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from Satellite Microwave Radiometry

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# Vicarious Calibration using Stationary $T_B$ Statistics

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# Summary

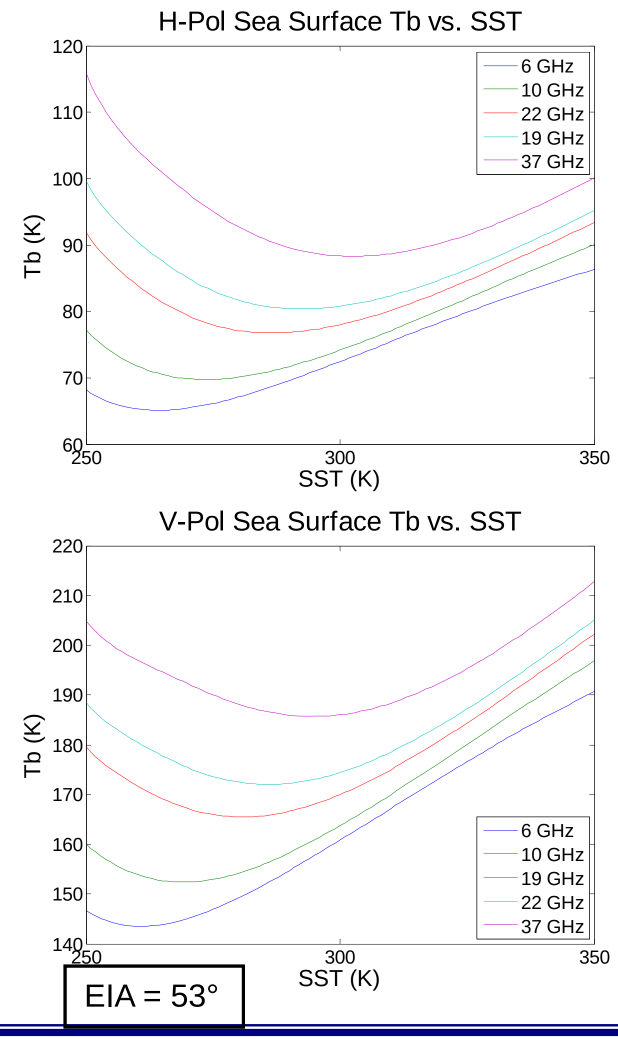
- Hot and Cold $T_B$ vicarious statistical references have been developed which provide
  - Excellent relative calibration (~ 0.1 K) between instruments and between modes of a single instrument
    - Correct for differences in frequency and incidence angle
    - Doesn't require coincident observations in time or space between instruments
    - Relative calibration is very insensitive to radiative transfer model errors
  - Good absolute calibration standard (~ 0.5 K) for each individual instrument
    - Accounts for specific frequency and incidence angle of each instrument
    - Doesn't require coincident observations with ground truth obs or numerical models
    - Absolute calibration IS sensitive to radiative transfer model errors

# Previous Applications of Vicarious Calibration Method

- **TOPEX Microwave Radiometer Absolute Calibration**
  - Ruf, C.S. “Detection of calibration drifts in spaceborne microwave radiometers using a vicarious cold reference,” IEEE Trans. Geosci. Remote Sens., **38**(1), 44-52, 2000.
  - Keihm, S.J., V. Zlotnicki and C.S. Ruf, “TOPEX Microwave Radiometer Performance Evaluation, 1992-1998,” IEEE Trans. Geosci. Remote Sens., **38**(3), 1379-1386, 2000.
  - Ruf, C.S., “Characterization and Correction of a Drift in Calibration of the TOPEX Microwave Radiometer”, IEEE Trans. Geosci. Remote Sens., **40**(2), 509-511, 2002.
- **TOPEX/SSM/I Cross Calibration**
  - Ruf, C.S., S.J. Keihm, B. Subramanya, and M.A. Janssen, “TOPEX/POSEIDON Microwave Radiometer Performance and In-flight Calibration,” J. of Geophys. Res., **99**(C12), 24915-24926, 1994.
- **Jason-1 Microwave Radiometer Absolute Calibration**
  - Brown, S.T., and C.S. Ruf, “Determination of a Hot Blackbody Reference Target over the Amazon Rainforest for the On-orbit Calibration of Microwave Radiometers,” AMS J. Oceanic Atmos. Tech., **22**(9), 1340-1352, 2005.
- **TOPEX/Jason-1 Cross Calibration**
  - Brown, S., C. Ruf, S. Keihm and A. Kitiyakara, “Jason Microwave Radiometer performance and on-orbit calibration,” Marine Geodesy, **27**(1-2), 199-220, 2004.
- **GEOSAT Follow-On/Jason-1 Cross Calibration**
  - Ruf, C.S., and A.M. Warnock, “GEOSAT Follow On Water Vapor Radiometer: Performance with a Shared Active/Passive Antenna,” IEEE Trans. Geosci. Remote Sens., **45**(4), 970-977, 2007.
- **WindSat Absolute Calibration**
  - Ruf, C.S., Y. Hu and S.T. Brown, “Calibration of WindSat Polarimetric Channels with a Vicarious Cold Reference,” IEEE Trans. Geosci. Remote Sens., **44**(3), 470-475, 2006.
  - Bettenhausen, M., E. Twarog and P. Gaiser, “On-Orbit Calibration of WindSat Brightness Temperatures, Proc. IGARSS, Barcelona, SPAIN, July 2007. **Aquarius Absolute Calibration**
  - Ruf, C.S., “Vicarious Calibration of an Ocean Salinity Radiometer from Low Earth Orbit,” AMS J. Atmos. Oceanic Tech., **20**(11), 1656-1670, 2003.
- **Aquarius Absolute Calibration**
  - Ruf, C.S., “Vicarious Calibration of an Ocean Salinity Radiometer from Low Earth Orbit,” AMS J. Atmos. Oceanic Tech., **20**(11), 1656-1670, 2003.
- **GPM Constellation Inter-Calibration**
  - McKague, D., C. Ruf and J.J. Puckett, “Microwave Radiometer Inter-Calibration Using the Vicarious Calibration Method,” Proc. 2009 IEEE International Geoscience and Remote Sensing Symposium, Cape Town, S.A., Vol. IV, 117-120, 13-17 July 2009.

# Vicarious Cold Reference: Approach and Signal Processing

- $\varepsilon * T_{surf}$ shown at 53$^{o}$ for typical radiometer window channels
- Minimum TB conditions
  - Optimum SST (vs. freq. and inc. angle)
  - No Clouds or Wind
  - Low humidity
- Signal Processing
  - Assemble $T_B$ histogram
  - Compute cumulative distribution function
  - Extrapolate CDF to highest TB with zero probability of occurrence
  - This corrects for small residual atmospheric contributions





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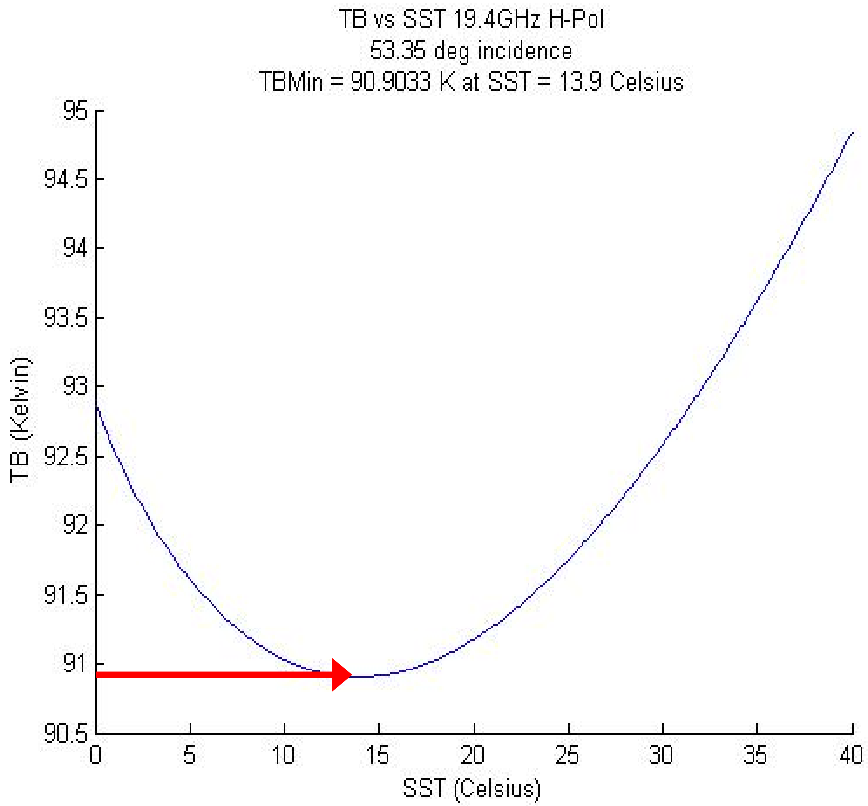
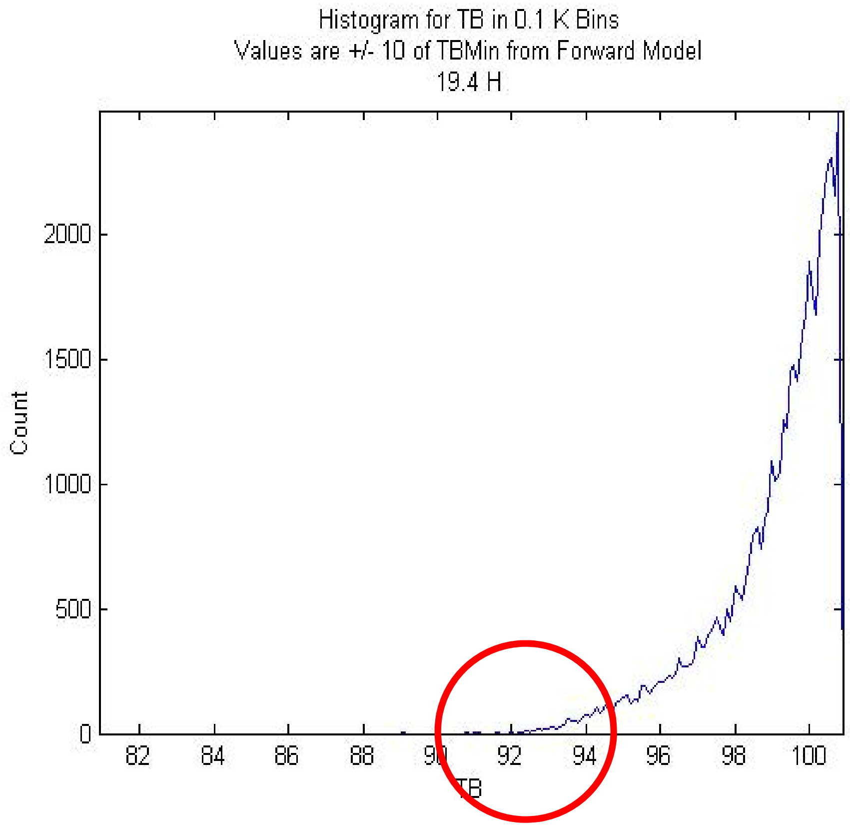
# Vicarious Cold Reference Example: TMI 19 GHz H-pol




- Ideal minimum with no atmosphere
- Actual histogram with atmospheric offset and additive noise



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# Vicarious Hot Reference: Approach and RTE Model

- Hot reference $T_B$ method uses depolarized regions of the world's rain forests as proxies for black body targets
  - Identify regions using |V-pol – H-pol| de-pol'z metric
- Trained RTE model for frequency and incidence angle dependence
  - Unpolarized underlying surface and vegetation canopy
  - Frequency dependent vegetation canopy temperature
  - Atmosphere model parameterized by full year of Amazon RaOb profiles
  - Diurnal and annual harmonics for surface temperature, atmos. effective radiating temperature, optical depth model v. freq.


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# Depolarized Amazon Rainforest Hot Reference Regions

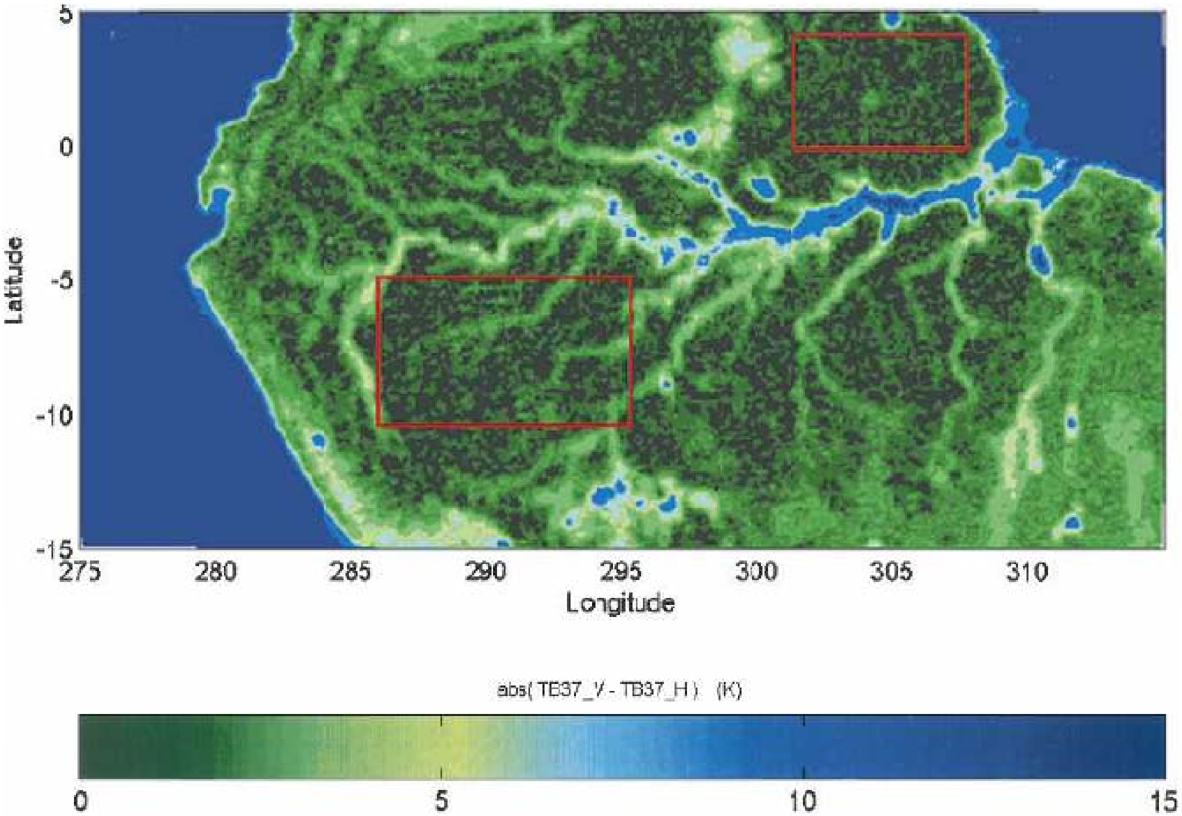


FIG. 1. Magnitude of the difference between vertically and horizontally polarized brightness temperature at 37 GHz, 53° incidence angle over the Amazon basin as measured by SSM/I. The red boxes denote regions of high depolarization, which have properties especially amenable to modeling as blackbody hot calibration reference sites.



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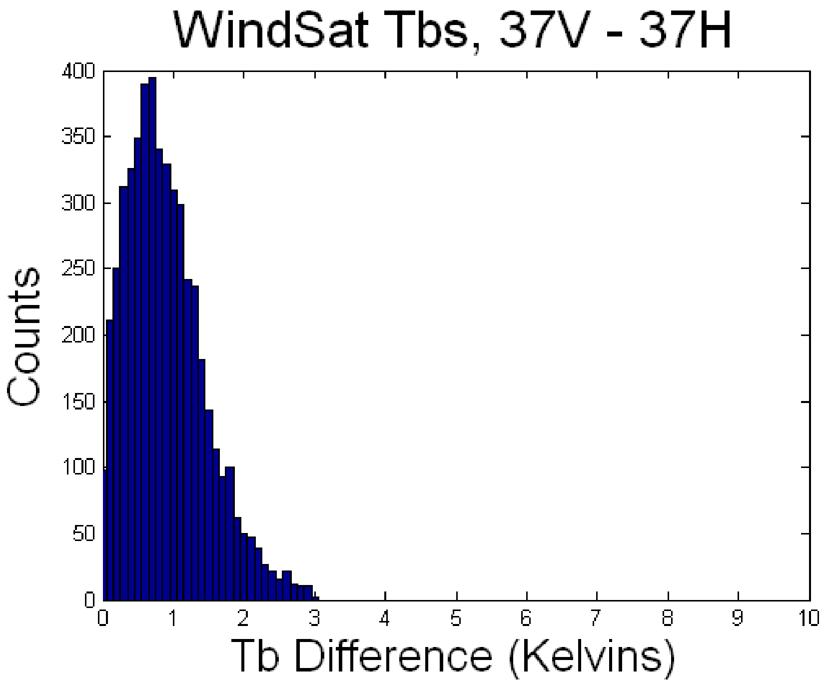
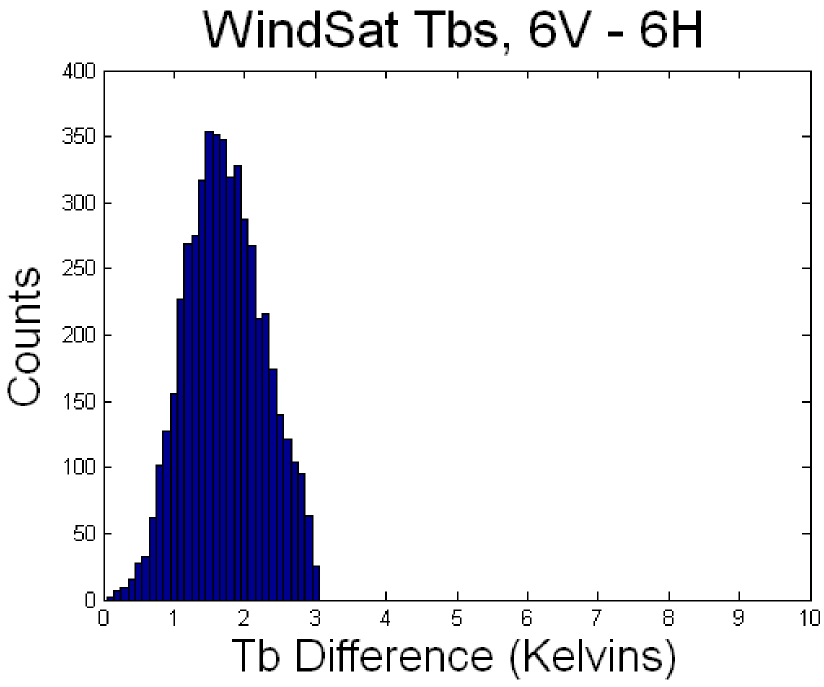
# Vicarious Hot Reference Example: WindSat Depolarization Histograms in Amazon Regions



# Forward Model for Vicarious Warm Reference Brightness Temperature

$$T_b(f,\theta) = \varepsilon(f) * T_{veg} e^{-\tau(f)\sec\theta} + T_b^{UP}(f,\theta) + (1 - e(f)) T_b^{DN}(f,\theta) e^{-\tau(f)\sec\theta}$$

$$T_b^{UP} = T_{eff}^{UP}(f)(1 - e^{-\tau(f)\sec\theta})$$

$$T_b^{DN} = T_{eff}^{DN}(f)(1 - e^{-\tau(f)\sec\theta}) + T_{coldsky} e^{-\tau(f)\sec\theta}$$

$$\tau = b_0(f) + b_1(f) A$$

$A = V + 2L$; V is water vapor, L is cloud water

$$\varepsilon = \varepsilon_0 + \varepsilon_1 f + \varepsilon_2 f^2$$

$$T_{veg} = T_0 + T_1 f$$

- Optical depth model fit to RTE model applied to GDAS dataset
- $T_{eff}$ calculated from RTE/GDAS at each frequency and incidence angle
- $T_{veg}$ allowed to vary with frequency because lower frequencies will penetrate to deeper, cooler areas of the vegetation canopy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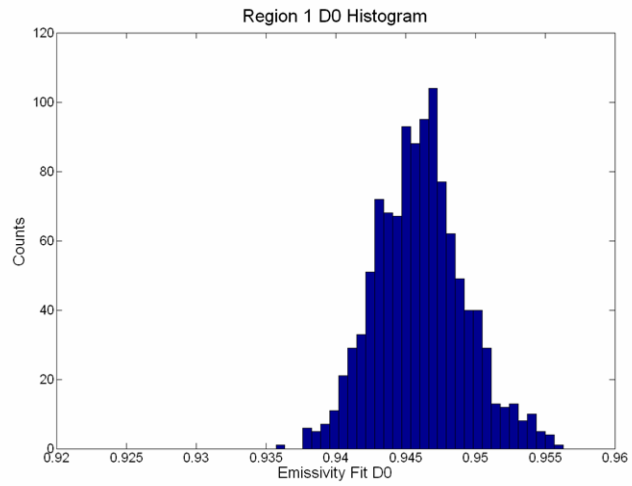
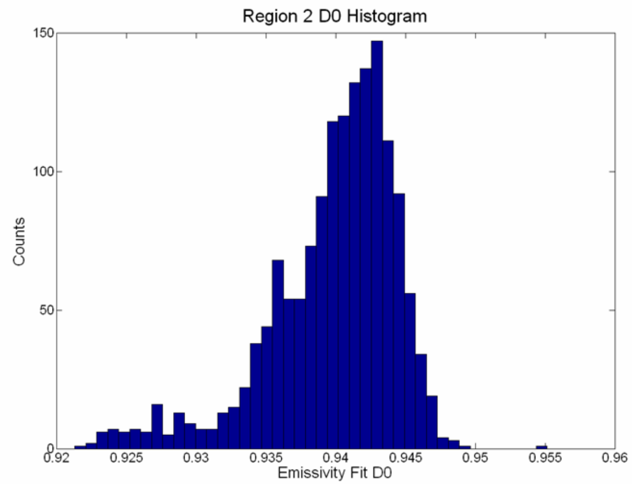
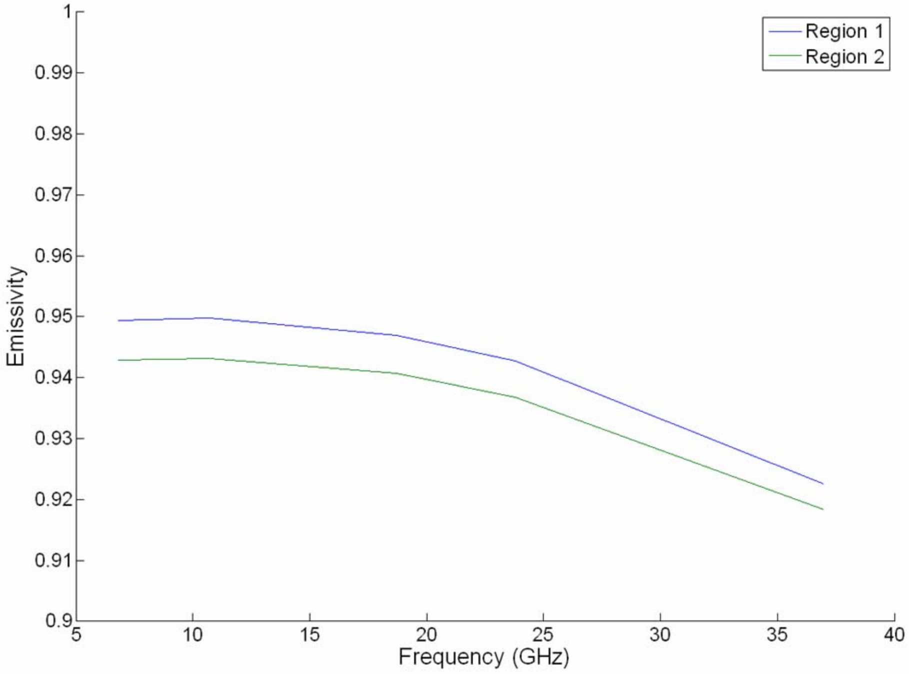
# Vicarious Warm Reference Example: Surface Emissivity TMI Histogram at 6 GHz and Empirical Model



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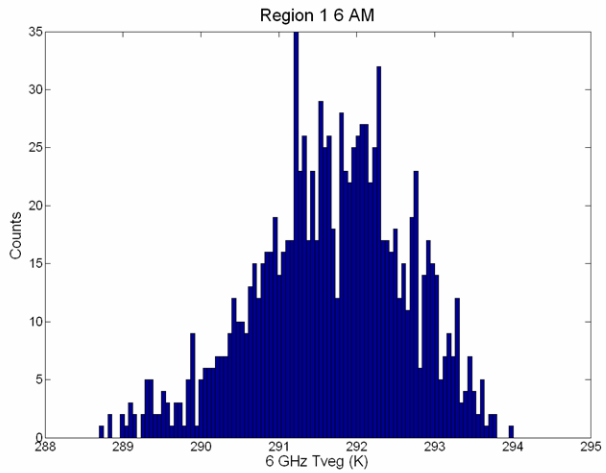
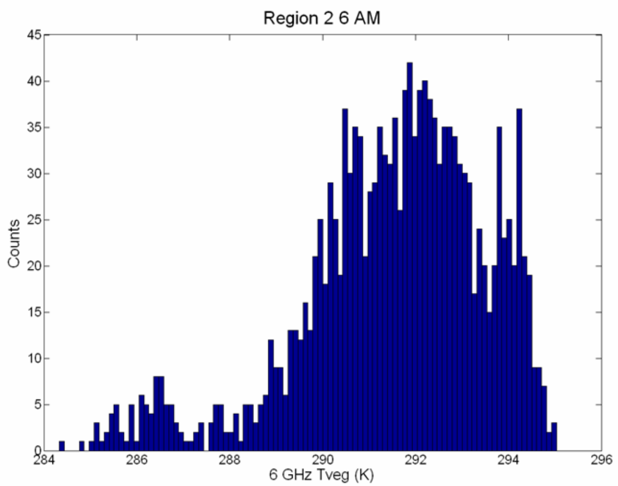
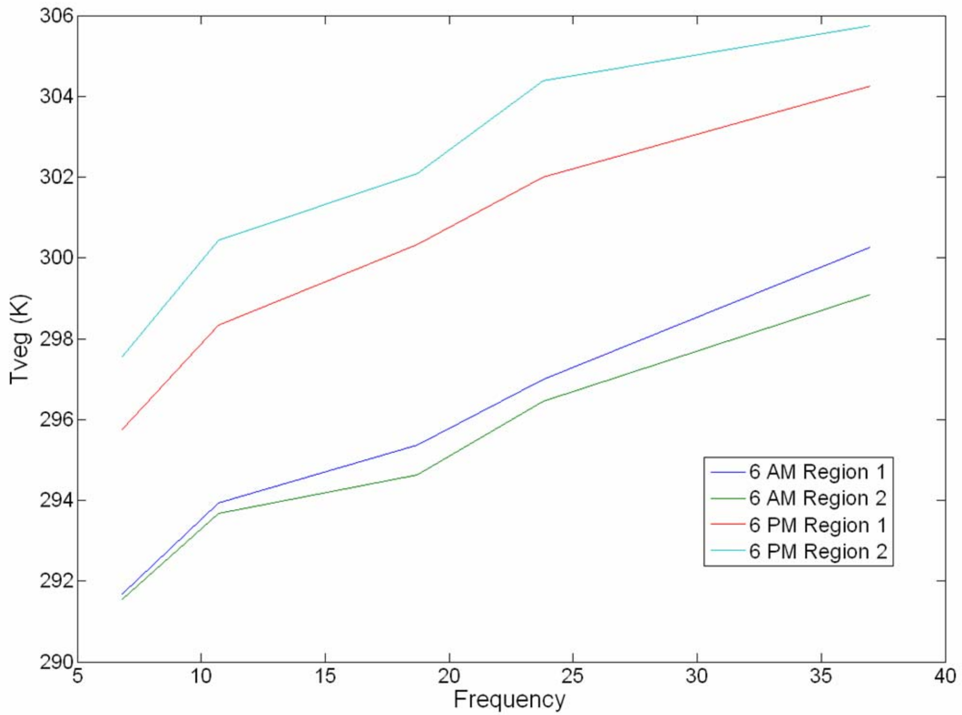
# Vicarious Warm Reference Example: Vegetation Canopy Temperature



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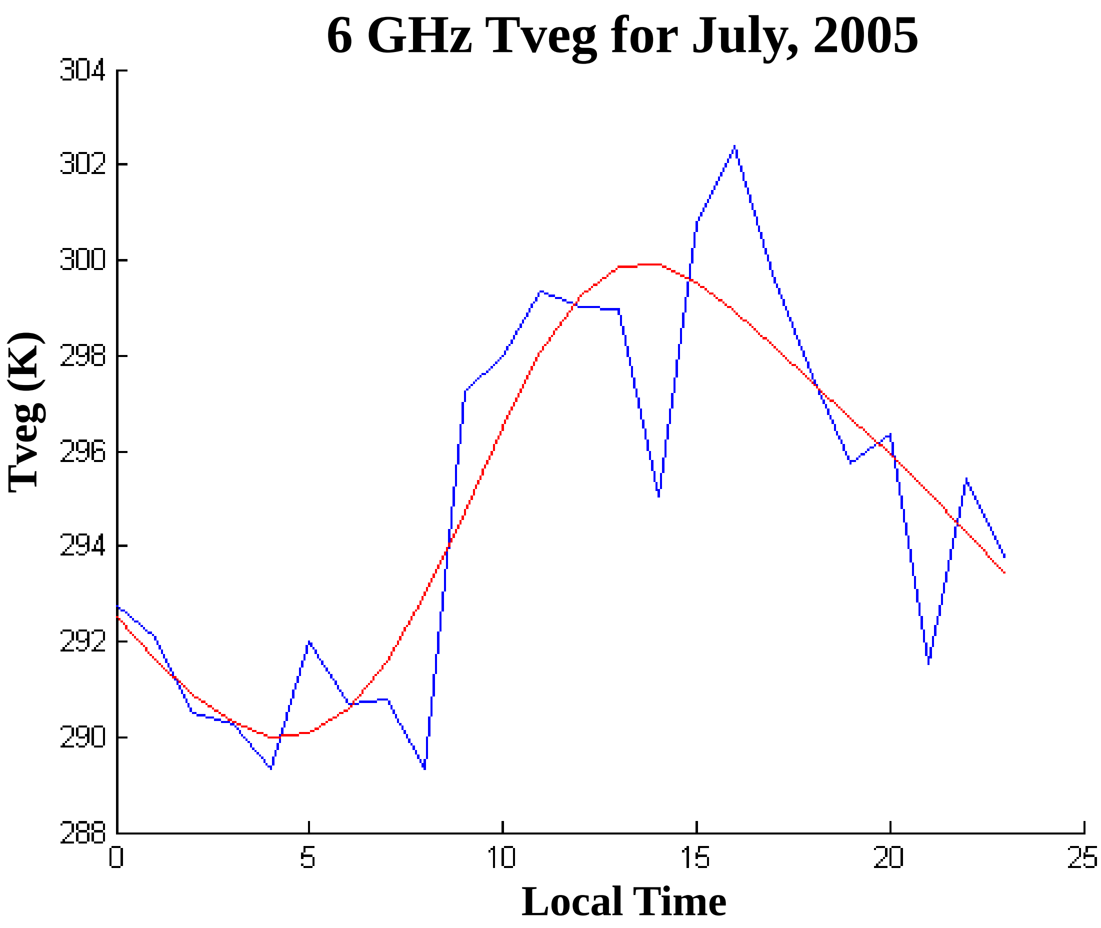
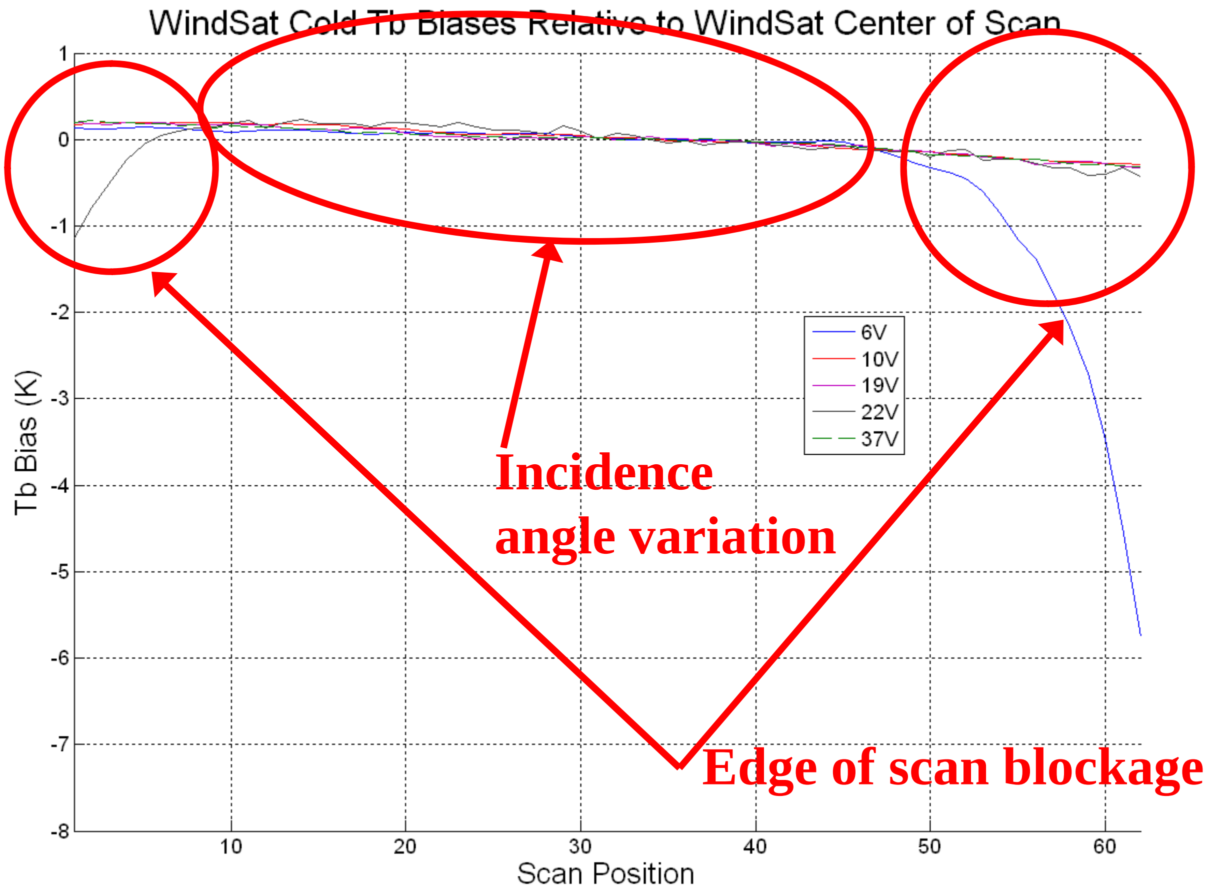
# Vicarious Warm Reference Example: $T_{veg}$ Diurnal Signal for TMI



# Example of Use of Vicarious Hot/Cold Calibration for Single Sensor Diagnostics

Incidence Angle Variations and Scan Dependent Biases with WindSat

# WindSat Vicarious Cold Reference vs. Scan Position TB (V-pol) w.r.t. Center of Scan







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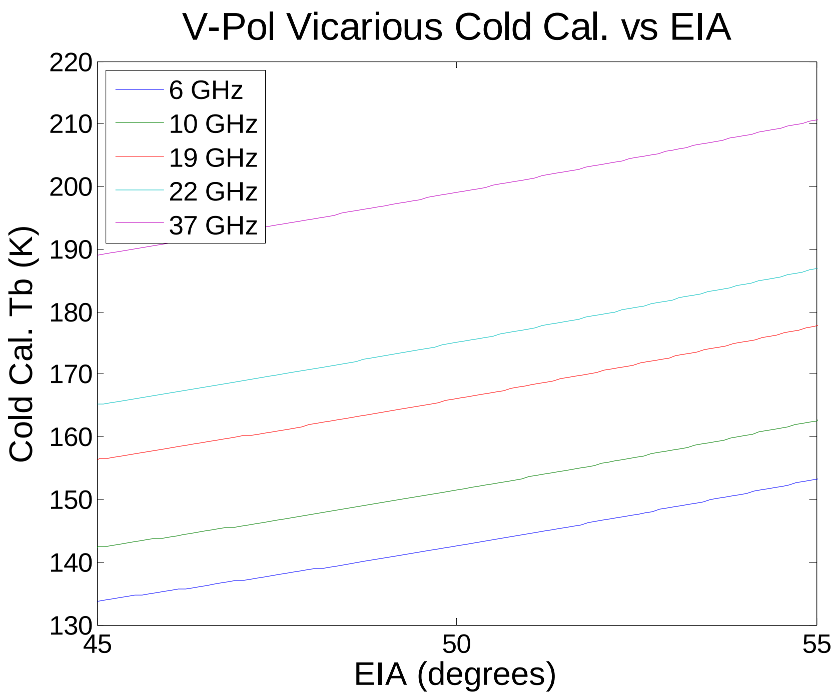
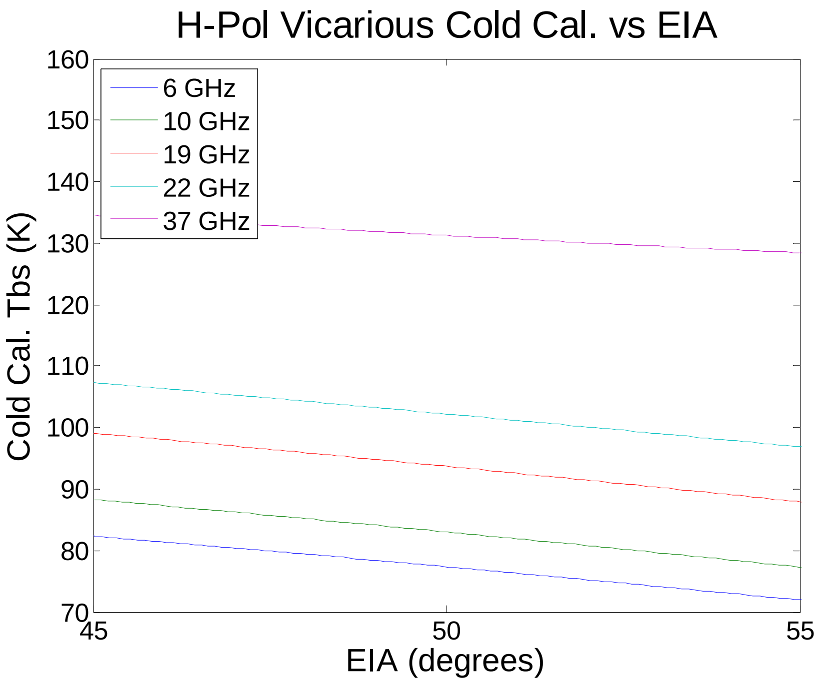
# Vicarious Cold Reference Dependence on Incidence Angle



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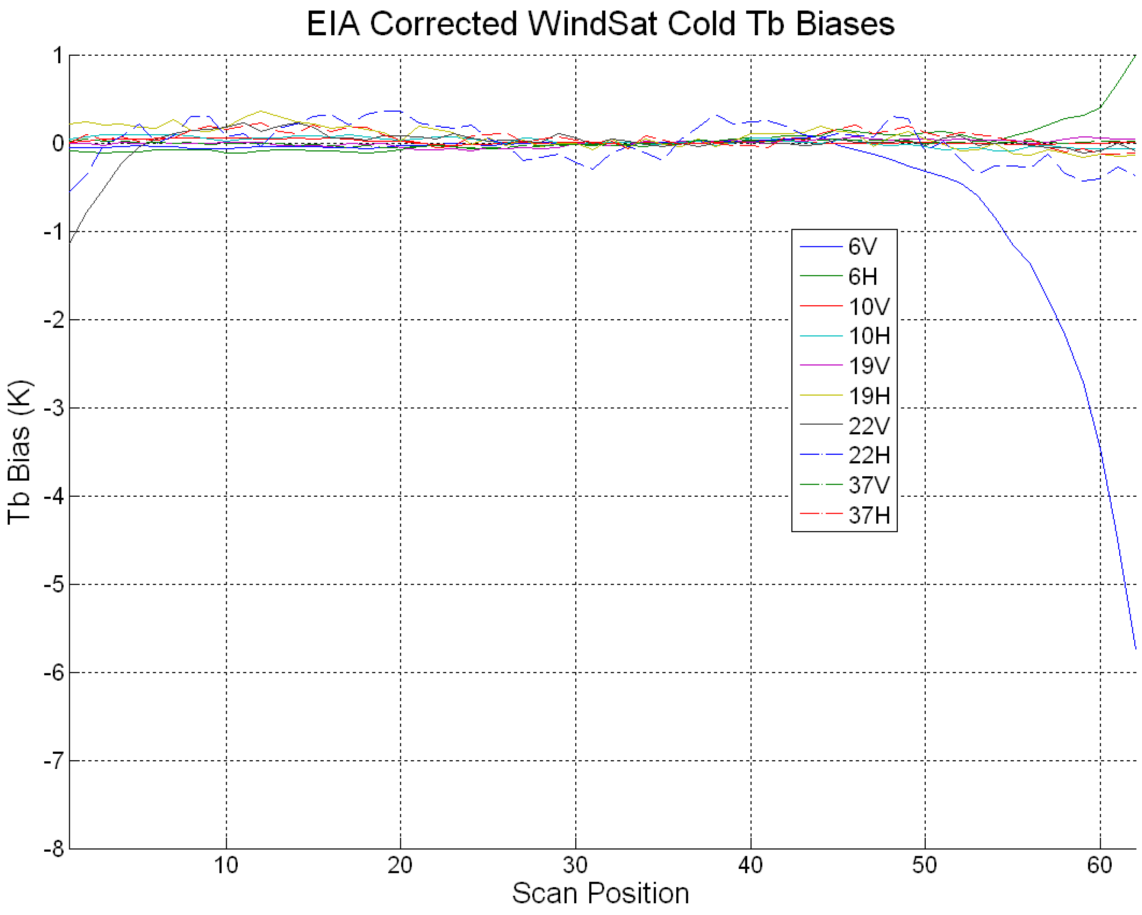
# WindSat Vicarious Cold Reference vs. Scan Position Corrected for Roll and Pitch Offsets




**Data are consistent with roll offset of .2° and pitch offset of .15°**



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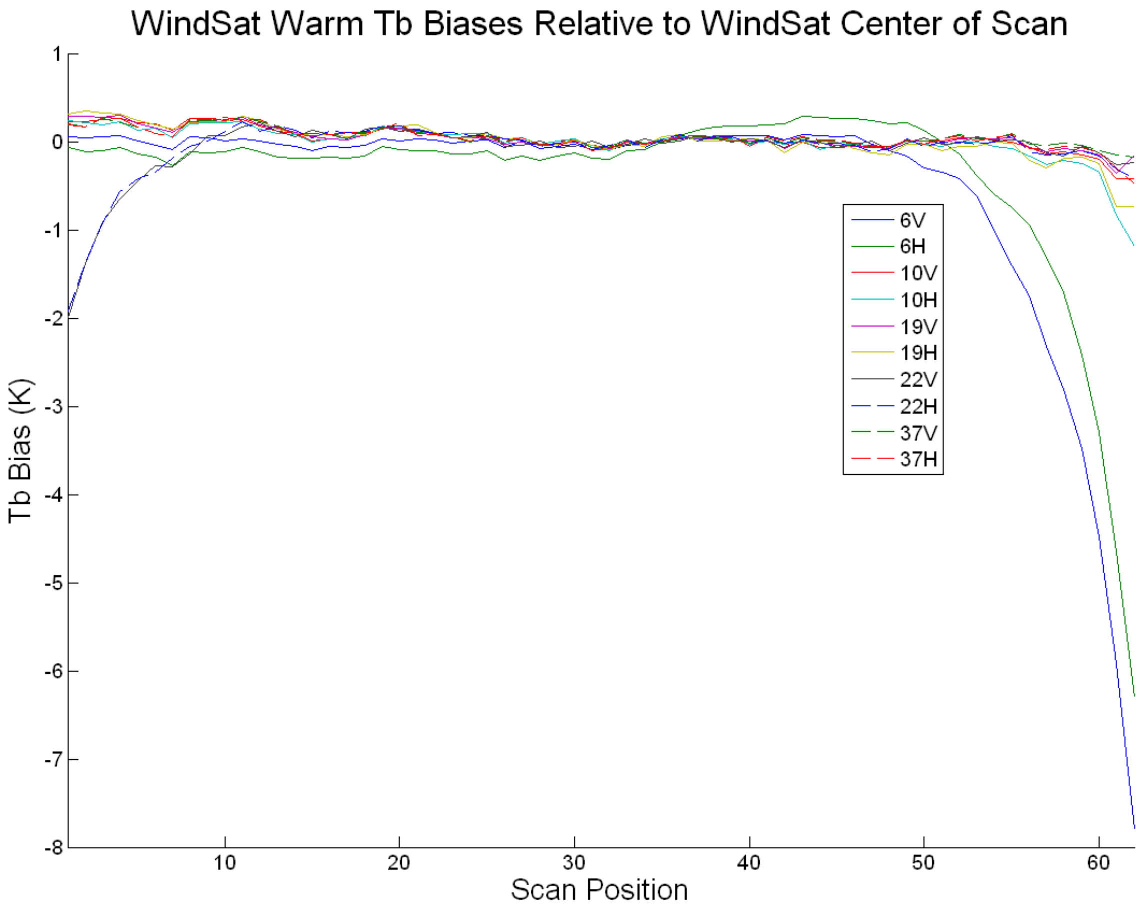
# WindSat Vicarious Warm Reference vs. Scan Position



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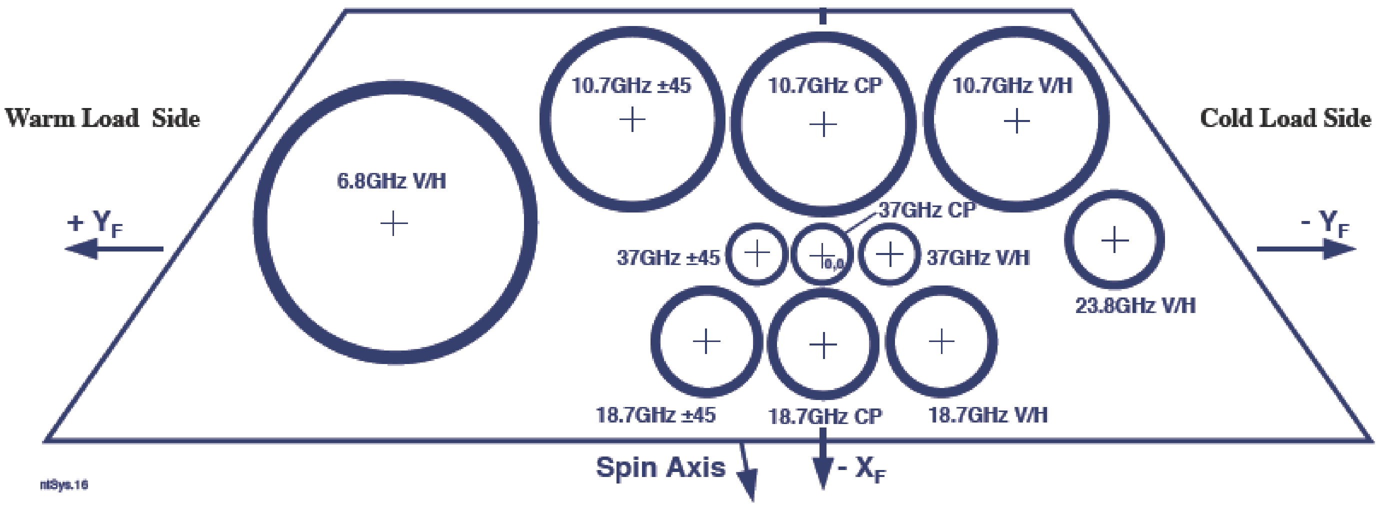
# WindSat Reference Tbs
# Edge of Scan Biases

- Both 6 GHz and 22 GHz Tbs show significant edge of scan biases
  - Emitter/scatter in side-lobes
    - Most likely from calibration loads
    - Must correct for in APC if we want to use edge of scan Tbs



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# WindSat Edge of Scan Bias Correction Algorithm

- Decompose measured antenna temperature into mainbeam and sidelobe contributions:

$$T_A = T_{b,mb} * (1 - bf_{sl}) + T_{b,sl} * bf_{sl}$$

- Solve for sidelobe effective average brightness temperature $T_{b,sl}$ and integrated sidelobe beam fraction, $f_{sl}$, as a function of scan position
- Separate retrieval for each frequency and polarization since blockage and resulting beam patterns will vary



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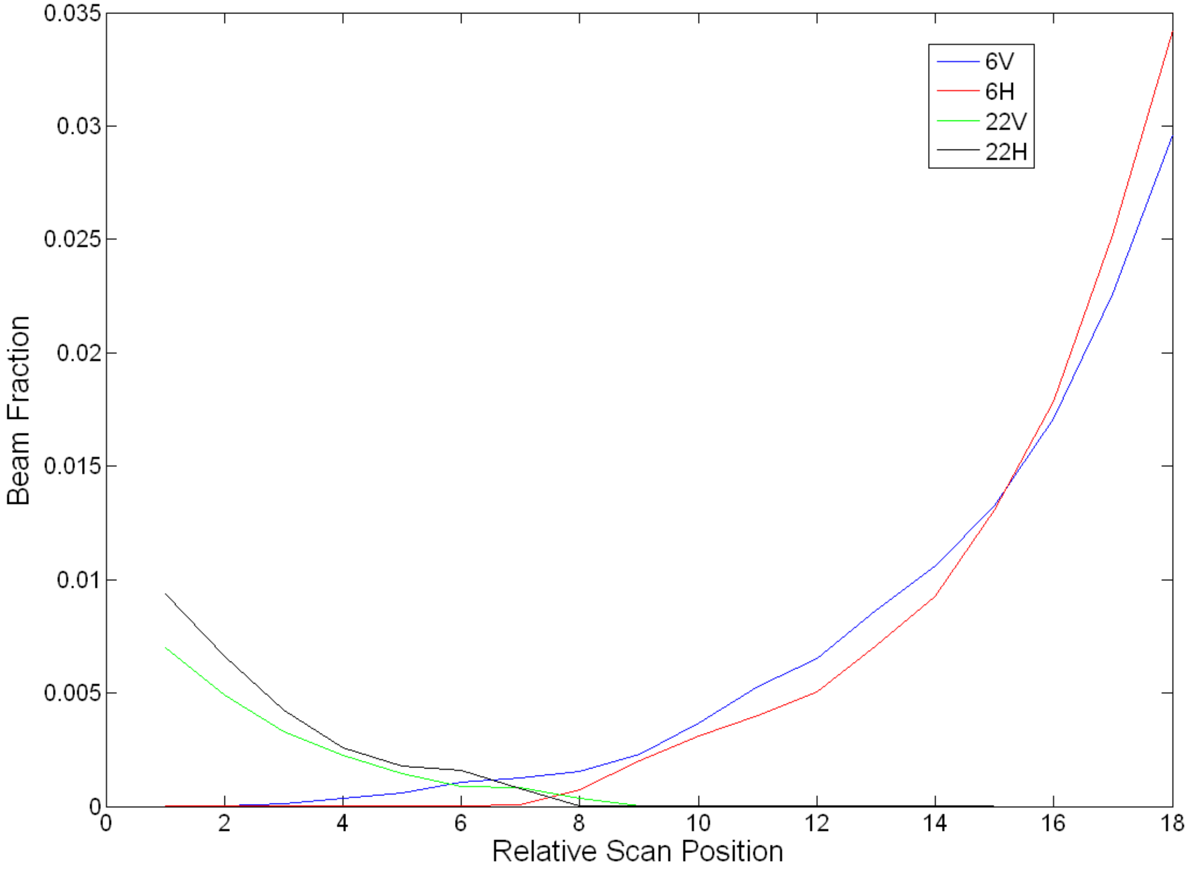
# WindSat Edge of Scan Sidelobe Correction Terms




| Channel | Sidelobe Effective $T_{b,sl}$ (K) |
|---|---|
| 6V | 2.7 |
| 6H | 94.4 |
| 22V | 2.7 |
| 22H | 78.2 |



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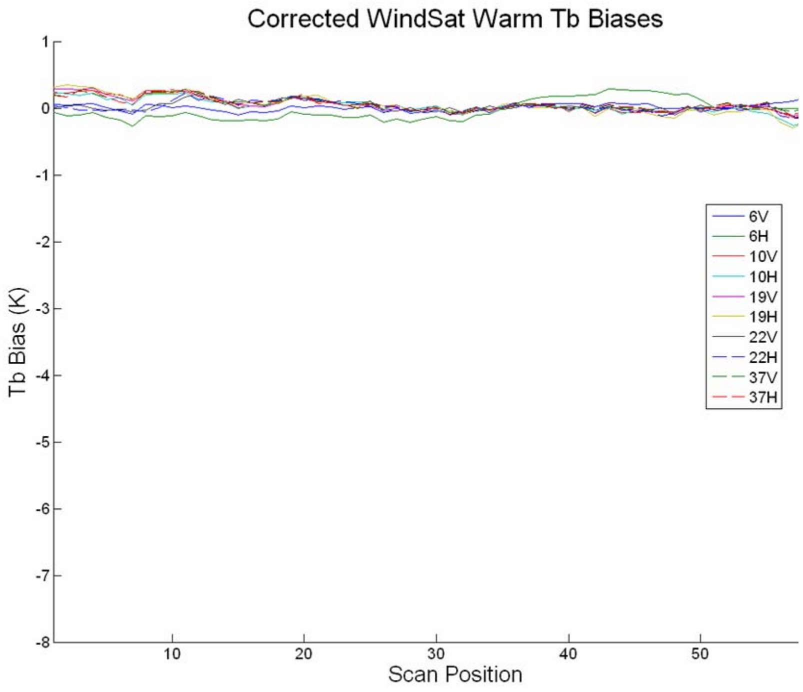
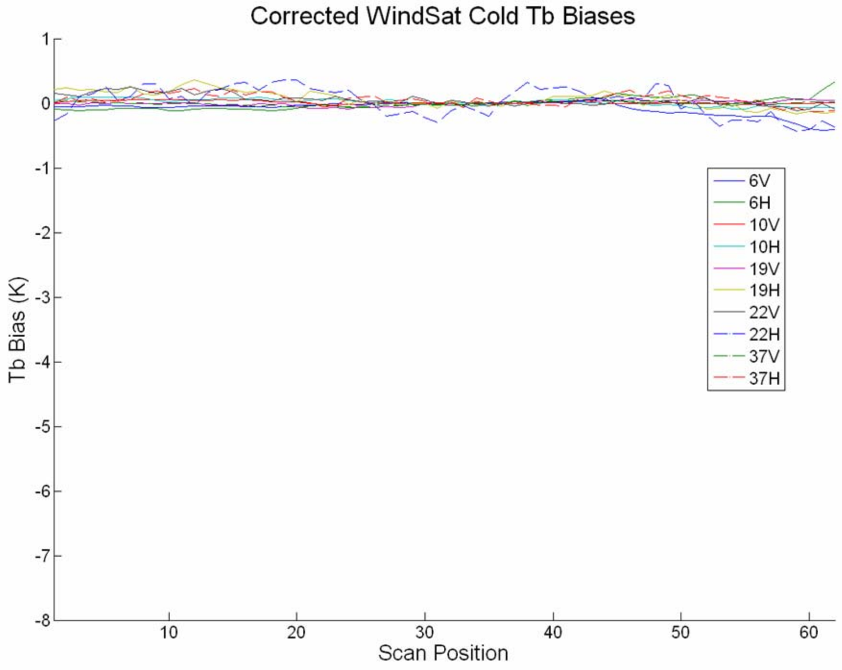
# WindSat Hot and Cold Vicarious Reference TBs with EIA and Sidelobe Corrections



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# Examples of Use of Vicarious Hot/Cold Calibration for Monitoring Long Term Drift

- TOPEX Microwave Radiometer: Drift in cal switch leakage
- Geosat Follow-On Water Vapor Radiometer: Stable calibration over mission life


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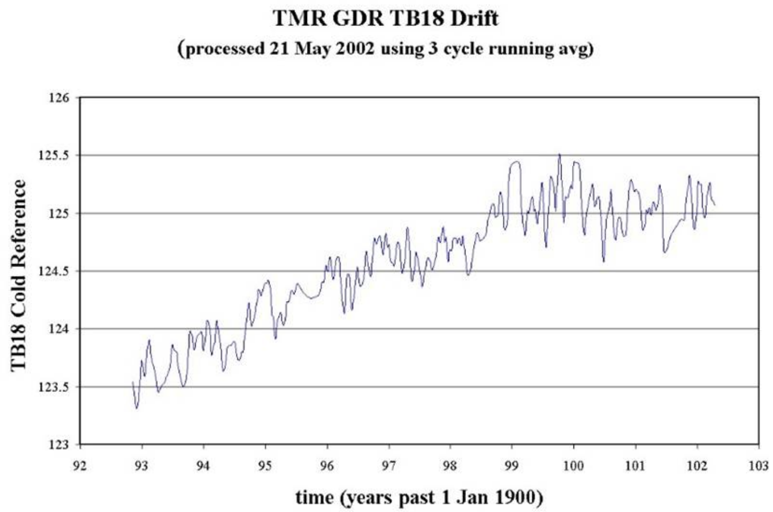
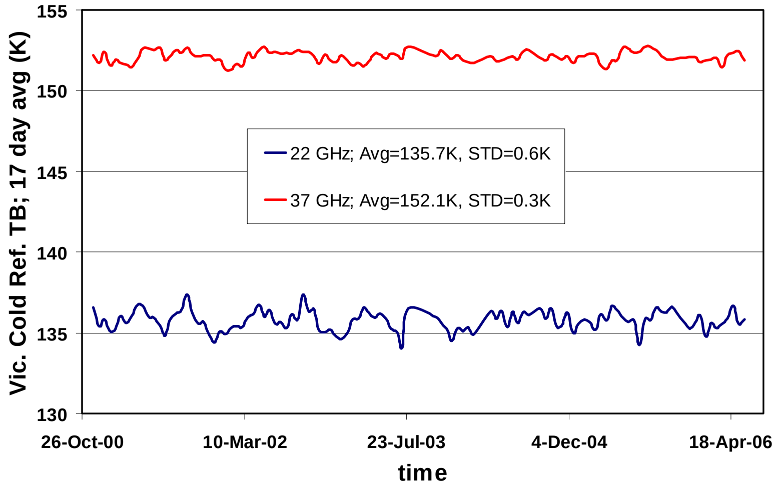
# TOPEX Microwave Radiometer vs. Geosat Follow-On Water Vapor Radiometer




- **TMR**
  - **~1.5 K drift in vicarious cold reference from Fall 1992 (launch) to Winter 1998**
  - **Hardware root cause identified as slow change in isolation of onboard calibration switch**
- **GFO**
  - **Constant vicarious cold reference from Oct 2000 through Apr 2006**



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# Example of Use of Vicarious Hot/Cold Satellite Intercalibration

Global Precipitation Measurement Mission

Constellation Intercalibration


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