Communications

Comment on "Uncertainties in the Temperature Dependence of the Line-Coupling Parameters of the Microwave Oxygen Band: Impact Study"

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Boukabara *et al.* [1] assert that uncertainties in oxygen line-coupling parameters in the Millimeter-wave Propagation Model (MPM92) [2] may introduce errors of several degrees in brightness temperature at frequencies used by satellite radiometers. However, the methodology used in [1] overestimates uncertainty in the model predictions, and it will be shown here that the simulations based on it are inconsistent with previously published atmospheric measurements.

In [1], the nonmonotonic temperature dependence of the 7– coupling coefficient in MPM92 is described as "nonphysical," without citing any physical principle that it violates. The temperature dependence is seen in a plot [1, Fig. 2] in which pressure is constant. If instead the gas density were held constant, the 7– coefficient would have been monotonically decreasing (becoming more negative) with increasing temperature, because the pressure in [1, eq. (1)] is proportional to the product of temperature and density. Since the temperature dependence depends on whether gas density or pressure is chosen as an independent parameter, it cannot have a special significance.

The method used to derive the MPM92 coupling coefficients [2], in essence, adjusted the line coupling to fit the differences between measured absorption band shape and a Van Vleck–Weisskopf line shape factor (with a small bias). Consequently, uncertainties in the coupling coefficients are highly correlated not only among themselves, but also with uncertainties in the line widths used in their derivation. The correlation between coupling and width errors is ignored in [1].

Noting that the absorption measurements in [2] cover the range of 279–327 K in temperature, the authors of [1] make use of a hypothetical perturbation consisting of a uniform 10% reduction in magnitude of line coupling for all temperatures less than 279 K, to calculate uncertainty in MPM predictions. The size of this perturbation is described as "near the lower end of the uncertainty range." Perturbing all coupling coefficients by the same factor while the line widths are unchanged produces large changes in brightness temperature on the wings of the oxygen band, as seen in [1, Fig. 3]. At frequencies below ~ 30 GHz, the perturbation has little effect. But it is not necessary to rely on hypotheses about errors in MPM92, because atmospheric attenuation on the wings of the oxygen band has been measured in published experiments.

Table I lists, in the third column, measurements of zenith attenuation by the dry components of the atmosphere. Ground-based radiometers at El Segundo, CA, measured solar extinction at the first three frequencies [3]. At 90 GHz, atmospheric emission was measured from the surface at Denver, CO and converted to attenuation by use of an effective atmospheric temperature [4]. Attenuations measured at various elevation angles were adjusted to zenith. The zenith attenuations measured on many days were regressed against total precipitable water vapor, and the y axis, i.e., zero-H_2O, intercept is interpreted as the dry-air attenuation. The authors of [3] and [4] also determined the standard errors on the attenuation. The December data at Denver were selected from the three datasets presented in [4, Table III] because its standard error is the smallest, probably due to the dryness of the atmosphere during that month.

TABLE I
DRY-AIR ZENITH ATTENUATION

elevation, m	frequency, GHz	observed, dB	MPM92 calc., dB	MPM92-obs., dB	perturbation [1], dB
50	51.75	2.43±0.06	2.540	0.11	0.16
50	68.14	2.60±0.05	2.611	0.01	0.31
50	70.26	1.36±0.04	1.386	0.03	0.20
1611	90.0	0.139±0.008	0.147	0.008	0.041

The fourth column of Table I gives my calculation of dry-atmosphere zenith attenuation using the MPM92 oxygen-band model. In addition to absorption from the spin-rotational transitions of oxygen, the calculation includes absorption from collision induced dipoles on the dry-air molecules, which amounts to 0.006, 0.011, 0.011, and 0.014 dB at these four frequencies. The 1976 U.S. Standard Atmosphere temperature profile was used in the calculations for the El Segundo data, and simultaneous radiosonde profiles were used for the Denver calculation. (Substitution of the Standard Atmosphere to calculate attenuation at Denver changed the result by only 0.001 dB.)

The fifth column of Table I gives the difference between the calculation using MPM92 and the observations. MPM92 predicts attenuation slightly higher (by 0.4 to 6%) than the measurements, but within one standard deviation at three of the frequencies, and two standard deviations at 51.75 GHz. For comparison, the last column is the change in calculated attenuation that results from the 10% perturbation of coupling coefficients prescribed in [1]. The hypothetical perturbation used by Boukabara *et al.* predicts larger errors at all four frequencies; on the high wing of the oxygen band, the perturbations are five to six times larger than either the MPM92-observation differences or the observations' standard errors.

In [5], satellite measurements in the high-absorption part of the oxygen band were compared to calculations using a rapid algorithm with oxygen absorption based on MPM92. Six channels, centered at 52.8, 53.6, 54.4, 54.94, 57.29, and 57.29 $\pm$ 0.217 GHz, had weighting functions that permitted validation using radiosonde profiles. The mean differences between measured and calculated brightness temperatures ranged from -0.42 to $+0.23$ K. Under the observed conditions, the 53.6-, 54.4-, and 54.94-GHz frequencies were the most sensitive of the six to atmospheric opacity: an error of 5% in calculated absorption would have caused mean brightness temperature errors of 0.7 to 0.9K.

There are some points in [1] with which I agree. The MPM, like any model based on laboratory measurements, could be improved by extension of the range of those measurements. Errors in atmospheric transmittance are not in general equivalent to a constant offset of brightness temperature. Hence, extension of the laboratory temperature range would be of benefit for the correct interpretation of precise atmospheric measurements.

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Reply to the Comment on "Uncertainties in the Temperature Dependence of the Line-Coupling Parameters of the Microwave Oxygen Band: Impact Study"

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The impact study described in [1] is, in essence, a theoretical sensitivity analysis of the temperature dependence of the line coupling coefficients in the microwave Oxygen absorption band as accounted for in the millimeter-wave propagation model (MPM). The study was driven by emerging highly demanding requirements in terms of accuracy of the brightness temperatures measurements and therefore equally demanding requirements for models that simulate them. The main conclusions of the study are twofold: 1) the need to extend experimental measurements to the lower range of the atmospheric temperatures and 2) that errors due to uncertainties in the temperature dependence, are not necessarily entirely removable by a bias correction. The spectral region, where most of the impact was found, is located at the edge of the absorption band, especially in dry conditions. The MPM absorption model is widely used in the microwave remote sensing community because it is accurate for current applications and uses for its spectroscopy the extensive work of Liebe *et al.* [2]. To the best of our knowledge, no serious deviations exceeding the estimated calculation uncertainty, were found comparing available experimental data and simulations performed with MPM. Nevertheless, as shown in the study, MPM (as well as other atmospheric absorption models) could benefit from extending the experiments to cover the lower end of the atmospheric temperature range in deriving the main factors including the line coupling coefficients. As described in the study, these overlapping factors (and line widths indeed) were derived in [2] using available measurements in the range 279–327 K. This represents roughly the third of the whole atmospheric range, approximately between 183 and 328 K.

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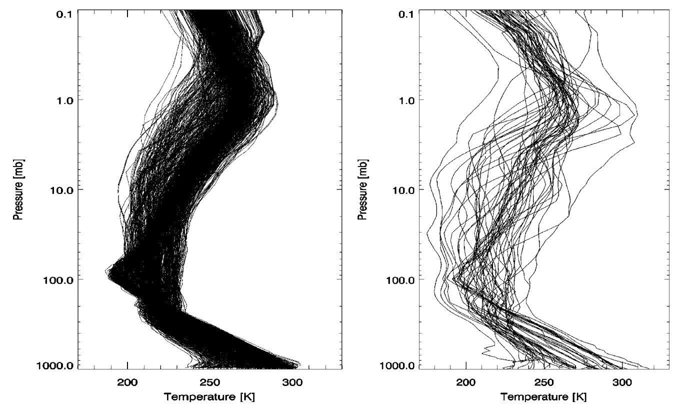

Fig. 1. Two sets of atmospheric temperature profiles, sampled from (left) a NOAA set of radiosondes and (right) a representative set of 52 ECMWF profiles, showing the natural variability of atmospheric temperature at the 1000-mbar pressure level.

The variation of the individual line coupling coefficient shown in the impact study [1, Fig. 2] consisted of considering a single layer with a constant pressure of 1000 mbar. It was tested at other pressures but these were not shown. For the modeling of the oxygen absorption, the two driving inputs to MPM are the pressure P and temperature T. To assess the impact of the temperature dependence on the absorption, the pressure was held constant and a varying temperature was used. The combination of the two variables (P, T) is realistic to a large extent. Fig. 1 shows two representative sets of atmospheric profiles where temperature at the level corresponding to 1000 mbar, covers the range between 235–300 K for the NOAA set and between 220–320 K for the ECMWF set. The temperature range used in the study was 200–320 K. The study has been performed as a function of temperature for fixed pressures, for the reasons stated above. As Dr. Rosenkranz has suggested, an analysis performed for fixed densities would have provided a more physical approach. The line coupling and collisional broadening are taken to result from binary collisions with the effects inversely proportional to the time between collisions, i.e., proportional to density.

Because the fitting of the coefficients in [2] was performed using the high end of the temperature range, it was the aim of the study to assess the impact on the lower end. By plotting the coefficients for the whole range, we noticed a nonmonotonic variation only at the 7– transition line. Because the formulation relies on a unique temperature dependence exponent (for all frequencies) and because the parameter was determined using just a portion of the temperature full range, it could be that the nonmonotonic variation seen in the 7– line is numerical, due to the two-term expansion formalism used to fit the limited range of temperature data available when deriving the MPM coefficients. Liebe *et al.* [2] had actually warned that this formalism could fail outside the temperature range that they used.

Another feature that could be noticed in [1, Fig. 2] is that any theoretical error in the X exponent (shown by three curves in each plot) is hardly detectable by fitting the 279–327-K range only. But the same error has a large impact in the lower range of temperature, especially at certain lines including the 7– transition one.

In the sensitivity study, the widths were purposefully held known in order to perform an impact study of the uncertainty on the line coupling coefficients themselves. An uncertainty in the line coupling could of course be hidden by another compensating uncertainty in the width (as well as by uncertainty in the line intensity) and therefore not be noticed. Although they would more likely impact the standard deviation metric. By holding the width constant, it is easier to assess the