# Statistical Analysis of a Lower Bound on Microwave Radiometer Brightness Temperatures from Space


Christopher S. Ruf
The Pennsylvania State University
121 Electrical Engineering East
University Park, PA 16802
Voice (814) 865-2363 / Email csr3@psu.edu



*Abstract* - A novel technique has been developed to verify the absolute accuracy and relative stability of a spaceborne microwave radiometer's calibration using a statistical analysis of the measured Earth brightness temperatures (TBs). This procedure relies solely on the final, main beam-referenced TBs and so tests the complete end-to-end system calibration, including instrument temperature and non-linearity corrections, the stability of reference TB calibration standards, and far-side lobe antenna pattern corrections. A very stable cold reference TB calibration point results which is known with high absolute accuracy. The data processing steps required to produce the cold reference TB are described here. The technique has been tested previously at a nadir viewing angle of incidence. Its application, at oblique angles, to both conical and cross-track scanning imagers is considered here.


## INTRODUCTION

Development of the vicarious cold reference TB calibration method has been introduced in [1]. In summary, an effective TB calibration target is extracted from a large ensemble of Earth viewing measurements by statistical analysis. The analysis consists of determining the lower bound on the TB cumulative distribution function (CDF) of the ensemble by polynomial extrapolation of the measured CDF in its low TB range. The lower bound on TB for a downward looking microwave radiometer operating in the atmospheric frequency windows occurs over calm wind oceans in clear and low humidity skies. This combination of conditions produces an extremely stable reference TB against which instrument calibration can be verified with tenths of Kelvin stability.

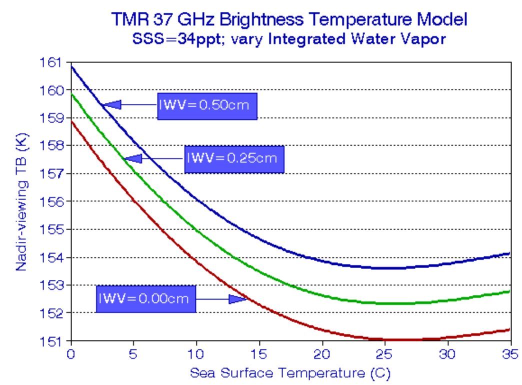


Figure 1. Modeled minimum TB at 37 GHz, nadir incidence angle.

An example of the 37 GHz TB lower bound observed at a nadir angle of incidence is shown in Figure 1. The example is based on a purely specular (flat and foam free) model for the ocean surface. It uses the dielectric model for sea water given by [2]. A sea surface salinity (SSS) value of 34 ppt is assumed, but the resulting coldest TB values are quite insensitive to salinity at frequencies near 37 GHz. Several possible values for the integrated water vapor burden (IWV) in the atmospheric column above the ocean surface are considered. They all correspond to conditions of fairly low humidity. The sea surface temperature (SST) is varied parametrically in the figure to highlight its critical relationship to the TB lower bound. Note in particular that TB does not vary monotonically with SST. This is a result of the temperature dependence of the dielectric constant of water. For each level of atmospheric opacity, there is a corresponding value of SST at which the specular ocean TB is a minimum. That minimum is the vicarious cold reference TB. In practice, the appropriate value to assume for IWV is found empirically.

## DATA PROCESSING TO EXTRACT VICARIOUS COLD REFERENCE TB

Use of the vicarious cold reference technique requires that a sufficiently large ensemble of ocean-viewing TB measurements be available. Nadir-only results presented in [1] were based on 10 day data sets, where 10 days represented one complete cycle of Earth coverage in an exact repeat orbit. The cold reference TBs that were extracted from successive 10 day ensembles were repeatable at the 0.3-0.5 K level over a 6 year period. For off-nadir scanning imagers, which have much greater Earth coverage and, typically, much shorter exact repeat orbit cycles, the length of time needed to assemble a satisfactory ensemble of measurements would likely be much shorter.

Data processing of an ensemble of data begins by constructing a fine scale histogram of the TB distribution. For the results presented in [1], occurrences of TB were counted within bin sizes of 0.1K over its full dynamic range. Examination of those histograms immediately confirms the existence of a sharp lower bound on TB, below which only erroneous outlier data lies. The standard histogram is then reprocessed to generate a modified CDF defined as:

$C(f_i) = TB_i \Rightarrow$ the fraction, $f_i$, of samples in the histogram have value less than or equal to $TB_i$.

The values, $f_i$, at which C is evaluated are incrementally stepped from $f_i$ = 0.03 to 0.10 in steps of 0.001. For each value, $f_i$, the corresponding $TB_i$ is determined from the histogram. This form of the CDF is used since C(0) represents the desired lower bound on TB. The lower bound is estimated using a polynomial extrapolation of C(f) back to C(0). A model for C(f) is assumed of the form

$$TB = \sum_{n=0}^{N} c_n f^n \qquad (1)$$

where N, the order of the polynomial, is determined empirically to be 3. Lower order models have a significantly larger unexplained variance when fit to the measurements over C(f=0.03-0.10). Higher order models offer negligible improvement and increase the sensitivity to noise in the data. Using this polynomial model, extrapolation to C(0) follows immediately since C(0) is the zeroeth polynomial coefficient, $c_0$. This procedure produces a new cold reference TB value, $c_0$, every 10 days.

One final correction can be made to the time series of cold TBs, provided it is sufficiently long. An annual component to the series can be removed by standard spectral analysis techniques. The analysis presented in [1] found a small residual annual signal, with a typical peak-to-peak magnitude of 0.03-0.10 K, in the 6 year time series. It was estimated and removed. The logic behind *ad hoc* removal of the annual signal revolves around the degree to which seasonal variations in the atmospheric opacity can influence the cold reference. Ideally, the CDF extrapolation procedure should remove any atmospheric influence on the cold TBs. (The fact that the residual annual signal is so small is one indication that it largely has.) The annual signal is viewed as an undesired leakage term and so is removed. It should be noted that various other methods were tried for estimating the coldest TB from the raw histograms. The polynomial extrapolation method was found to be clearly superior with regard to removing atmospheric artifacts.

## RESULTS AT NADIR INCIDENCE

A six year time series of the cold reference TB at 37 GHz, nadir incidence angle, is shown in Figure 2. The mean value of the cold reference TB in Fig. 2 is 153.3 K. The RMS variation about the mean is 0.3 K. The cold TB value is

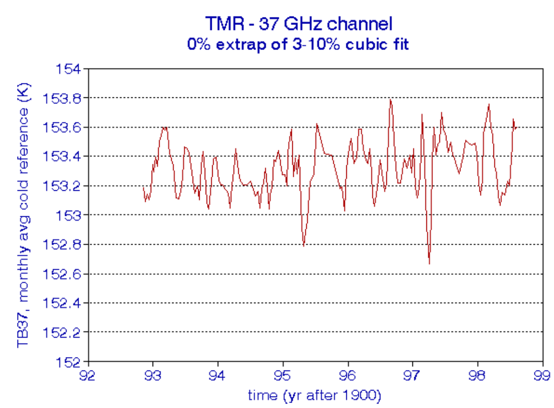


Figure 2. Time series of coldest TB at 37 GHz for the TOPEX Microwave Radiometer.

seen to be an extremely stable absolute reference over time. Comparing this value of 153.3 K to the model predictions shown in Fig. 1, the appropriate values for IWV and SST are found to be 0.44 cm and 25.3 C, respectively. This calibration approach was successfully used for the TOPEX/Poseidon Mission to identify a very small (~0.27K/yr) drift in one of the channels its microwave radiometer [3].

## RESULTS AT OBLIQUE INCIDENCE

*Conical Scan - Constant Incidence Angle*

Conically scanning microwave radiometers such as SMMR, SSM/I, TMI, and AMSR maintain a constant oblique angle of incidence as they scan their antenna beam. This changes the minimum possible TB value, relative to nadir, and also makes it polarization dependent. For example, model predictions at 37 GHz, horizontal linear polarization, with a 53.1 deg angle of incidence are shown in Figure 3. Note that the minimum TB has dropped well below its nadir value. The minimum is now 128K, assuming an IWV of 0.4 cm. By contrast, the minimum TB at vertical polarization is 207K. It is especially noteworthy that any other polarization than H-pol linear will have a higher minimum. This includes other linear orientations and all elliptical states as well.

The cold reference predictions of 128K and 207K can be tested using the results presented in [4]. In [4], histograms of SSM/I TBs are assembled from 7 years of measurements. There is a sharp lower bound evident at 37 GHz H-pol that agrees very closely with the 128K prediction. At 37 GHz V-pol, however, a significant number of occurrences are reported

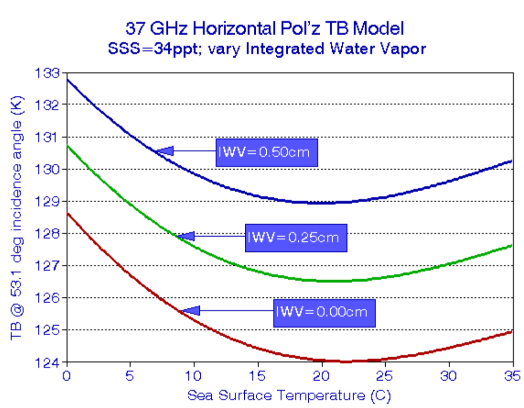


Figure 3. Modeled coldest TB at 37GHz, H-pol, 53.1deg incidence angle.

at values as low as 201-202K. This is an indication that there may be a significant level of polarization-mixing caused by the antenna system and/or spacecraft attitude which has not been properly accounted for by the software calibration algorithm.

*Cross-track Scan - Variable Incidence Angle*

Cross-track scanning sensors may benefit most from the use of this cold reference TB. Variations in the TB minimum with incidence angle are easily modeled and they provide an excellent opportunity to evaluate the performance of a spaceborne sensor over a significant part of its operating dynamic range. An example of the TB minimum at 10.7 GHz is shown in Figure 4. The minimum ranges from 113K (nadir) to 89K (45 deg) at H-pol and to 146K (45 deg) at V-pol.

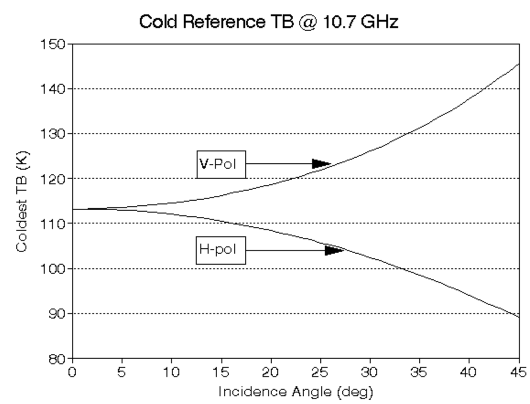


Figure 4. Cold reference TB at 10.7 GHz H- and V-pol versus incidence angle

## REFERENCES

[1] 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.

[2] Ellison, W., A. Balana, G. Delbos, K. Lamkaouchi, L. Eymard, C. Guillou, and C. Prigent, "New permittivity measurements of seawater," *Radio Science*, **33**(3), 639-648, 1998.

[3] Keihm, S.J., V. Zlotnicki and C.S. Ruf, "TOPEX Microwave Radiometer Performance Evaluation, 1992-1998,” *IEEE Trans. Geosci. Remote Sens.*, *in press*, 2000.

[4] Colton, M.C. and G.A. Poe, “Intersensor calibration of DMSP SSM/I’s: F-8 to F-14, 1987-1997,” *IEEE Trans. Geosc. Remote Sens.*, **37**(1), 418-439, 1999.