MOD3D: A model for incorporating MODTRAN radiative transfer into 3D simulations

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ABSTRACT

MOD3D, a rapid and accurate radiative transport algorithm, is being developed for application to 3D simulations. MOD3D couples to optical property databases generated by the MODTRAN4 Correlated-*k* (CK) band model algorithm. The Beer's Law dependence of the CK algorithm provides for proper coupling of illumination and line-of-sight paths. Full 3D spatial effects are modeled by scaling and interpolating optical data to local conditions. A C++ version of MOD3D has been integrated into JMASS for calculation of path transmittances, thermal emission and single scatter solar radiation. Results from initial validation efforts are presented.

Keywords: MODTRAN, JMASS, 3D simulation, remote sensing, hyperspectral imaging, band model, infrared, radiative transfer

1. INTRODUCTION

MODTRAN4[1,2] is the U.S. Air Force (USAF) standard moderate spectral resolution radiative transport model for wavelengths extending from the thermal InfraRed (IR) through the visible and into the ultraviolet (0.2 to 10,000.0 μm). The MODTRAN4 radiative transport was developed collaboratively by Spectral Sciences, Inc. and the USAF Research Laboratory, and it is based on a 1 cm^{-1} statistical band model coupled to a Correlated-*k* (CK) algorithm[3]. MODTRAN4 provides a fast alternative (100-fold increase in speed) to the USAF first principles and more accurate line-by-line (LBL) radiative transport models, FASCODE[4] and **FAS**CODE for the **E**nvironment, FASE[5]. Comparisons between MODTRAN4 and FASE spectral transmittances and radiances show agreement to within a few percent or better in the thermal IR. MODTRAN4 includes flux and atmosphere-scattered solar calculations, essential components in analysis of near-IR and visible spectral region data that are not readily generated by LBL models.

One built-in limitation of the MODTRAN model is that it assumes a stratified atmosphere and a spherical earth. Thus, molecular, aerosol and even cloud densities are solely functions of altitude, and the ground is modeled as a uniform and constant altitude surface. For many real world problems, the horizontal *in*homogeneity of the atmosphere and ground, elements of which are illustrated in Figure 1, greatly influences radiance signatures. In particular, shadowing from clouds, vegetation and surface structures, the spatial variability gaseous H_2O, and the surface topography will complicate contrast signatures and increase scene clutter. In order to model these effects, MOD3D, a radiative transfer algorithm based on the MODTRAN4 band model and CK algorithm, is being developed for application to 3D simulations. The current version of MOD3D computes path spectral transmittances, thermal emission and single scatter solar radiance over the

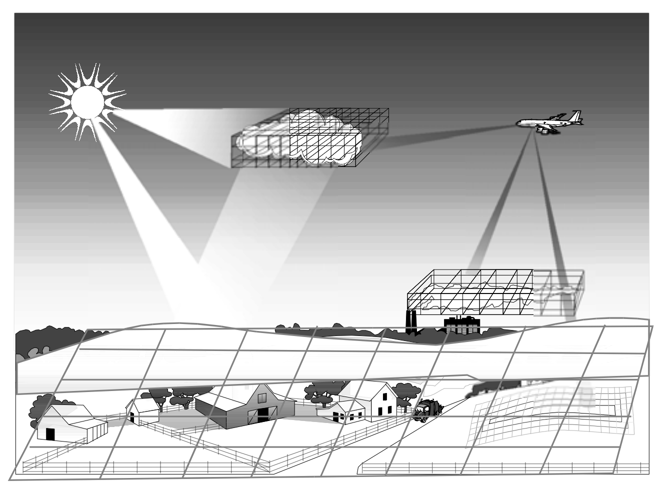
Figure 1. Illustration of 3D simulation scene elements.

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entire MODTRAN spectral range, and it has been incorporated into the EO/IR player of the simulation support environment known as JMASS, the Joint Modeling and Simulation Systems. An early version of MOD3D which only calculated of spectral transmittance in the 3-5 μm spectral window was described in an earlier paper[6].

MOD3D, unlike MODTRAN, assumes an external model such as the JMASS atmospheric player defines the 3D environment. For a given image, defined as collection of lines-of-sight, MOD3D prompts the environment for pressures, temperatures and molecular and particulate concentrations, which in turn are used to compute the path spectral transmittances and radiances. Both FORTRAN and C++ versions of the MOD3D algorithm are being developed. This paper describes the MOD3D RT approach and illustrates the results of validation calculations.

2. MOD3D RADIATION TRANSPORT

MODTRAN4 and its predecessors have been integrated into many imaging simulation models, such as SPIRITS[7] and GTSIMS[8]. Generally, these models use MODTRAN to predict path spectral transmittances and radiances as a function of range for a fixed sensor geometry, and then the transmittances are the multiplied by at-source signatures to obtain the apparent source signatures. This approach is problematic in that the illumination of the source is not correlated with the path transmittance. Monochromatically it is true that path transmittances $T_\nu(a)$ and $T_\nu(b)$ for adjoining segments a and b are multiplicative, but this Beer's Law relationship is not obeyed for the in-band transmittances of a band model:

$$\int_{\Delta\nu} T_\nu(a)\,T_\nu(b)\,d\nu \neq \int_{\Delta\nu} T_\nu(a)\,d\nu \times \int_{\Delta\nu} T_\nu(b)\,d\nu \quad . \quad (1)$$

The severity of this approximation is demonstrated in Figure 2. A 15 cm^{-1} MODTRAN calculation has been performed for a 160-km path from 10.5 to 10.5 km, i.e., with a tangent altitude near 10 km. This is compared to the product transmittance from two adjoining 80-km path segments covering the same overall path. The excess absorption from the product transmittance is significant, near 0.05 on average.

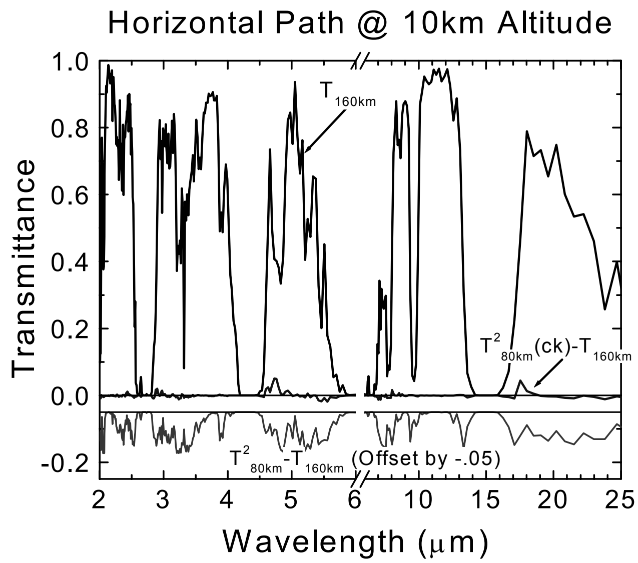

Figure 2: Comparison of Correlated and Uncorrelated Path Transmittances at 15 cm^{-1} Spectral Resolution. The baseline MODTRAN calculation is a 160-km path from 10.5 to 10.5 km altitude. The baseline path was split into two identical 80 km segments. Residuals are shown between the baseline and the combined path transmittances with and without CK.

The CK algorithm re-introduces Beer's Law into the radiation transport. In-band transmittances are fit to a weighted sum of monochromatic values:

$$\int_{\Delta\nu} T_\nu(a)d\nu = \sum_{i=1}^{n}\left(g_i - g_{i-1}\right)\exp\left[-\,\overline{\tau}_i(a)\right] \quad ; \quad 0 = g_0 < g_1 < \cdots < g_n = \Delta\nu \quad . \quad (2)$$

For the MODTRAN CK implementation, the set of g_i is independent of spectral frequency for a given spectral bin width $\Delta\nu$ with n is generally set to 17. The optical depths $\overline{\tau}_i(a)$ are determined from k-distribution tables and molecular band model data (see ref. 3 for a detailed description). Each $(\Delta g)_i = g_i - g_{i-1}$ sub-interval is treated independently/monochromatically; so, for example, the transmittance through segments a and b is calculated from

$$\int_{\Delta\nu} T_\nu(a)\,T_\nu(b)\,d\nu = \sum_{i=1}^{n}(\Delta g)_i\exp\left[-\,\overline{\tau}_i(a) - \overline{\tau}_i(b)\right] \quad . \quad (3)$$

In Figure 2, the calculation of the product transmittance was recomputed using the CK algorithm. The differences between the full path band model transmittance and the CK results are small with no strong bias towards too much or too little absorption. The largest discrepancies occur at 4.76 and 17.5 μm, where multiple molecular species have significant absorption. Since the band model assumes random correlation between molecular species, it is unclear whether the CK result is actually inferior to the MODTRAN band model calculation.

Figure 3 illustrates the operation of the MOD3D model within a JMASS simulation and is included here to help describe the interface between the MODTRAN4 CK data and MOD3D. During initial setup, the "Atmosphere Player" defines a 3D world consisting of the solar position, atmospheric pressures, temperatures and densities, and a baseline vertical profile for each molecular and particulate source. Also during an initialization step (not shown), the sensor geometry (possibly as a function of time), sensor imaging specifications, and sensor spectral characteristics are fixed. The simulation begins and line-of-sight transmittances and radiances are requested as needed. Based on these requests, MOD3D prompts the atmosphere player for local data at specified intervals along the lines-of-sight and along bent paths to the sun. MOD3D then uses this information to compute column densities and to determine optical depths from MODTRAN4-generated look-up tables (LUTs). MOD3D next performs the monochromatic radiative transfer calculations. Finally, CK weighted sums are calculated to determine spectral transmittance, thermal emission and single scatter solar radiance.

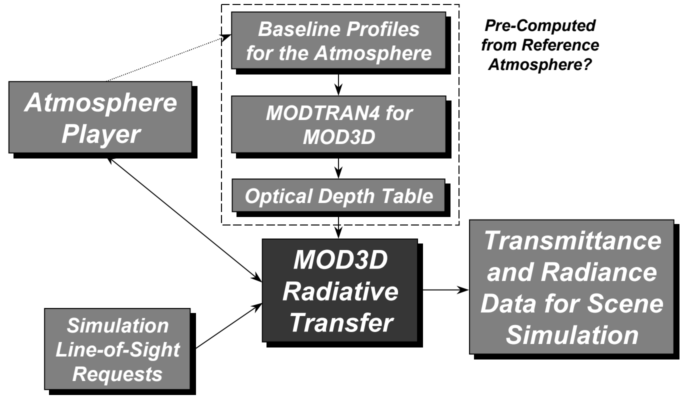

Figure 3. Flow Chart of the role of the MOD3D Module in JMASS Simulations.

A new MOD3D database generation option has been added to MODTRAN4 to output optical depths as a function of atmospheric pressure. As illustrated in Figure 3, MOD3D can use either pre-existing MODTRAN4-generated data files or files generated on-the-fly. In the latter case, MODTRAN4 is initially run with the "Atmosphere Player" baseline profiles and subsequently with scaled molecular profiles. Two databases are generated. A particulate database file contains the optical depth profiles for each band model spectral bin in the input bandpass; these optical depths can be scaled based on local particulate densities. A molecular database file contains molecular optical depth profiles for each spectral bin CK sub-interval and over a grid of molecular mixing ratios. In MOD3D, local mixing ratios are used to interpolate into the MODTRAN4 generated data file.

The MOD3D calculations are relatively fast considering their complexity and accuracy. The pre-computation of the optical data greatly speeds up the radiative transport when compared to standard line-by-line, or even band model methods. Extensive prompting of localized data is required to map out the spatial variability of the 3D world, but this information is not spectrally dependent. Also, the user can specify up front a spatial resolution parameter that dictates how finely the atmosphere will be queried. Fine spatial resolution may be necessary for imaging complex clouds, but much lower resolution will suffice for many clear skies scenarios.

The current capabilities of MOD3D as compared to MODTRAN4 are listed in Table 1. Since MOD3D relies on the MODTRAN band model approach coupled to the MODTRAN CK algorithm to perform its radiation transport, the two models share a common spectral range and resolution. In MODTRAN, the atmosphere is stratified. In addition, the user defines the ground surface and target based on the models within MODTRAN. In MOD3D, the user is given both the flexibility and the responsibility to couple to external atmosphere, surface and target models. Also, MOD3D does not include a multiple scattering or refractive geometry model; proposals have been submitted to introduce these capabilities. Finally, the only MOD3D outputs are path spectral transmittances and radiances. It is anticipated that future versions of MOD3D will generate output files consistent with those of MODTRAN.

Model	***MODTRAN4***	***MOD3D***
Radiative Transfer Algorithm	Correlated-k Band Model	Correlated-k Band Model
Spectral Range and Resolution	0.2 to 10,000 μm; 2 cm^{-1} resolution	0.2 to 10,000 μm; 2 cm^{-1} resolution
Molecular, Aerosol, Cloud Atmosphere	Stratified, Built-in or Radiosonde	Voxelized 3D, Externally Defined
Atm. Scattering	Multiple	Single Solar
Geometry	Spherical Refractive	Spherical
Ground Surface	Spectral BRDF	Coupled Externally
Targets	Blackbody	Coupled Externally
Outputs	Radiances, Fluxes, Transmittances, …	Path Radiances & Transmittances

Table 1. Comparison of MODTRAN4 and MOD3D Current Capabilities.

3. MOD3D INITIAL VALIDATIONS

To validate the MOD3D RT model, predictions have been made for a horizontally homogeneous atmosphere and compared to MODTRAN. The calculations are not expected to be identical for a number of reasons. MODTRAN includes refraction in its path geometry; however refractive effects are minimal for the selected scenarios. More importantly, lines-of-sight segmenting is different between the two models, as is the mapping from local conditions to optical properties. Thus, the comparisons presented here will illustrate the consequence of these latter two differences.

Two scenarios have been considered. In both the 1976 U.S. Standard Atmospheric profiles are used along with the MODTRAN 23-km Visibility Rural aerosol model, a hazy atmosphere. Cloud or rain effects can be modeled within MODTRAN4 and MOD3D, but the current scenarios are clear sky. The comparisons are performed at 15 cm^{-1} spectral resolution for wavelengths between 2 and 25 μm. The first scenario is a ground-to-ground case, and the initial and final altitudes are both 0.77-km. Calculations have been performed for ranges of 0.1, 1.0, 10.0 and 100.0 km. The sun is at a 45° zenith and the sensor-to-sun relative azimuth is 0°, i.e. forward scattering. In the ground-to-air scenario, the final altitude is near 26 km and four view angle are considered, 0°, 30°, 45° and 60° zenith. Again, calculations are performed for a 45° sun, but the relative azimuth is 180°, i.e. a backscatter case.

3.1 Ground-to-ground scenario

In Figure 4, MOD3D and MODTRAN4 predictions are compared for the ground-to-ground scenario. Results are shown for path transmittance, for thermal emission (on a *log* scale), for single scatter solar radiance (also on a *log* scale), and for the thermal plus solar components (on a *linear* scale). The primary absorption features evident in the transmittance curves are the 2.7, 4.3 and 15 μm CO_2 vibrational bands, the 2.7 and 6.3 μm H_2O vibrational bands, and the long-wave H_2O rotations. As the path length increases from 0.1 to 100.0 km, the 3-5 μm and 8-12 μm atmospheric windows become less and less transparent. In the thermal emission plots, the 100 km path results are essentially blackbody curves at the surface air temperature (the discontinuity in shape arises from the break in the wavelength scale at 6 μm). For shorter paths, less emission is observed, esp. in the atmospheric windows. The single scatter solar contributions dominate in the mid-wave infrared (MWIR). Here, the radiance levels are essentially proportional to the number of scatterers or the path length until absorption becomes appreciable; thus, the maximum single scatter solar spectral radiance has values of 1.5, 11, 102 and 600 μflicks for path lengths 0.1. 1.0, 10.0 and 100.0 km. Combining the two radiance components on a linear scale, the thermal emission dominates between 4 and 25 μm, and the scattering components dominate between 2 and 4 μm.

At all the modeled path ranges, the agreement between the MOD3D and MODTRAN predictions is high. Both models capture the features described in the previous paragraph. However, there are differences in some of the details. In particular, the maximum MOD3D single scatter solar radiance is about 600 μflicks, while the MODTRAN maximum is closer to 550 μflicks; near 9.6 μm and again near 17 μm, the spectral structure of the 10 km path transmittances differ between the two models; and the single scatter solar predictions differ near 4.8 μm. A careful examination of each of these cases shows that multiple molecular species have significant absorption when discrepancies occur. This suggests the MODTRAN and MOD3D are coupling the absorption from multiple species differently. As was true in the analysis of Figure 2, it is unclear which of the models is to be preferred. Sometimes the correlation is accurately modeled as being random (the MODTRAN assumption), but in other instances it is not.

3.2 Ground-to-air scenario

The ground-to-air scenario validation calculations with varying viewing angles test different aspects of MOD3D model from the ground-to-ground calculations. The 0.77 to 26.0-km altitude range passes through 26 MODTRAN layers as compared to the single layer ground-to-ground calculation. Also, varying viewing angle changes the solar scattering angle, and the phase function contribution.

The results are illustrated in Figure 5. Since the column amount only changes by a factor of two for the range of angles, the transmittances curves all have relatively similar shape. The thermal emission is strongest in the center of the 6.3 μm H_2O and 15 μm CO_2 bands because the atmosphere is warmest near the surface and absorption is greatest in these spectral regions. As the viewing angle increases away from zenith, the solar scattering angle is increasing and the solar single scatter radiance drops off. However, between viewing angle of 45° and 60° the decrease in the phase function is a smaller effect than the increase in column density, and the single scatter solar radiance begins to increase.

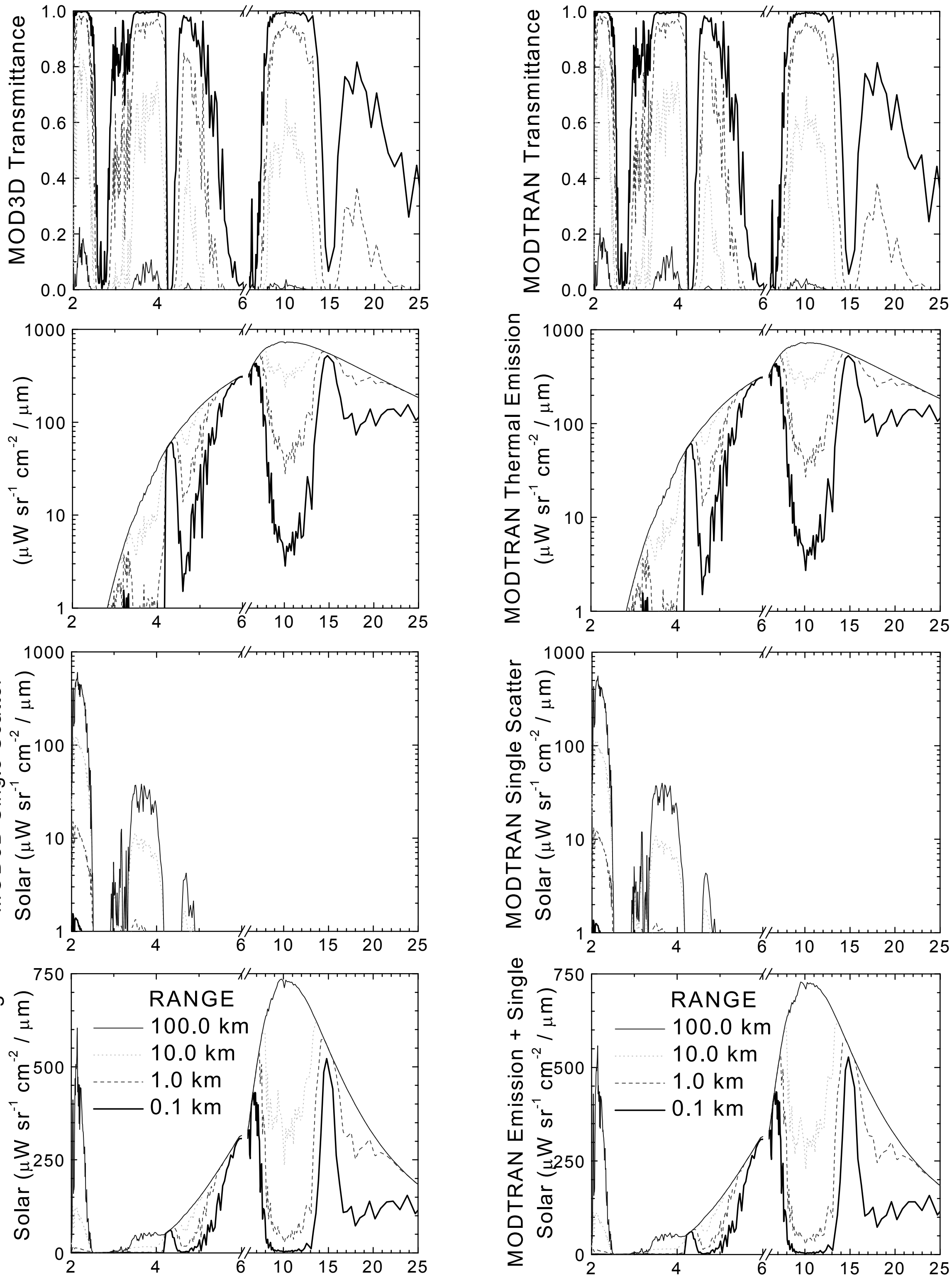

Figure 4. Comparison of MOD3D (left) and MODTRAN (right) 15 cm^{-1} Predictions for a Ground-to-Ground Scenario. The 4 curves in each figure are for ranges of 0.1 (thick_line), 1.0 (dash), 10.0 (dot) and 100.0 (thin_line) km.

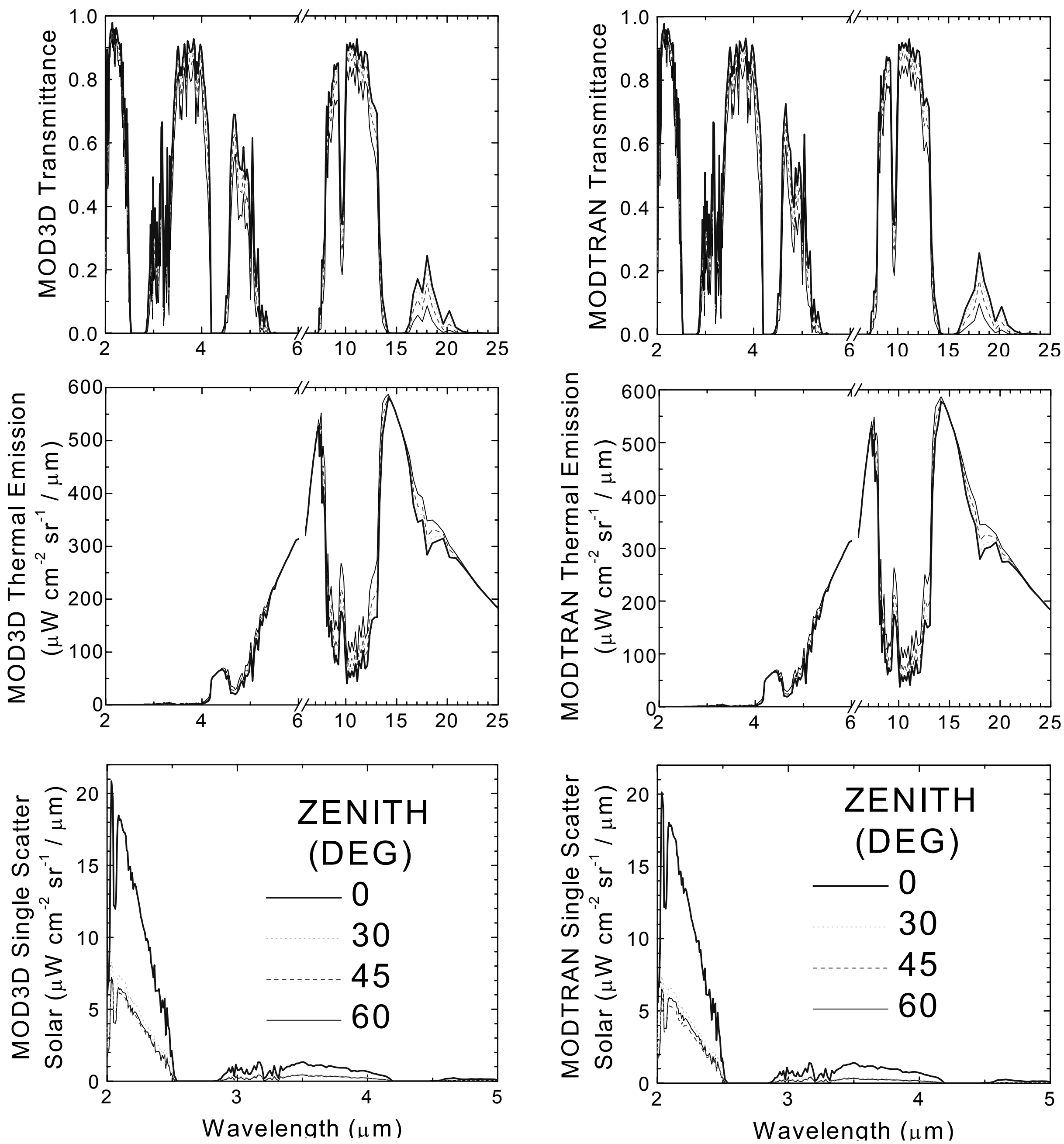

Figure 5. Comparison of MOD3D (left) and MODTRAN (right) 15 cm^{-1} Predictions for a Ground-to-Air Scenario. The 4 curves in each figure are for viewing zenith angles of 0° (thick_line), 30° (dash), 45° (dot) and 60° (thin_line).

Qualitatively, the comparisons between MOD3D and MODTRAN4 predictions in the ground-to-air case are similar to the earlier comparisons. Both models capture the primary RT features; however, there are some differences, which again can be attributed to absorption from multiple species. In particular, MOD3D and MODTRAN predict different spectral structure near 17 μm, where both CO_2 and H_2O have strong absorption features. Also, the MOD3D peak value for the single scatter solar radiance is about 4% higher than the MODTRAN4 value.

4. CONCLUSIONS AND FUTURE DIRECTIONS

The development of a rapid radiative transfer model for application to 3D simulations based on the MODTRAN band model and Correlated-*k* algorithms provides an important link between state-of-the-art RT and near real-time 3D simulations. The validations performed to date give confidence that accuracy comparable to that of MODTRAN can be achieved in these simulations. Upgrading the model to incorporate a multiple scattering will be the next major improvement.

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