**

1. Ghazi, Z.; Biswas, S.; Jones, L.; Hejazin, Y.; Jacob, M.M., "On-orbit signal processing procedure for determining Microwave Radiometer non-linearity," Southeastcon, 2013 Proceedings of IEEE , vol., no., pp.1,5, 4-7 April 2013 doi: 10.1109/SECON.2013.6567504
2. Ghazi, Zoubair; Santos-Garcia, Andrea; Jacob, Maria Marta; Jones, Linwood, "CONAE Microwave Radiometer (MWR) counts to Tb algorithm and on-orbit validation," Microwave Radiometry and Remote Sensing of the Environment (MicroRad), 2014 13th Specialist Meeting on , vol., no., pp.207,210, 24-27 March 2014 doi: 10.1109/MicroRad.2014.6878941
3. Santos-Garcia, A; Biswas, S.; Jones, L.; Ghazi, Z.; "Aquarius/SAC-D Microwave Radiometer brightness temperature validation," Oceans, 2012 , vol., no., pp.1,4, 14-19 Oct. 2012 doi: 10.1109/OCEANS.2012.6404830

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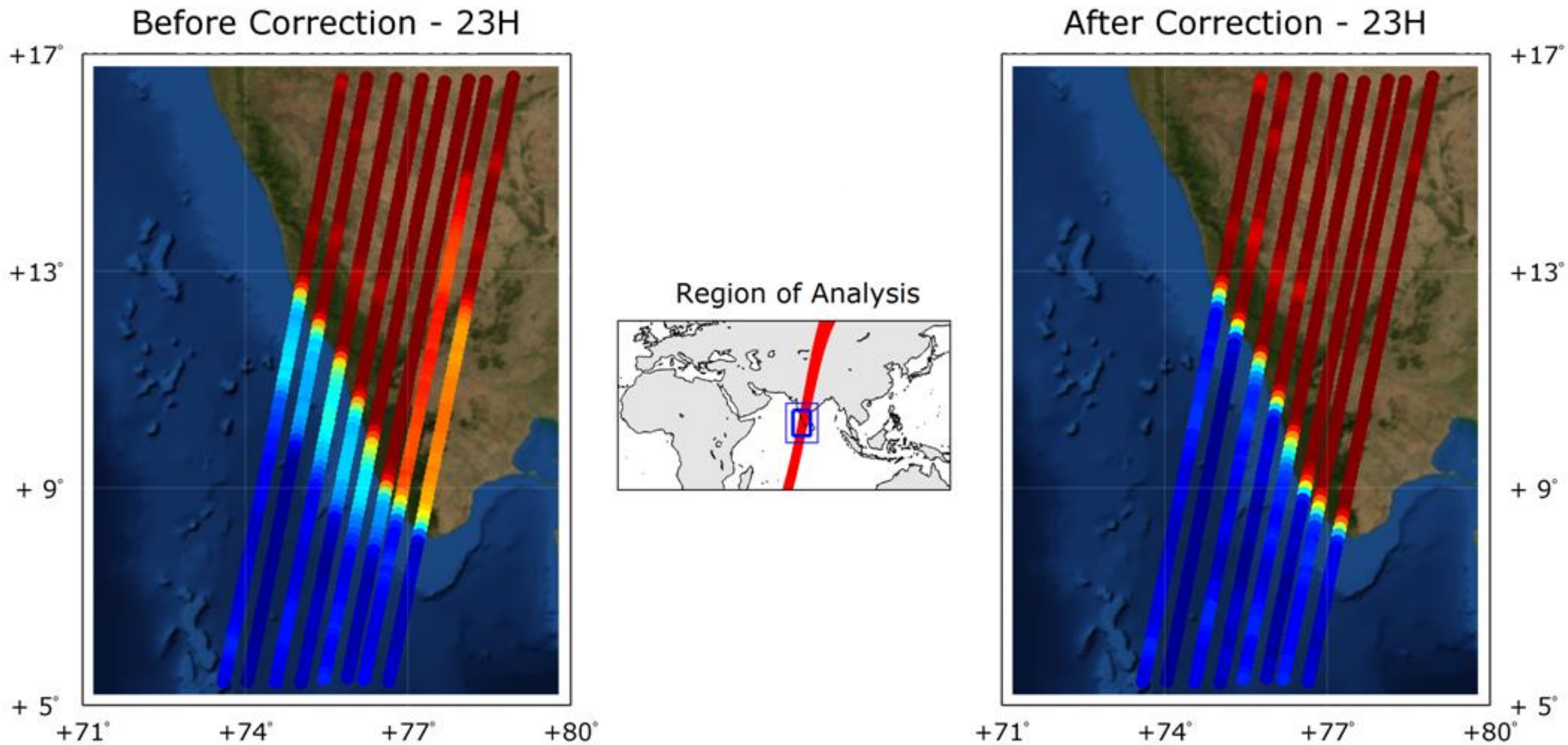
Back UP

MWR Tb measurements for 8 beams of the 23 GHz H-pol channel during a descending orbital pass over the tip of India



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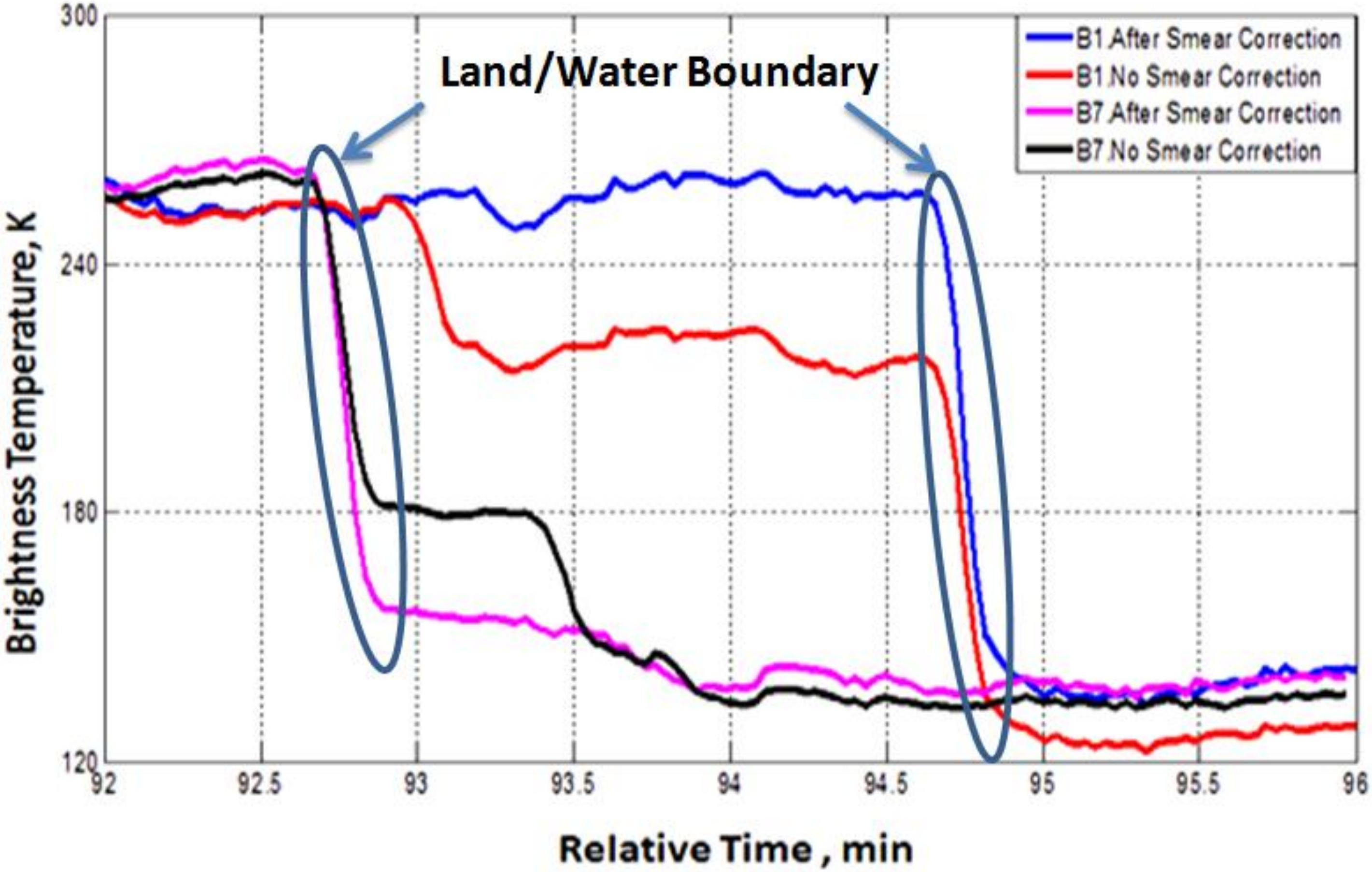
Corresponding MWR Tb time series for beam # 1 and beam # 7 of the MWR 23.8 GHz channel



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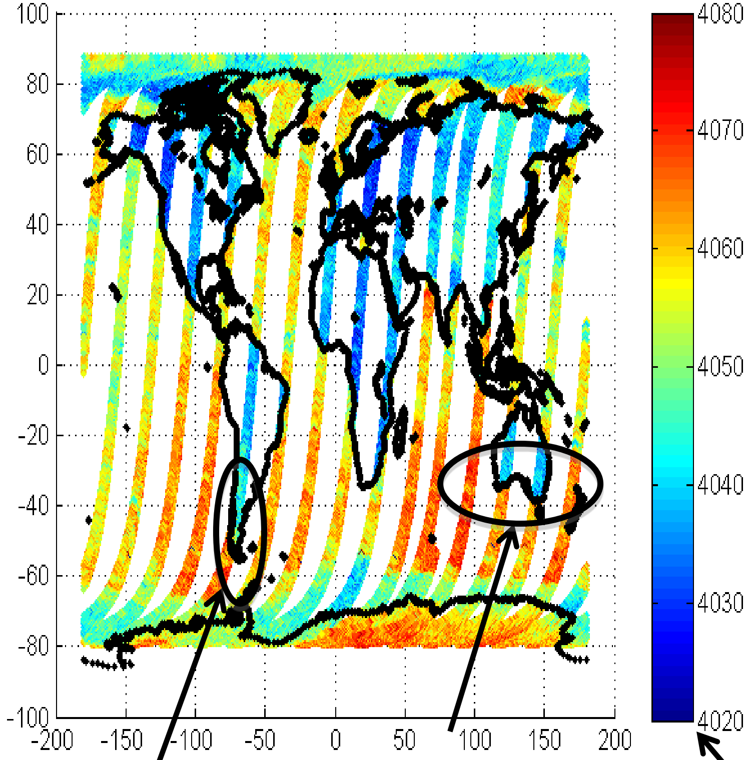
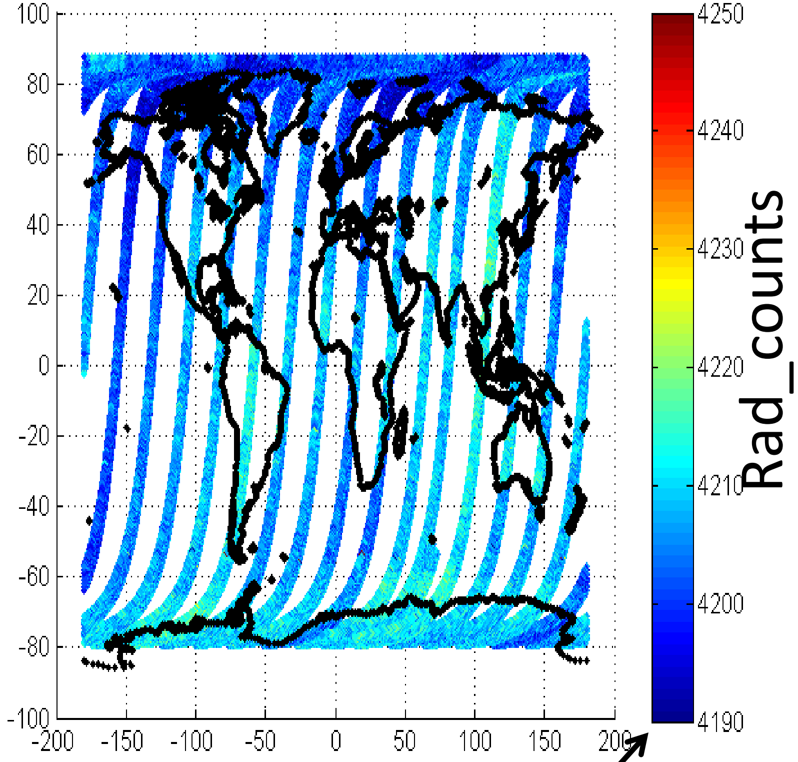
37GHz V-pol, On-orbit Noise Diode Deflection (NOT gain normalized), Descending Passes for One Day (All Beams)

V5.0S



V6.0



Note: "gain jumps" @ land/water boundaries

Dynamic range = 60 counts

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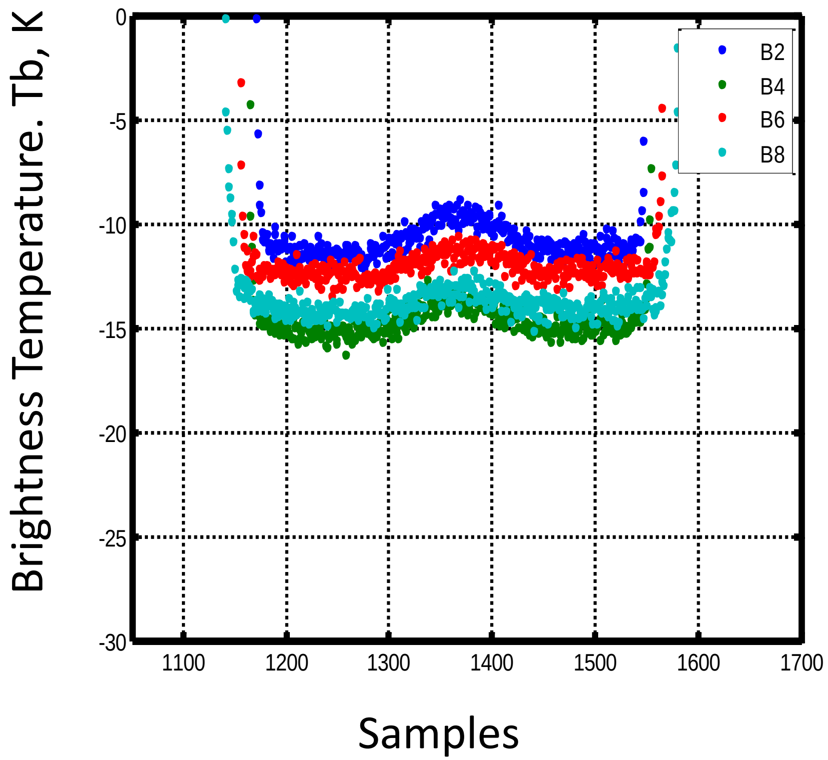
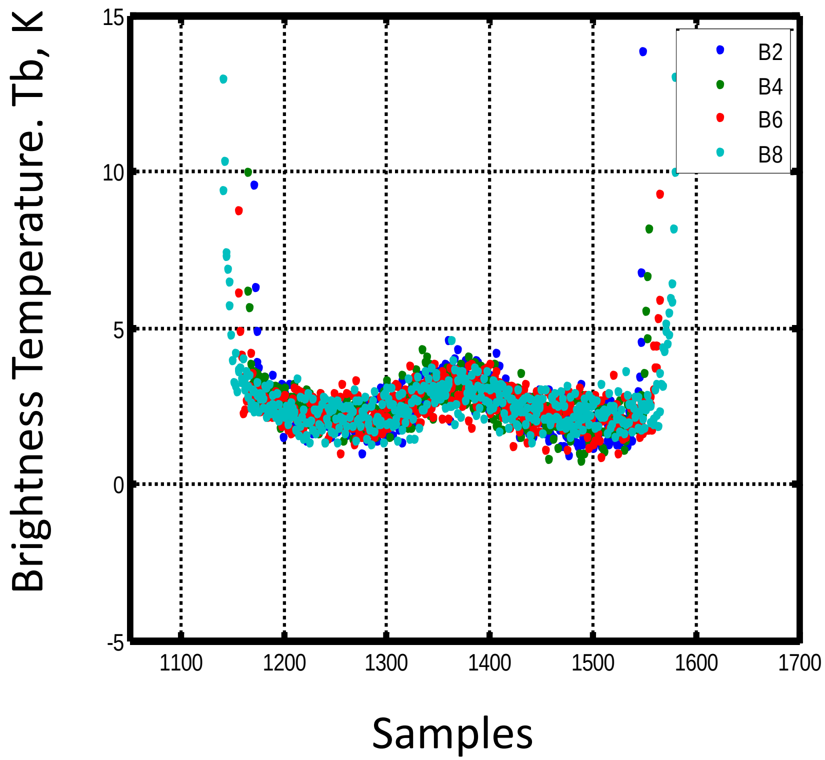
37H Even Beams

Version 5.0S



Version 6.0



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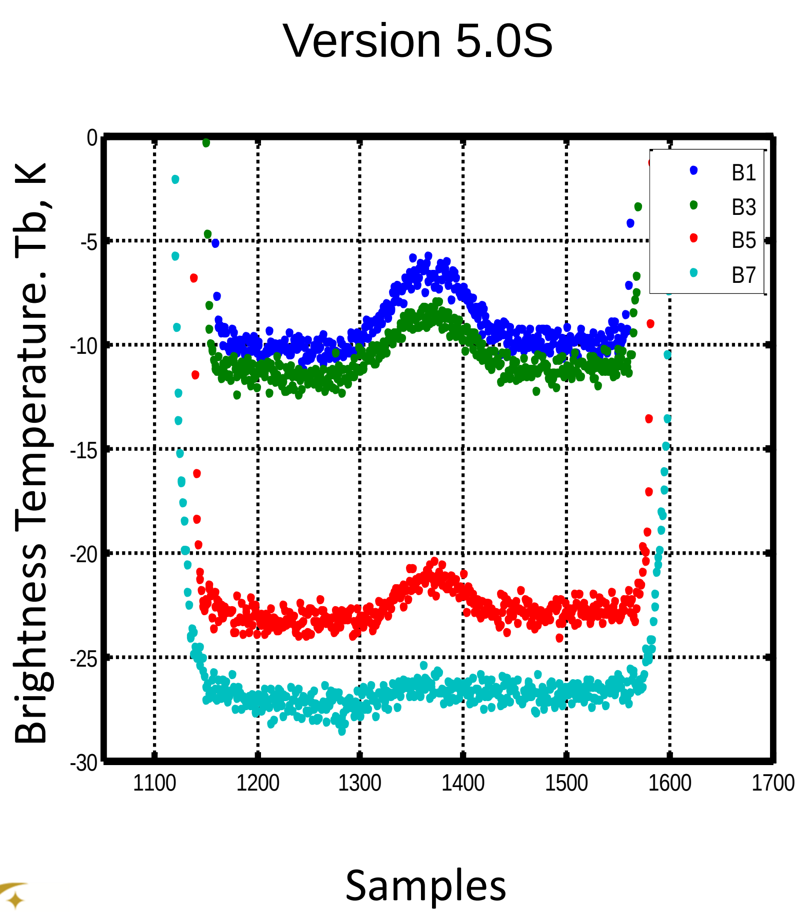
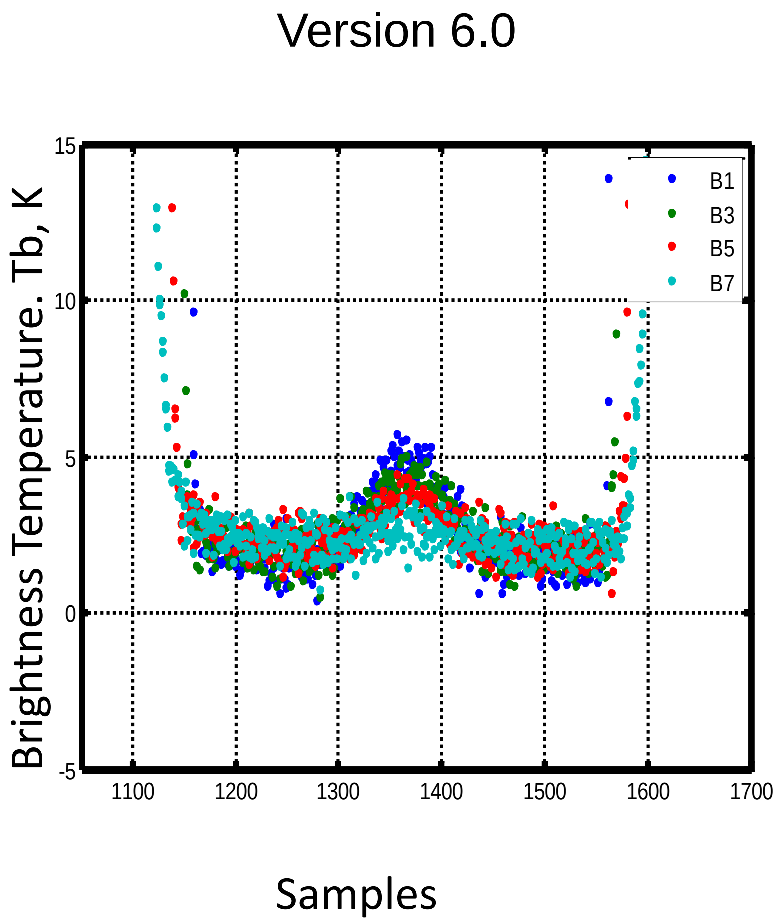
37H odd Beams





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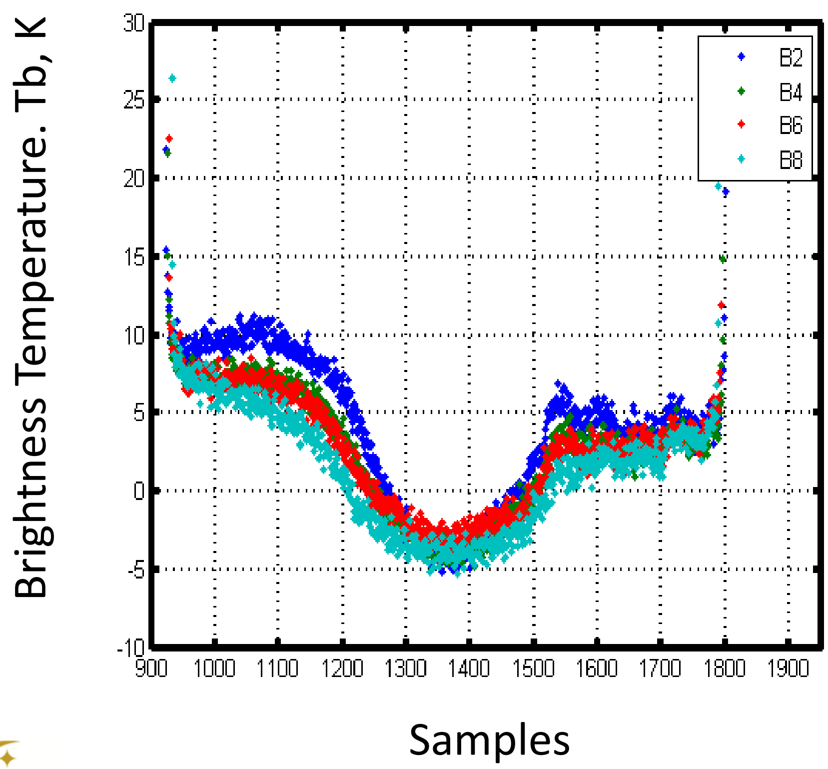
23H Even Beams

Version 5.0S



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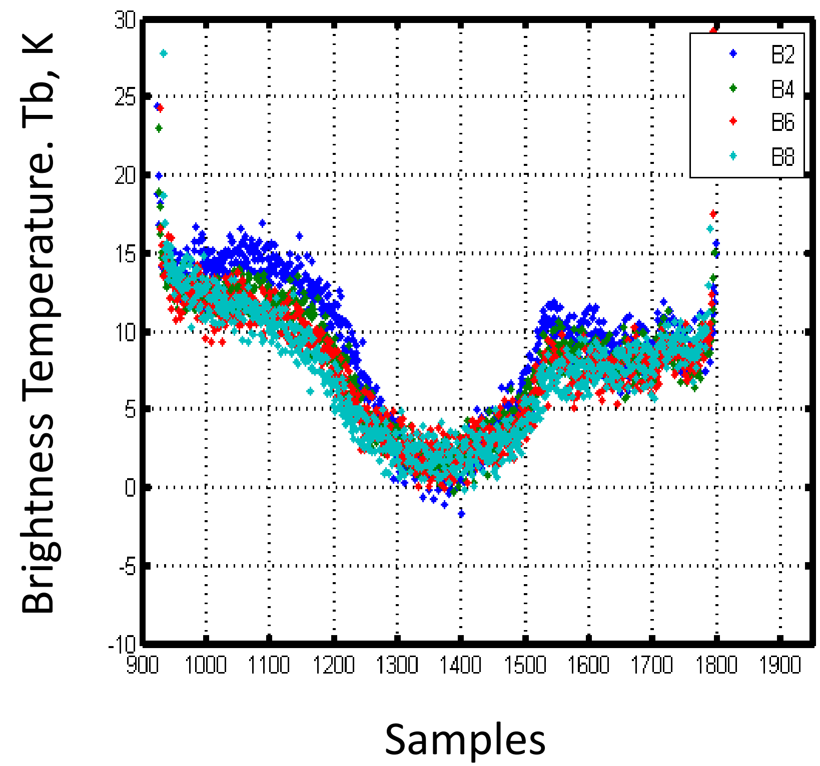
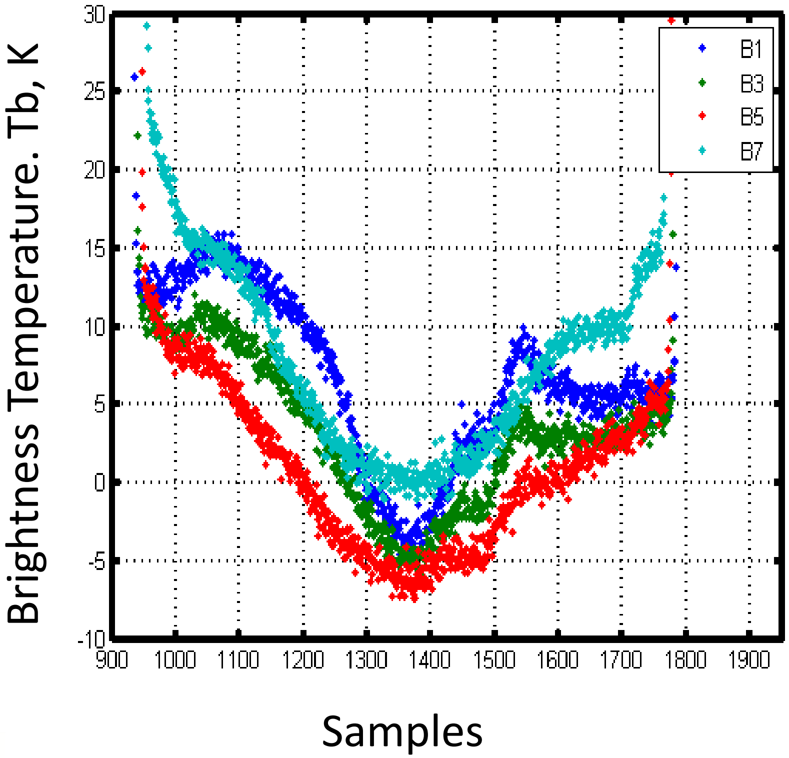


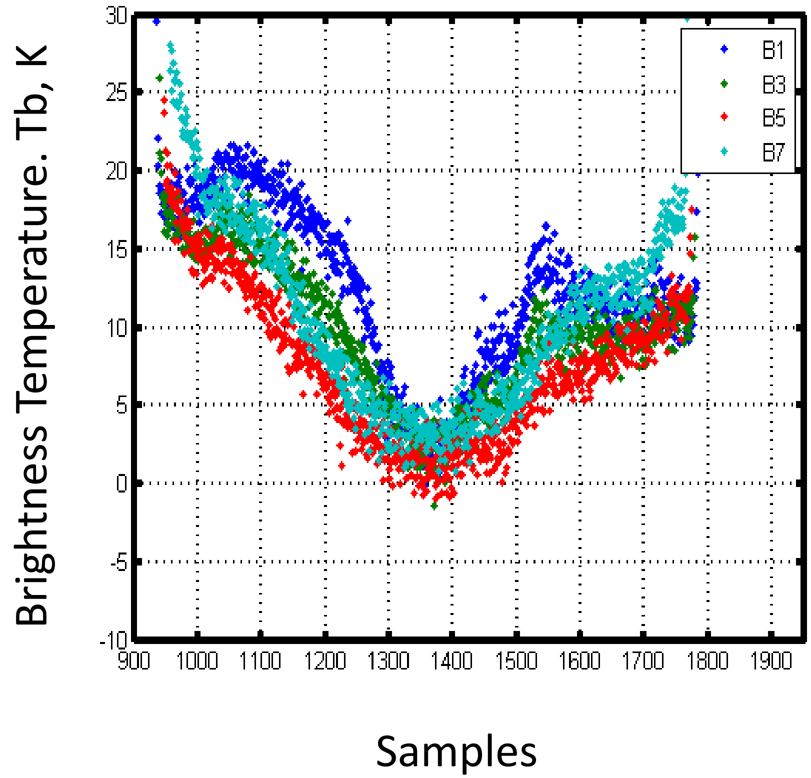
CFRSL

23H odd Beams

Version 5.0S



Version 6.0



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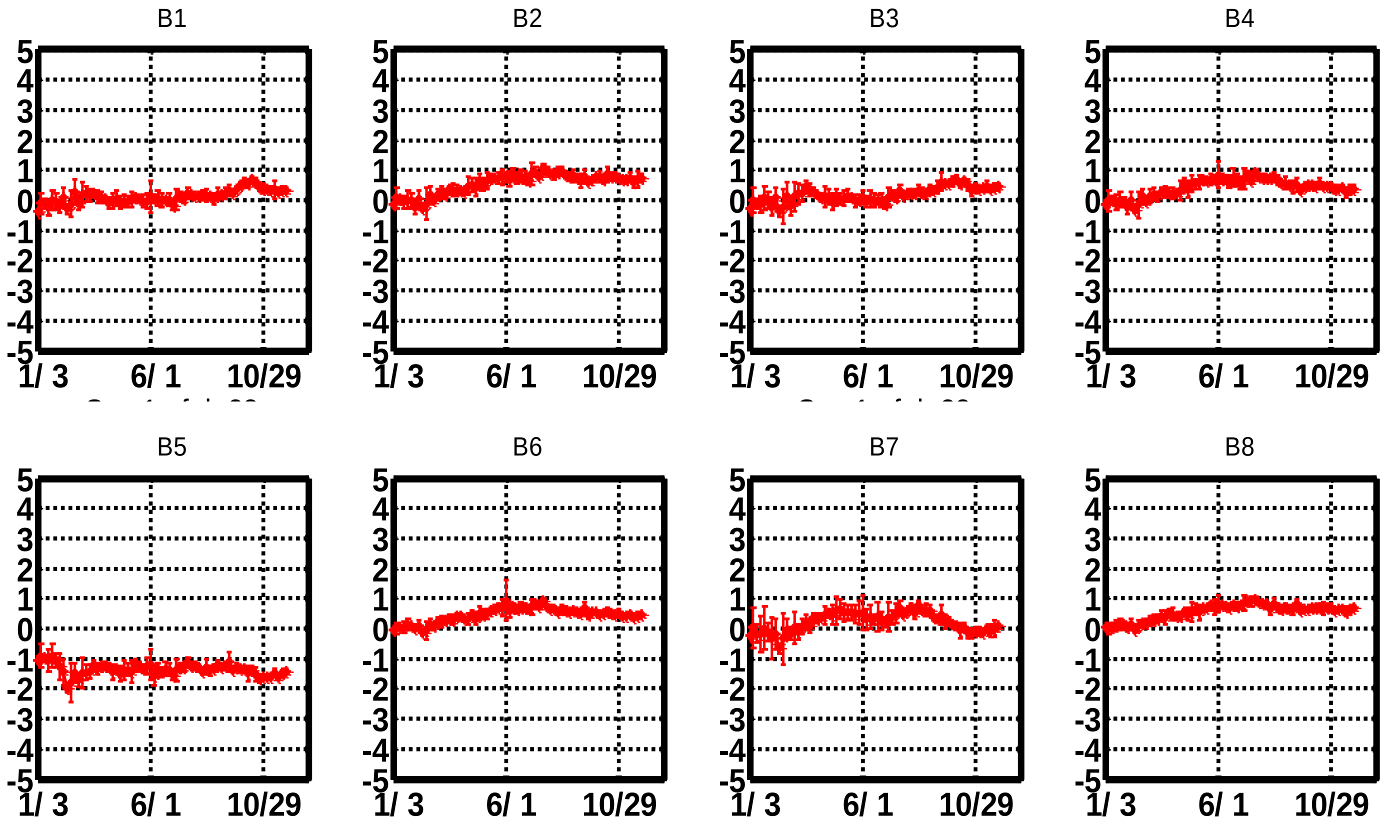
Double Difference Biases 37V (K), 2013



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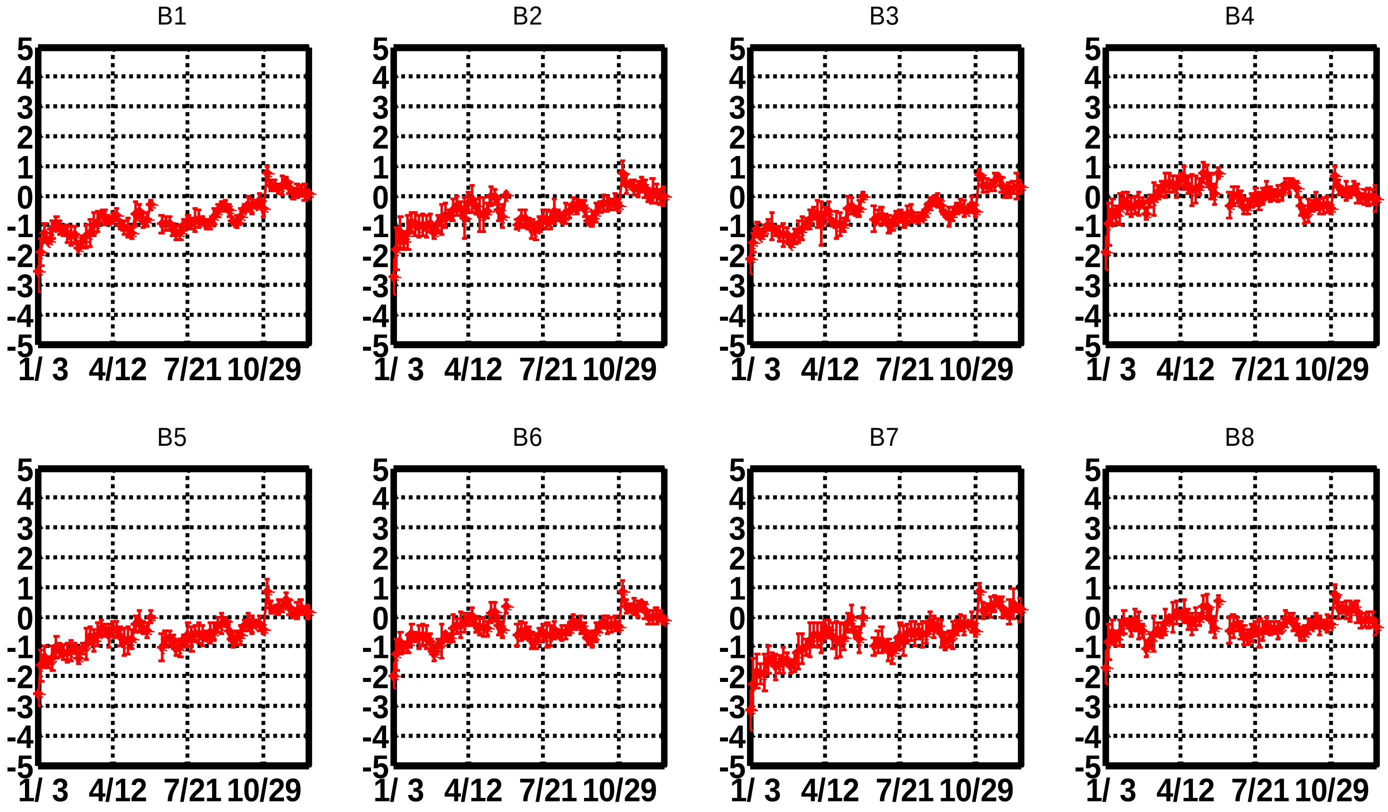
Double Difference Biases 37H (K), 2012



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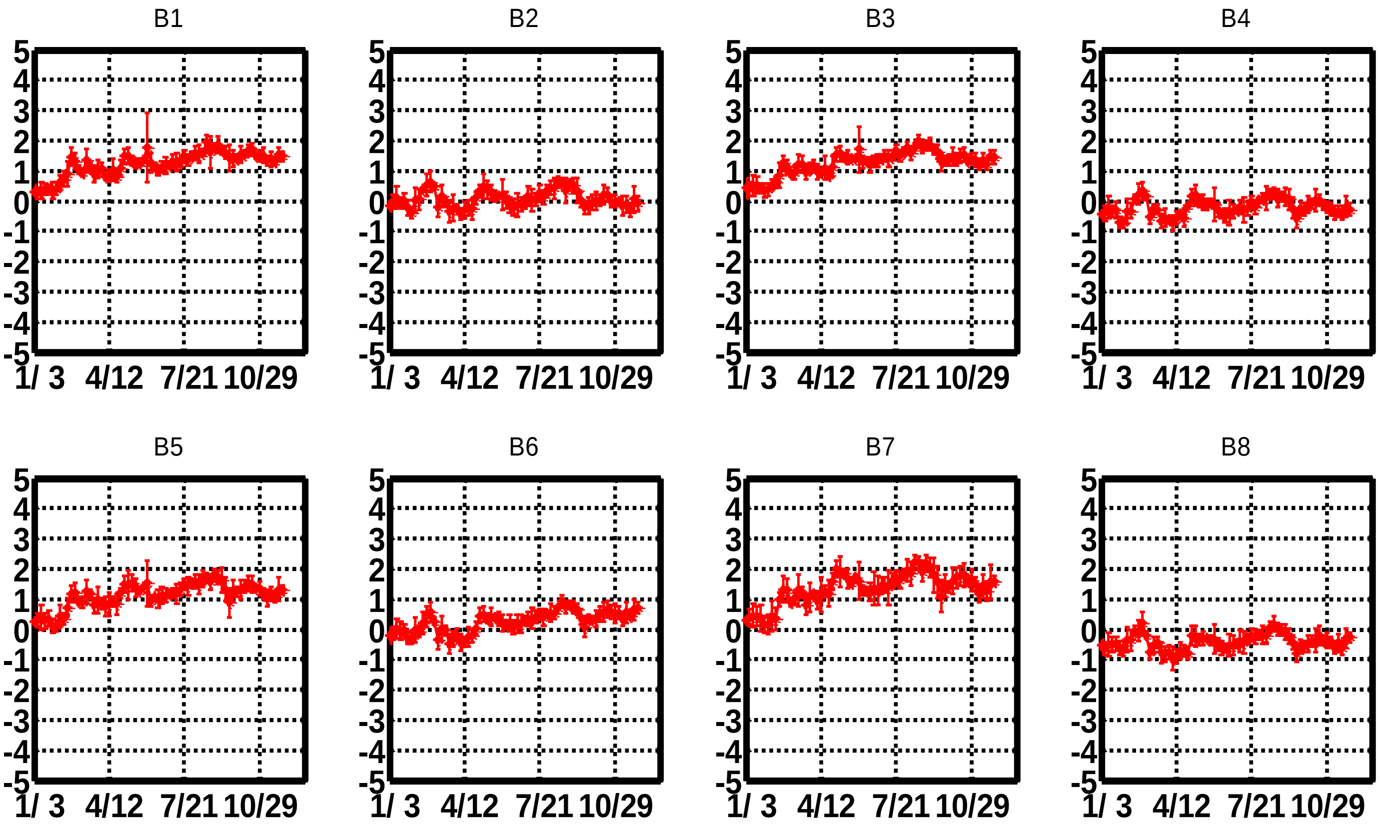
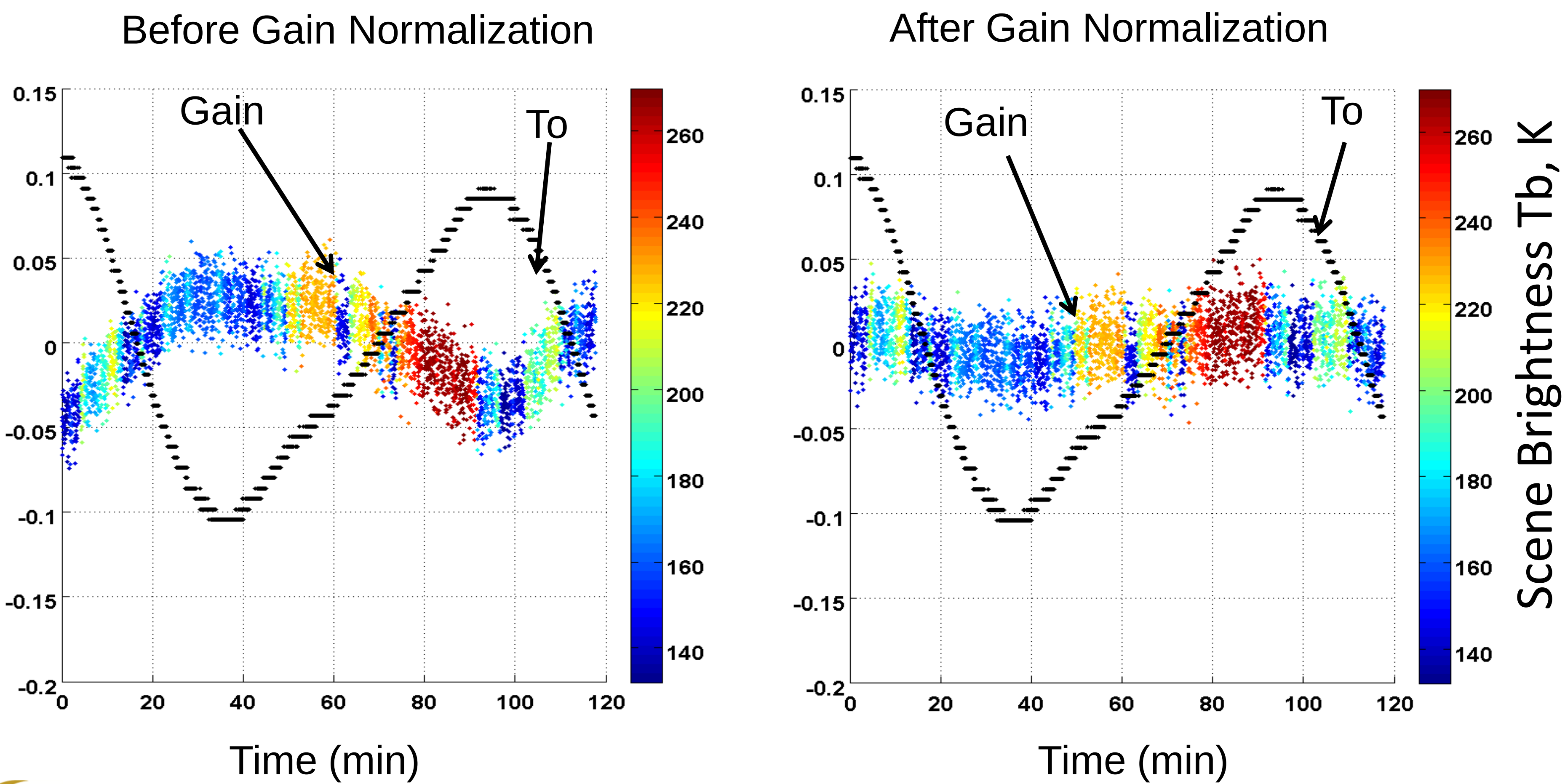
Double Difference Biases 37H (K), 2013



Example Gain Normalization



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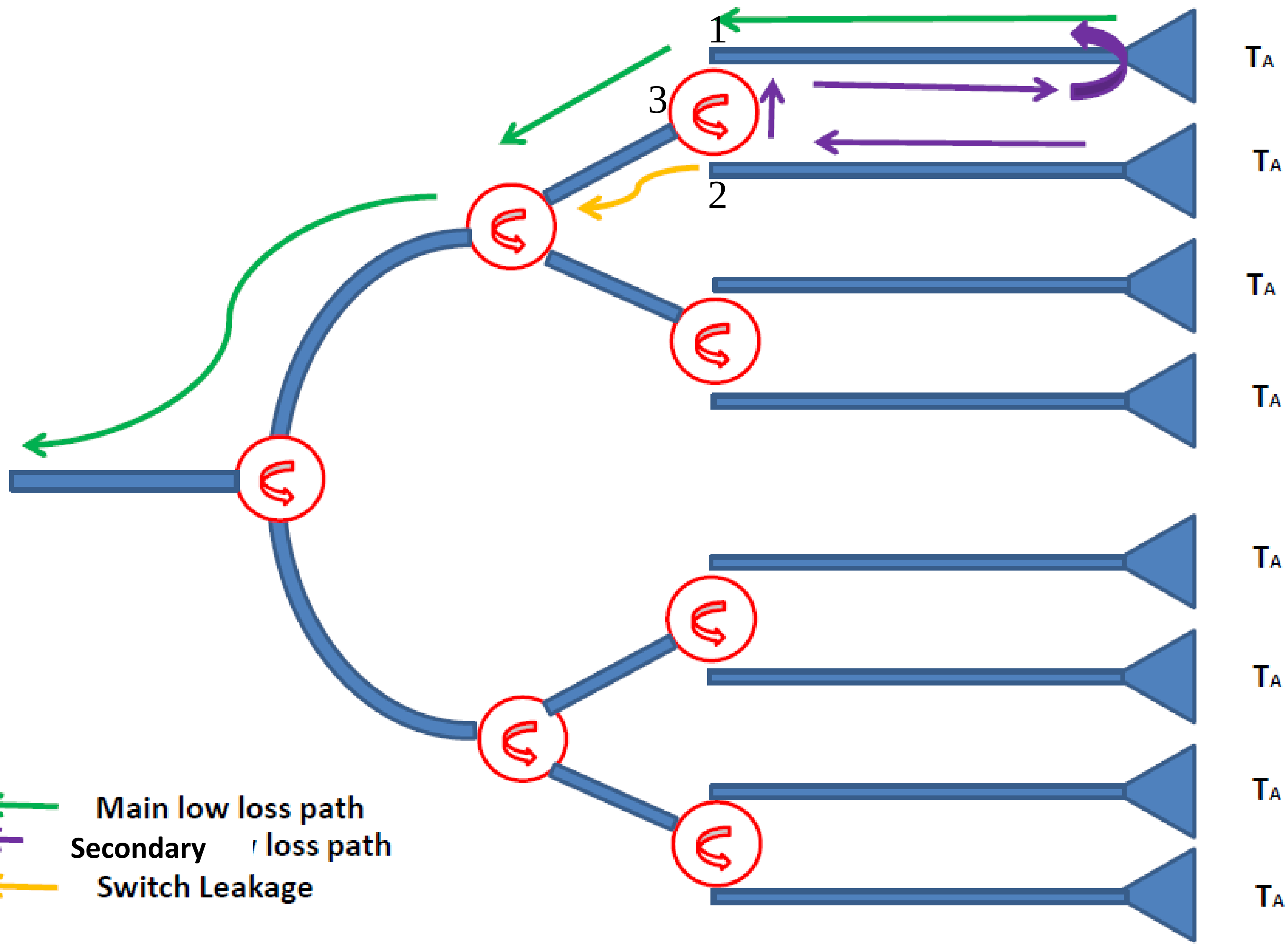
SW Matrix : Primary & Secondary Path



Main low loss path
Secondary ' loss path
Switch Leakage

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MWR L1B Data (V7)

- New MWR Tb data set to be used for tuning and validation of the wind speed algorithms
- XCAL 5 day double difference (DD) biases calculated between WindSat & MWR
  - **DD = MWR-WS**
- Applied triangular moving average on the 5 day DD time series to smooth the correction
- The new MWR Tb's V7.0 = V6.0 – Tb_{biases}
  - These V7.0 Tb's will be normalized to match the WindSat Tb's in the mean i.e., have zero DD Tb-bias
- The new "adjusted DD" given in the following charts was derived as:
  - $\mathbf{DD_{adj} = DD_{V6.0} - Tb_{biases}}$

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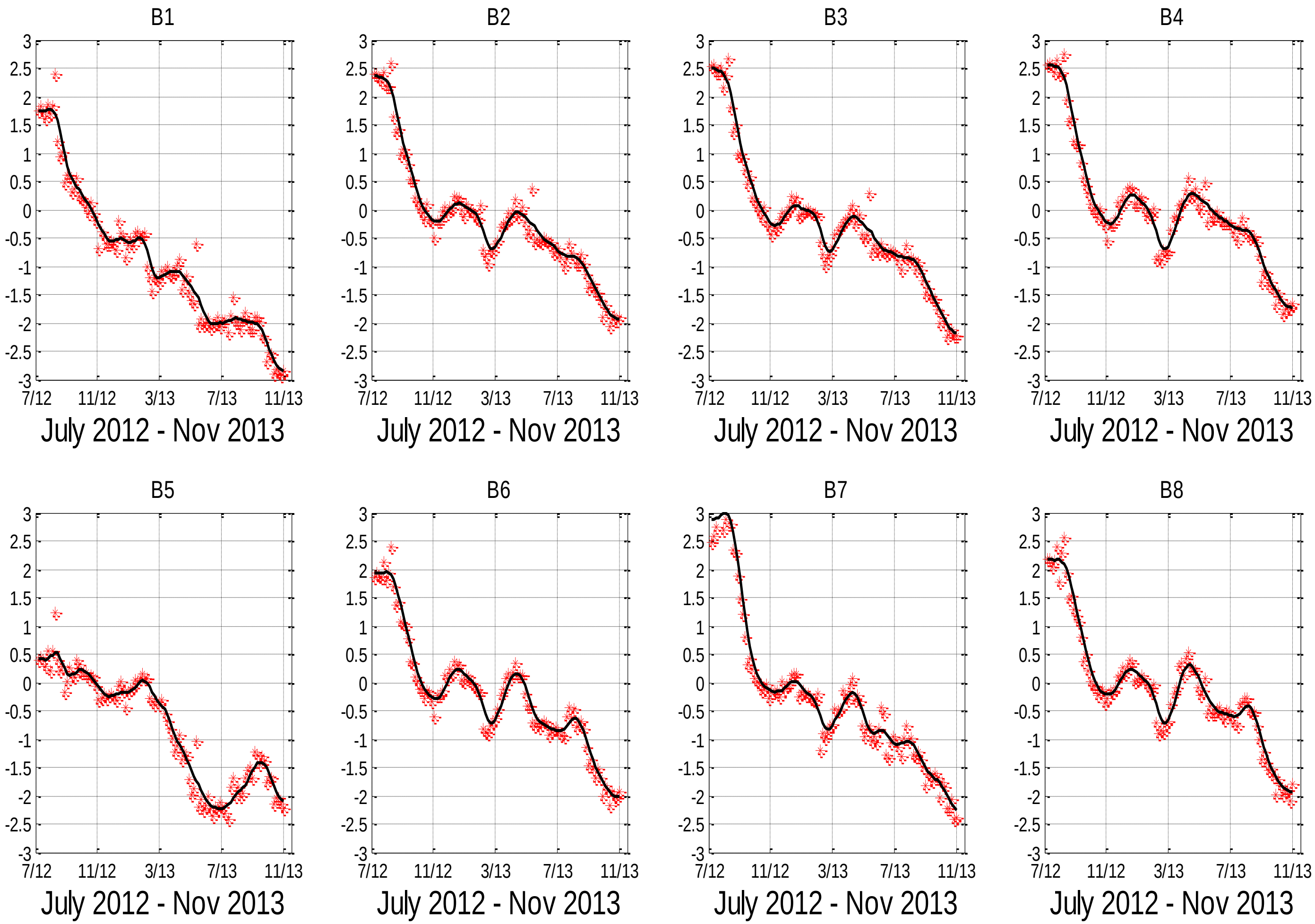
V6.0 23H, DD biases (MWR-WS)



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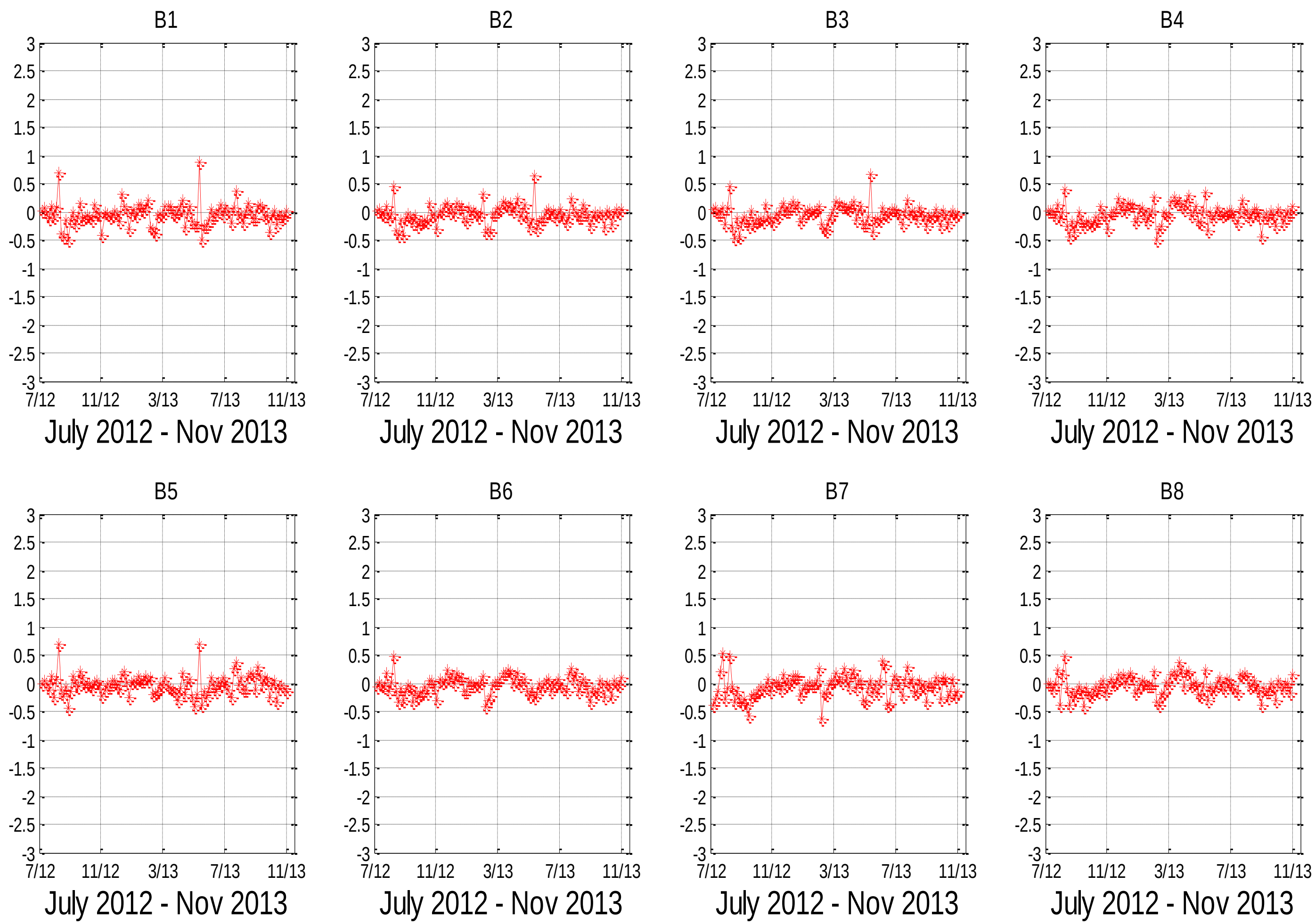
V7.0 23H DD Adjusted



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