

# **Effect on the Calculated Spectral Surface Radiances Due to MWR Scaling of Sonde Water Vapor Profiles**

*S. A. Clough and P. D. Brown  
Atmospheric and Environmental Research, Inc.  
Cambridge, Massachusetts*

*D. D. Turner and T. R. Shippert  
Pacific Northwest National Laboratory  
Richland, Washington*

*J. C. Liljegren  
The Center for Non-Destructive Evaluation  
Applied Sciences Complex II  
Ames, Iowa*

*D. C. Tobin, H. E. Revercomb, and R. O. Knuteson  
Space Science and Engineering Center  
University of Wisconsin-Madison  
Madison, Wisconsin*

## **Introduction**

The accuracy limitation of the Atmospheric Emitted Radiance Interferometer/Line-by-Line Radiative Transfer Model (AERI/LBLRTM) Quality Measurement Experiment (QME) is principally attributable to uncertainties in the measurement of atmospheric water vapor. The QME is a closure experiment on the surface spectral radiance using AERI spectral radiances, LBLRTM calculations and atmospheric state obtained from the Atmospheric Radiation Measurement (ARM) Program measurements. It has previously been demonstrated that the scaling of the sonde water vapor profiles to obtain consistency with the Microwave Radiometer (MWR) measurement substantially reduces the spectral residuals in the longwave region. This approach has the potential to achieve two key objectives: 1) a significant reduction in the effects on the QME of sonde-to-sonde variability, diurnal variation, and ambient conditions; and 2) a significant increase in the absolute accuracy of the QME due to the knowledge of the intensity of the 22.2-GHz water vapor line used by the MWR. A detailed study of the MWR brightness temperatures for 1996 and 1997 has been performed in which it is demonstrated that the MWR performance has been remarkably robust with respect to a quadratic regression against sonde measurements over the two-year period. The existence of ARM data sets associated with the QME over the longer term, April 1994 to the present, has been instrumental in assessing annual effects and the long-term stability of the approach.

## **Theoretical Background**

The microwave spectral region is an excellent regime in which to measure column water vapor and cloud liquid water vapor for three principal reasons: 1) the spectral values for absorption are in the linear regime, 2) the Planck function is in the Rayleigh-Jeans regime, and 3) the strengths of the two main water vapor lines are known to high accuracy from Stark effect measurements (Clough et al. 1973). Consider the expression for the absorption coefficient,  $k(\nu)$

$$k(\nu) = \nu \tanh(hc\nu / 2kT) \langle \phi(\nu) + \phi(-\nu) \rangle \quad (1)$$

where  $\nu$  is the wavenumber value,  $T$  is the temperature and  $\langle \phi(\nu) + \phi(-\nu) \rangle$  is the symmetrized power spectral density function associated with the absorbing media. The first bracketed term in Eq. (1) is related to the radiation field and is independent of the absorber. In the microwave for which  $h\nu/kT$  is small, we obtain

$$k(\nu) = \frac{h\nu^2}{2kT} \langle \phi(\nu) + \phi(-\nu) \rangle \quad (2)$$

$$= \frac{h\nu^2}{2kT} \left\langle \tilde{S}(T) \frac{1}{\pi} \left[ \frac{\alpha P}{(\nu - \nu_0)^2 + (\alpha P)^2} + \frac{\alpha P}{(\nu + \nu_0)^2 + (\alpha P)^2} \right] \right\rangle \quad (3)$$

$$= \frac{h\nu^2}{2kT} \left\langle \tilde{S}(T) F(\nu - \nu_0) \right\rangle + C_s * \frac{W_s}{W_0} + C_f \frac{W_f}{W_0} \quad (4)$$

with  $S(T)$  the line intensity, the bracketed term the Van Vleck-Weisskopf line shape,  $\alpha$  the collisional broadening coefficient,  $P$  the pressure. The canonical sum in Eq. (3), denoted by  $\langle \rangle$ , implies a summation over all lines associated with a given species. The proper line shape is a combination of the Van Vleck-Weisskopf for line centers with a continuum contribution to properly account for the wing and collision induced contributions. This is represented in Eq. (4) in which  $F(\nu - \nu_0)$  is the appropriate line shape and  $C_s$  and  $C_f$  the self and foreign continuum contributions, respectively.  $W_s/W_0$  and  $W_f/W_0$  are fractional volume mixing ratios with respect to  $W_0$ .

To establish the dependence of the MWR brightness temperature on column water vapor, we approximate the atmosphere as a single layer characterized by a Curtis-Godson temperature ( $T$ ), pressure ( $P$ ) and column amount ( $W$ ). We obtain for the downwelling spectral radiance,  $R(\nu)$ , as

$$R(\nu) \approx B(\bar{T}_{atm})(1 - T_{atm}) + T_{atm} B(2.75k) \quad (5)$$

where the first term is associated with the radiance from the atmosphere and the second term, which is small, is the cosmic radiation attenuated by the atmosphere.  $T_{atm}$  is the atmospheric transmittance and  $B(\bar{T}_{atm})$  is the Planck function associated with the average atmospheric temperature. Writing the expression for  $T_{atm}$  in terms of the absorber column amount,  $W$ , and the absorption coefficient we obtain

$$R(\nu) \approx 2c\nu^2 kT \{1 - \exp[-W k(\nu)]\} + \exp[-W k(\nu)] B(2.75k) \quad (6)$$

$$\approx hc^2 \nu^4 W \left\langle \tilde{S}(T) F(\nu - \nu_0) \right\rangle + C_s \frac{W_s}{W_0} + C_f \frac{W_f}{W_0} \left\{ + [1 - W k(\nu)] B(2.75k) \right\} \quad (7)$$

in which the exponential associated with  $T_{atm}$  has been expanded with the assumption that the absorption is in the linear regime and the Planck function for the atmospheric temperature is in the Rayleigh-Jeans

limit. The radiance has a linear dependence on the column amount of the absorber, both for the atmospheric and cosmic contributions, and aside from the contribution from the cosmic term, is dependent on the atmospheric temperature only through the temperature dependence of the line intensity. As long as the radiance is large enough, the brightness temperature  $T_b(\nu)$  may be expressed as

$$T_b(\nu) \approx \frac{h\nu^2}{2k} W \left\{ \left( 1 - \frac{B(2.75K)}{2c\nu^2kT} \right) \langle \tilde{S}(T)F(\nu - \nu_o) \rangle + C_s \frac{W_s}{W_o} + C_f \frac{W_f}{W_o} \right\} + \frac{1}{2c\nu^2k} B(2.75k) \quad (8)$$

where the terms with  $B(2.75k)$  are small. The essential point is that the brightness temperature is proportional to the column amount of the absorber to a high order of approximation.

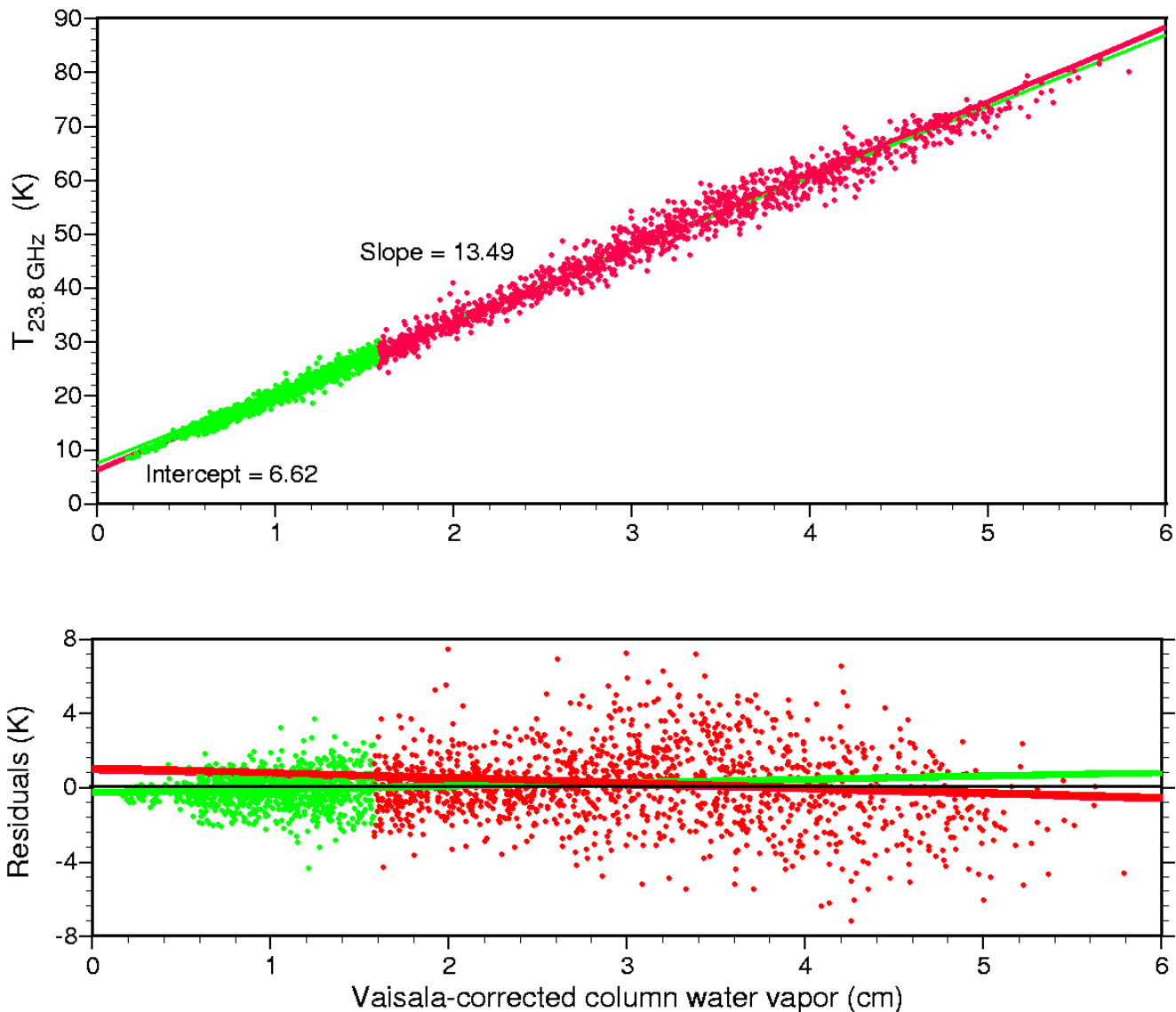
## Brightness Temperature Analyses

The principal absorbing mechanisms at the frequencies of interest are water vapor and oxygen. Eq. (8) is readily extended by summing over relevant species. For wavenumber values at which the self continuum is not significant, the linear dependence on absorber amount in this formulation is fully supported by the MWR measurements at the Cloud and Radiation Testbed (CART) site. In Figure 1 we plot the brightness temperature at 23.8 GHz on the high wavenumber side of the 22.2 GHz water vapor line as a function of column water vapor as obtained from sonde profiles corrected as recommended by Vaisala (Lesht 1999). The need for the correction is attributed by Vaisala to an interaction between the sonde packaging material and the polymer used for the humidity sensor. This consequently implies a dependence on time since calibration. This information is obtained from the serial number and has been applied as recommended. In the analysis of this data set a rigorous screening to include only clear cases has been performed.

The slope of the regression line in Figure 1 is principally dependent on  $S(T)$  and the intercept is due to the absorption by oxygen. In Figure 1b we indicate the regression coefficients for the simple linear model and the residuals as a function of water vapor column for 988 clear-sky cases at the CART site spanning the time period from 1996 through 1998 (Liljegren 1999). The value of the slope from line and foreign continuum contribution is 13.65 K/(prec cm). Different colors have been used to emphasize that regression lines for high and for low watercases are different and that the residuals are not normally distributed. The root mean square (rms) variation around the regression line is ~2.5 K and is principally attributable to sonde-to-sonde variations. The MWR variability is estimated as 0.5 K. A more extensive assessment of the atmospheric variability over the duration of the sonde measurement should be undertaken, but most of the column is obtained in a reasonably short time period in the lower troposphere.

Although the linear model with respect to water vapor is a very good approximation, there are higher order dependencies that must be considered. A higher order model for the brightness temperature has been developed to address these issues

$$T_b(\nu) \approx a(P_o, T_o) + b_1 \cdot W_{h_2o} + b_2 \cdot W_{h_2o}^2 + c(P_s - P_o) + d_1(T_s - T_o) + d_2(T_s - T_o)^2 \quad (9)$$

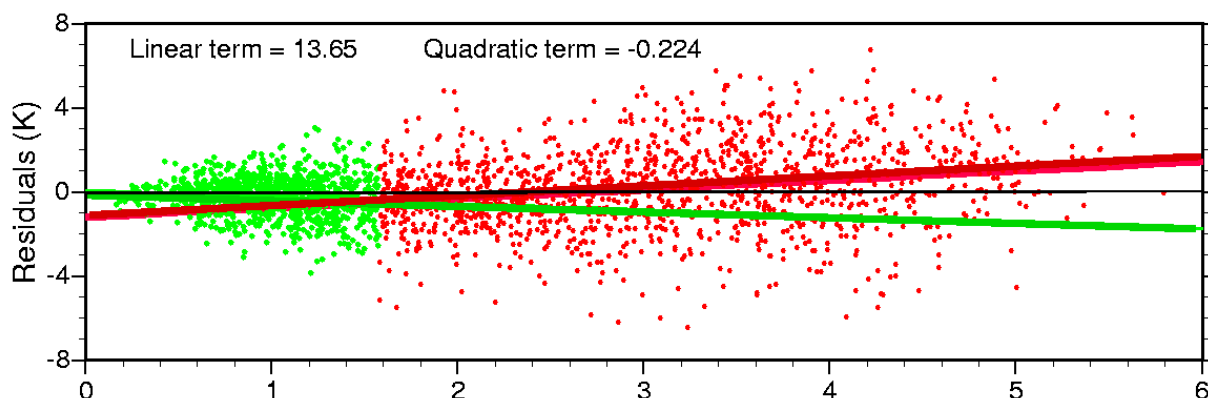


**Figure 1.** (a) MWR brightness temperature at 23.8 GHz as a function of column water vapor. Low water cases are in green, high water in red. (b) Brightness temperature residuals between the MWR and a two-parameter linear regression model. Low water cases are in green, high water in red with respective regression lines.

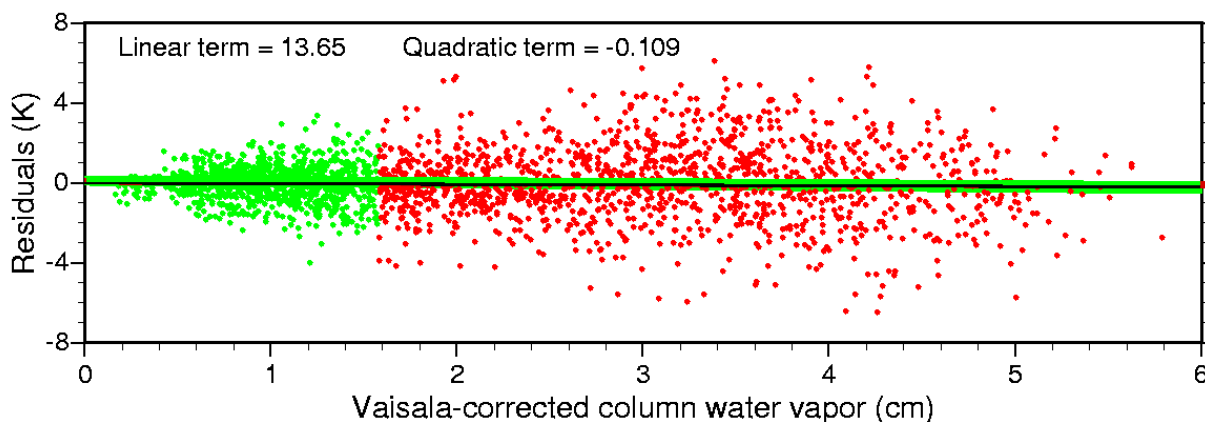
where  $P_S$  and  $T_S$  are the surface pressure and temperature and  $P_0$  and  $T_0$  are reference values.  $P_S$  is a proxy for the dependence of the brightness temperature on the column amount of oxygen and to a much lesser extent nitrogen. The linear dependence on water vapor is represented by  $b_1$  with contributions from the line intensity which is known to high accuracy, and from the foreign continuum, which is less well known. The quadratic dependence is represented by  $b_2$  and includes second order effects due to the self water vapor continuum ( $W^2 C_2$ ) and to approximations in the radiative transfer development.

The same data set has been analyzed with this extended model with  $b_1$  constrained to  $-0.224$ , a value obtained from a detailed line-by-line model using the CKD\_2.2 continuum (LBLRTM). In these analyses the constants  $c$  and  $d$  are obtained from a least squares fit. Figure 2a provides the residuals for the case in which the quadratic constant is also constrained to the LBLRTM value,  $b_2 = -0.224$ . It can be seen from the distribution and the respective regression lines, that this does not provide a satisfactory result. Figure 2b provides the residuals for the case in which  $b_2$  is obtained from a least squares fit resulting in a value of  $-0.109$ . An effort is currently under way to assess the magnitude of the self continuum required to obtain this value of  $b_2$ . It should be pointed out that there is high correlation

**T<sub>23.8 GHz</sub> Residuals Using Extended Model With "Theoretical" Linear and Quadratic Values**



**T<sub>23.8 GHz</sub> Residuals Using Extended Model With "Theoretical" Linear Value**



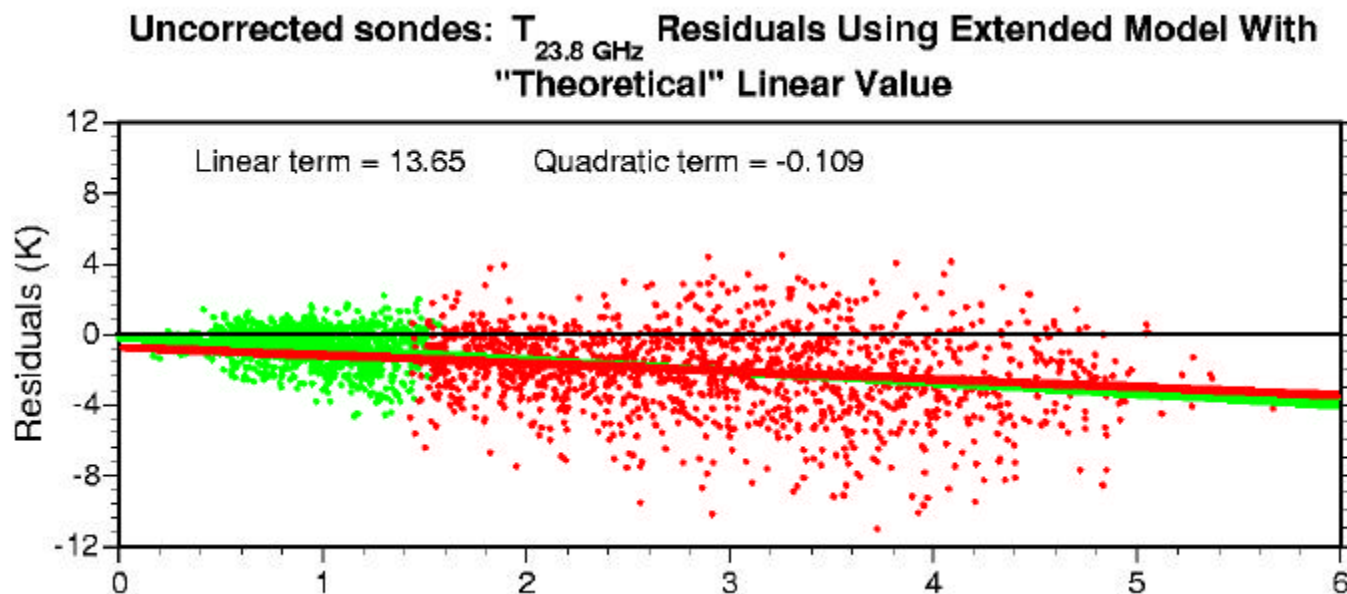
**Figure 2.** (a) Brightness temperature residuals between the MWR and a higher order model with a linear and quadratic dependence on water vapor. The values for the linear and quadratic terms have been constrained to theoretical values. (b) Brightness temperature residuals between the MWR and a higher order model with a linear and quadratic dependence on water vapor. Only the value for the linear terms has been constrained. The value for the quadratic constant is obtained from a least squares fit.

between  $b_1$  and  $b_2$ . The large magnitude of the standard deviation of the residuals, presumably due to sonde to sonde inconsistencies, precludes an unambiguous assessment of these constants from the sonde data.

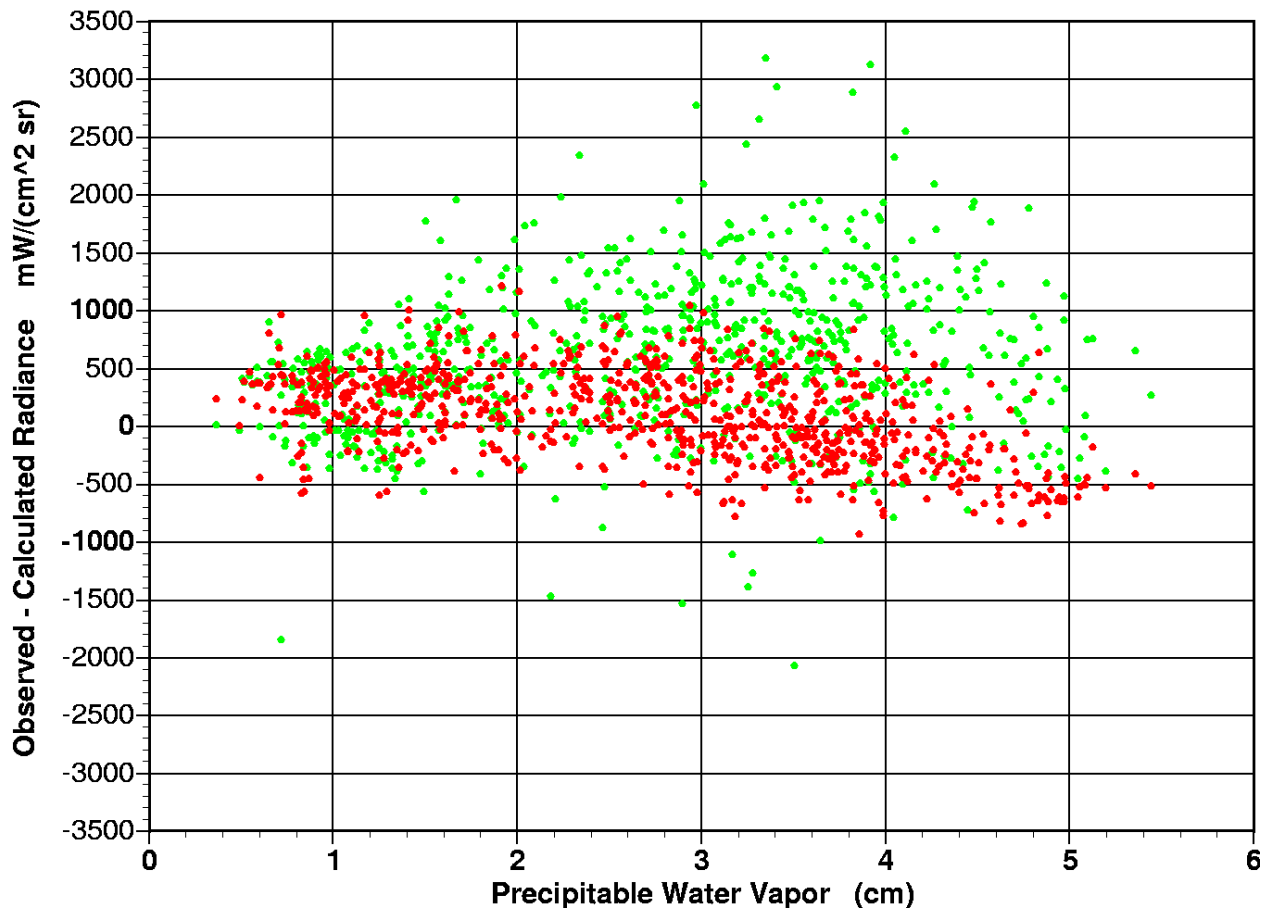
Having established the situation with respect to modeling of the MWR brightness temperatures, we are in a position to assess the effect of the Vaisala correction procedure on the sondes. In Figure 3, we provide the residuals for the uncorrected sondes using the same model and constants as that used for the corrected sondes in Figure 2b. There is little change in the distribution around the model result indicating that the sonde-to-sonde variability is not improved through the correction procedure. The difference in  $b_1$  is approximately 5% with the uncorrected sondes providing water vapor dependence that is 5% drier than that from the MWR. This is qualitatively consistent with other analyses we have performed using different MWRs. Summarizing the MWR results, the observed MWR brightness temperatures are consistent with the higher order model with the linear constant constrained and the quadratic constant unconstrained. A similar result cannot be obtained for the uncorrected sondes and the linear term constrained to the model value. A similar study has been conducted for the 30-GHz measurement.

## Implications for the AERI/LBLRTM QME

The objective of this MWR study is to obtain improved water vapor fields for the AERI/LBLRTM QME. For an extensive number of cases, the residuals between the AERI observed radiances and those obtained from LBLRTM are shown in Figure 4. The residuals using the original sonde profiles are



**Figure 3.** Identical with Figure 2b except that the uncorrected sonde profiles have been used for the column water vapor amounts,  $W_{H_2O}$ . The column associated with the uncorrected sondes is 5% drier than with the corrected sondes.



**Figure 4.** Residuals between the spectral radiances measured by AERI and those calculated with LBLRTM integrated over the spectral elements associated with the window region for data from 1994 to 1997. The residuals using the uncorrected sonde profiles are shown in green and those using profiles scaled to provide agreement with the MWR column water vapor are shown in red.

designated uncorrected (green) and the residuals with profiles scaled to provide agreement with the MWR water vapor column are designated corrected (red). The first observation is that the case to case variability has been significantly reduced. The second important point is that the dependence of the residuals as a function of column water is much lower in the case of the corrected sondes, although some apparently nonlinear dependence remains. The residuals provided in Figure 4 for the corrected sondes correspond to an error in the downwelling flux of  $\sim 2 \text{ W/m}^2$  (Ellingson 1999).

The characterization of the water vapor field is the limiting error in assessing radiative transfer model performance. It is a reasonable question whether validations to significantly greater accuracy are possible given the errors in these supporting measurements and uncertainties resulting from atmospheric variability. Although the results of this study are generally positive, the question of the quadratic constant is in need of resolution.

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