MODTRAN Cloud and Multiple Scattering Upgrades with Application to AVIRIS


Recent upgrades to the MODTRAN atmospheric radiation code improve the accuracy of its radiance predictions, especially in the presence of clouds and thick aerosols, and for multiple scattering in regions of strong molecular line absorption. The current public-released version of MODTRAN (MODTRAN3.7) features a generalized specification of cloud properties, while the current research version of MODTRAN (MODTRAN4) implements a correlated-k (CK) approach for more accurate calculation of multiply scattered radiance. Comparisons to cloud measurements demonstrate the viability of the CK approach. The impact of these upgrades on predictions for AVIRIS viewing scenarios is discussed for both clear and clouded skies; the CK approach provides refined predictions for AVIRIS nadir and near-nadir viewing.

INTRODUCTION

Downward-viewing airborne and spaceborne imaging spectrometers such as the AVIRIS instrument provide valuable information on Earth surface properties for a variety of applications. To properly interpret these measurements, both atmospheric attenuation and path radiances need to be modeled. MODTRAN (Berk et al., 1989; Kneizys et al., 1988), the Air Force Research Laboratory/Geophysics Directorate moderate spectral resolution (2 cm⁻¹) background radiance and transmittance model, has been widely used to analyze AVIRIS data due to its computational speed and its ability to model molecular and aerosol/cloud emissive and scattered radiance contributions as well as the atmospheric attenuation. The accuracy of MODTRAN, typically 2–5% in transmittance (Bernstein et al., 1996a; Anderson et al., 1993), has been confirmed through extensive validation against both measurements and the line-by-line (LBL) high spectral resolution model, FASCODE (Clough et al., 1988).

Recently, several new features have been introduced into MODTRAN which improve its predictive capabilities under cloudy and/or heavy aerosol loading conditions. The newly released MODTRAN3.7 allows the default model clouds to be varied (altitudes, thickness, etc.), clouds to be overlaid, and user-specified clouds to be easily defined via explicit water and ice particle profiles and spectral optical properties (extinction coefficients, scattering albedos, etc.). In addition, MODTRAN4, which is currently under development, introduces a correlated-k (CK) algorithm which significantly improves the accuracy of radiance calculations, particularly for multiple scattering in spectral regions containing strong molecular line absorption.

This paper briefly discusses MODTRAN’s radiance transport methodology, focusing on scattered radiance and on the MODTRAN3.7 and MODTRAN4 upgrades. Initial comparisons between predictions and airborne measurements of a solar illuminated cumulus cloud top are presented, and the influence of the CK upgrade on AVIRIS scenarios is demonstrated with two illustrative calculations.

RADIANCE CALCULATION OVERVIEW

The radiance observed from a down-looking sensor is comprised of many components, as illustrated in Figure 1. Typically, the quantity to be determined from these measurements is the spectrally dependent surface reflectance function or albedo. For a near-infrared (NIR) and visible...
A (VIS) sensor such as AVIRIS, the dominant contribution to the observed radiance is the surface-scattered sunlight. In the limit in which atmospheric attenuation and scatter are negligible, the reflectance function is simply the ratio of the observed spectral radiance to the solar spectral irradiance (the normalized ratio includes a factor of $\pi$ steradians over the cosine of the solar zenith angle). In reality, other radiance components and atmospheric absorption are present. The “data correction” usually involves forward calculations with a comprehensive radiative transport model such as MODTRAN.

The basic approach in MODTRAN is to approximate the atmosphere and Earth surface as a sequence of quasihomogeneous layers for which the individual layer radiance contributions from each of the source terms depicted in Figure 1 is considered. The surface is treated as a layer of infinite opacity, an opaque boundary with variable emissivity/reflectivity. Spherical refraction geometry effects are incorporated into calculation of path sums and scattering angles, although multiple scattering radiances are based on plane-parallel models. Approximate corrections are made for the effects of inhomogeneous distributions of temperature and species concentrations within the atmospheric layers. The approximate layer radiance models used in MODTRAN derive from the general solution to the radiative transport equation for an absorbing-scattering atmosphere,

$$
\Delta I = \int_{T_b}^{T_a} J(T) \, dT,
$$

where $\Delta I$ is the radiance contribution from a single layer along the line of sight, $T$ denotes the transmittance to the observer, $J(T)$ is the total source term (i.e., the sum of the individual terms in Fig. 1), and $T_a$ and $T_b$ are the total path transmittances between the observer and the beginning and end of the layer, respectively. For notational simplicity, the explicit dependence of $\Delta I$ and the other quantities in Eq. (1) on frequency $\nu$ is omitted, and all quantities are 1 cm$^{-1}$ interval averages unless otherwise noted. The total path radiance is obtained by summing the layer radiances along the line of sight. Equation (1) is exact for monochromatic radiation, following from formal integration of the differential expression for $I$ (Chandrasekhar, 1960), and is the starting premise for band model formulations; in both cases, the problem is to determine the appropriate layer and/or layer boundary transmittances and source terms.

Transmittance Calculation

In MODTRAN3.7 and the developmental MODTRAN4 the band model transmittance algorithms are essentially the same as in previous versions. The transmittance is calculated for each 1 cm$^{-1}$ bin using: 1) band model parameters for molecular line absorption based on HITRAN96 (Rothman, personal communication, 1996; Rothman et al., 1992), with a approximate treatment of line tails extending across multiple bins; 2) extinction coefficients for continuous and quasicontinuous molecular absorptions, such as the H$_2$O (Clough et al., 1989) and N$_2$ continua, CFC and HNO$_3$ vibrational bands, and electronic transitions (Anderson et al., 1990) of O$_2$, O$_3$, etc.; and 3) extinction coefficients for water particulates (i.e., clouds, fogs, and rain) and aerosols. Total transmittance is calculated as a product of individual species transmittances, and multilayer paths are modeled using Curtis–Godson averaging (Curtis, 1952; Godson, 1953). Calculations of equivalent widths, line tail contributions, and Lorentz half-width temperature scaling have recently been refined. Details of the MODTRAN band model transmittance algorithm in general and recent refine-
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Planck blackbody function. In practice, due to temperature variations within the layer and the steep temperature dependence of the Planck function, converging the calculation through fine layering is very computationally intensive. An alternative approach, widely used in monochromatic codes (Clough et al., 1992), is to use coarser layering (≈1 km resolution in the lower atmosphere) with the "linear-in-tau" approximation. [A similar approach for band models has been suggested by Cornette (1992)]. In this approximation, the source variation within a layer is given by

\[
J(\tau') = J_a + \frac{\Delta \tau'}{\Delta \tau} \Delta J,
\]

where \( \Delta \tau = \ln(T_a/T_b) \), \( \Delta \tau' = \ln(T'/T) \), and \( \Delta J = J_b - J_a \). \( \Delta \tau' \) represents an effective incremental optical depth from boundary \( a \) and \( \Delta \tau \) is the total effective optical depth across the layer. For monochromatic radiation (i.e., obeying Beer's law), \( \Delta \tau' \) is the actual optical depth, and Eq. (3) is nearly exact for thermal emission when the temperature in the layer varies linearly with density and scattering is negligible. Substituting Eqs. (3), (4), and (5) into Eq. (1) yields the following expression for the layer radiance contribution:

\[
\Delta I = T_0 \left[ J_a e^{-\Delta \tau} + \frac{1-e^{-\Delta \tau}}{\Delta \tau} \Delta J \right].
\]

Although it is not as rigorous when applied to non-monochromatic band model calculations such as those in MODTRAN, the linear-in-tau approximation still gives good results and has therefore been chosen for both the direct thermal emission and the two-stream (thermal and solar) multiple scattering radiance components in MODTRAN3.7. In particular, Eq. (6) has the correct behavior in the following limits: 1) as \( \Delta \tau \to \infty \), the opaque limit is attained, \( \Delta I \to T_0 J_a \), and only emission from the front surface of the layer is observed; and 2) for a constant source function, \( J_a = J_b \), Eq. (2) is recovered, that is, \( \Delta I = (T_a - T_b) J_a \). The linear-in-tau expression does not reduce to the correct weak-line limit for a non-uniform species distribution, and MODTRAN adjusts the direct thermal far boundary source term \( J_b \) to account for this (Clough et al., 1992).

For more accurate results, a correlated-\( k \) (CK) approach, described later in this article, is used to convert the MODTRAN band model calculations into a set of equivalent monochromatic calculations. In this way, the full accuracy of the linear-in-tau approximation is preserved. Other successful approaches have also been explored (Bernstein, 1995; Berstein et al., 1996a).

Accounting for scattering, the direct thermal source function for Eq. (6) is given by Eq. (7):

\[
\Delta I = T_0 \left[ J_a e^{-\Delta \tau} + \frac{1-e^{-\Delta \tau}}{\Delta \tau} \Delta J \right].
\]
where $\omega$ is the single scattering albedo and $B(\Theta)$ is the Planck blackbody function evaluated at the local temperature $\Theta$.

For monochromatic calculations, the single scattering albedo is rigorously defined for a homogeneous layer by Eq. (8):

$$\omega = \frac{\Delta \tau_s}{\Delta \tau + \Delta \tau_s + \Delta \tau_m},$$

where $\Delta \tau_s$ is the layer vertical scattering optical depth, $\Delta \tau$ is the vertical absorption optical depth due to particle and molecular continuum absorption, and $\Delta \tau_m$ is the spectrally rapidly varying optical depth due to molecular line absorption. The problem in defining $\omega$ for a band model code is in determining an effective spectral-interval average value for the molecular optical depth. This can only be done approximately; no single effective value $\Delta \tau_s$ can be determined *a priori* that accurately reproduces exact monochromatic results averaged over the finite spectral interval. The approach adopted in MODTRAN is to define an effective molecular optical depth using

$$\Delta \tau_m = \ln (T_{\text{mid}} T_{\text{top}}),$$

where $T_{\text{mid}}$ and $T_{\text{top}}$ are the cumulative molecular band transmittances to the bottom and top layer boundaries for a vertical path from the ground.

This approach for defining molecular line absorption layer vertical optical depths preserves the correct qualitative effects of molecular line absorption on scattering; however, it can produce poor quantitative results if the monochromatic $\Delta \tau_m$’s exceed $\Delta \tau_s$ in a large fraction of the spectral interval. In the AVIRIS down-looking sensor scenario, if a given spectral interval contains one weak line and one strong line, the strong line can be absorbed in the top part of the atmosphere, while the weak line can penetrate all the way down to the surface and back to space. Under this circumstance, the effective molecular optical depth for the bottom layers of the atmosphere are incorrectly represented by Eq. (9). This problem is addressed in the CK approach discussed later.

**Atmospheric Scattering of Thermal and External Sources**

The radiance sources in Figure 1, other than direct thermal emission, involve scattering of radiation originating from other layers or external sources. Both thermal (skyshine and earthshine) and solar (or lunar, if specified) radiation are scattered by the Earth’s surface and by atmospheric particulates such as background and volcanic aerosols, water and ice cloud particles, and boundary layer fogs. Molecular or Rayleigh scattering is more important at shorter wavelengths (NIR and UV/VIS) where the solar contributions dominate. MODTRAN models the single scatter solar radiation accounting for the solar spectrum (Kurucz, 1992; 1994), the curvature of the Earth, refractive geometry effects (Ridgway et al., 1982; Gallery et al., 1983; Kneizys et al., 1983), and a general scattering phase function. Multiple scattering, which is much more difficult to treat accurately, is handled with a plane-parallel atmospheric approximation (Anderson, 1983) and a Henyey-Greenstein phase function. The Henyey-Greenstein functions are good for modeling fluxes, but less accurate when used to predict radiant intensities.

**Single Scattering Source Term and Layer Radiance**

The single scattering source term is given by Eq. (10):

$$J = \omega P(\theta) I_0 \frac{T_0}{T},$$

where $P(\theta)$ is the scattering phase function at scattering angle $\theta$, $I_0$ is the irradiance at the top of the atmosphere, $T$ is the transmittance from the scattering point to the observer, and $T_0$ is the transmittance for the L-shaped path from the external source to the observer. Rather than using the linear-in-tau approximation for $J$, MODTRAN assumes that log($T_0$) varies linearly with $\Delta \tau$ and that $\omega P(\theta)$ is constant within the layer; this yields the correct monochromatic single scatter radiance for an isolated layer. The approach was validated by comparison to UV measurements in the upper stratosphere (Minschwaner et al., 1995). The resulting layer radiance is given by Eq. (11):

$$\Delta I = T_0 \left[ \frac{\Delta \tau}{\Delta \tau_0} \left( I_0 - J e^{-\Delta \tau} \right) \right],$$

where $\Delta \tau_0$ is the difference between log($T_0$) for the path through scattering point $a$ and log($T_b$) for the path through scattering point $b$.

**Multiple Scattering Source Term and Layer Radiance**

MODTRAN provides two models for evaluating the scattered thermal and multiply scattered solar radiances: a simple but faster two-stream model (Isacss et al., 1987; 1996; Meador and Weaver, 1980) and the more accurate but slower DISORT N-stream discrete ordinates method (Stamnes et al., 1988; Stamnes and Swanson, 1981; Goody and Yung, 1989). Both models calculate upwelling $F^+$ and downwelling $F^-$ fluxes at layer boundaries by performing lower and upper hemispherical integrations. The source term for scattered thermal and multiply scattered solar radiance is a product of the scattering albedo and the flux scattered towards the observer. In the two-stream method, all hemispherical integrations are performed with a 1-point Gaussian quadrature ignoring azimuthal dependencies, and $J$ has the form as shown in Eq. (12):

$$J = \frac{\omega}{\pi} \left[ (1-\beta) F^- + \beta F^+ \right],$$

where coefficient $\beta$ is the integral of the scattering phase function over the lower hemisphere at the path zenith angle (Wiscombe and Grams, 1976). DISORT performs
the zenith integrations using $N/2$ Gaussian quadrature points. Both methods assume Beer’s law extinction, an inadequate approximation for MODTRAN’s band models. The CK approach developed for MODTRAN4 overcomes this limitation, as described below.

**MODTRAN3.7 CLOUD/RAIN MODELS UPGRADE**

The cloud/rain models in MODTRAN3.7 (Berk, 1995) allow for generalized specification of layering and optical and physical properties as well as the presence of multiple overlapping and nonoverlapping clouds. The cloud models affected are the MODTRAN cumulus and stratus clouds, both with and without rain (cloud/rain models 1–10). The upgrades include: 1) adjustable cloud parameters (thickness, altitude, vertical extinction, column amounts, humidity, and scattering phase functions); 2) decoupling of clouds from aerosols; 3) introduction of ice particles; 4) user-defined water droplet, ice particle, and rain rate profiles; 5) user-defined cloud spectral properties; and 6) output of cloud/rain profiles and spectral data to the “tape6” file.

The decoupling of the cloud and aerosol models has a number of implications. Clouds and aerosols can coexist at a single altitude, or clouds can be modeled with no aerosol profiles included. When clouds and aerosols coexist, the cloud water droplets, cloud ice particles, and aerosol particles may all have different scattering phase functions. The single scatter solar contribution for each component is properly combined. However, for multiple scattering a single effective phase function is required. It is defined using the “scattering optical depth”-weighted Henyey–Greenstein asymmetry factor which was previously used to combine only the aerosol and molecular multiple scattering contributions (Isaacs et al., 1986).

Cloud profiles are merged with the other atmospheric profiles (pressure, temperature, molecular constituent, and aerosol) by combining and/or adding new layer boundaries. Any cloud layer boundary within half a meter of an atmospheric boundary layer is translated to make the layer altitudes coincide; new atmospheric layer boundaries are defined to accommodate the additional cloud layer boundaries.

**ADDITION OF A CORRELATED-K CAPABILITY TO MODTRAN**

Addition of a CK capability (Lacis and Oinas, 1991; Goody and Yung, 1989) in MODTRAN4 provides an improved means for calculating atmospheric radiances including the effects of multiple scattering (Bernstein et al., 1996b). Since MODTRAN computes molecular transmittance using a narrow-band model, it is not suitable for direct interfacing with standard multiple scattering algorithms. This is because these algorithms require Beer’s law (exponential) behavior of the transmittance, whereas band model transmittances do not follow Beer’s law. To properly integrate MODTRAN with these scattering algorithms, the transmittance for a given layer must be expressed as a weighted sum of exponential terms:

\[ T = \sum_{i=1}^{i_{\text{max}}} \Delta g_i e^{-k_i u_i} \]  

where the $\Delta g_i$ are weighting factors and the $K_i$ are monochromatic absorption coefficients.

The use of real time LBL simulation or inverse Laplace transformation to derive the $(\Delta g_i, K_i)$ pairs during a MODTRAN run is much too slow to be of practical value. Creation and storage of temperature and pressure dependent CK look-up tables for each molecule contributing to each 1 cm⁻¹ spectral bin is also not a practical alternative. The basic approach and key assumptions of the CK implementation developed for MODTRAN4 are described below; further details are provided elsewhere (Bernstein et al., 1996b).

MODTRAN’s transmittance model for a single molecular species is based on four parameters: 1) the integrated line strength $S$ in each 1 cm⁻¹ spectral bin, 2) an effective number of equivalent line $n$ in the bin, 3) the average pressure-broadened Lorentz line width $\gamma_L$, and 4) the Doppler line width $\gamma_D$. In MODTRAN’s band model algorithm, the transmittance is approximated from these parameters using analytical expressions for a set of $n$ identical lines randomly located in the bin. In MODTRAN4, the cumulative distribution $g(k)$ of absorption coefficients $k$ associated with this set of lines serves as the starting point for the CK calculation.

From $g(k)$ distributions for selected values of the line parameters $n$, $\gamma_L$, and $\gamma_D$, a “$k$-distribution” table of discrete $g_i/k$ pairs was constructed. (Different values of $S$ were not required, as they simply scale the $k$ values.) The ranges of line parameter values covered by this table were chosen to be compatible with radiative transfer calculations extending up to 70 km altitude, covering the spectral range from 0 to 25,000 cm⁻¹ (above 25,000 cm⁻¹ all molecular absorption in MODTRAN is treated as continua), and including all of the MODTRAN atmospheric species. The $g$ values were selected so that the $k$-distribution with the largest dynamic range in $k$ would have each decade of $k$ values covered by approximately three $g_i/k_i$ pairs. This tabulation required a fixed grid of 33 $g$ values ranging from $g_0=0$ to $g_{32}=1$. For low altitude paths, fewer $g$ values are required, and an approach for optimally combining the subintervals is presently being developed.

At run time, the line parameters are calculated for each layer and spectral bin, and interpolated between the table values to generate the appropriate $k$-distributions. The effective absorption coefficients $K_i$ for the subintervals $\Delta g_i=g_i-g_{i-1}$ [see Eq. (13)] are defined to insure that the integral averaged subinterval transmittances are preserved.
When only one molecular species is present in a spectral bin, the CK calculation of transmittance is straightforward and matches the band model. A single pseudogas can be defined for multiple molecular species with fixed mixing ratios (Goody et al., 1989). Varying mixtures of individual species are more difficult to model. Generally, the assumption is made that absorption among different molecular species is uncorrelated, or equivalently that their transmittances are multiplicative. In terms of the $k$-distribution formulation, the combined transmittance for $M$ overlapping gases is given by the multiple sum of the $M$ distributions. This approach is computationally very intensive, requiring $iM_{\text{max}}$ separate calculations. To alleviate the computational burden, the $iM_{\text{max}}$ absorption coefficients can be ordered and combined into a smaller set (Lacis and Oinas, 1991). For the MODTRAN4 CK implementation, an alternative, approximate approach is used. The net MODTRAN band model transmittance (assumed to be the product of the individual species transmittances) is calculated for each layer. A CK calculation is then performed and iteratively adjusted to match this net transmittance. For the CK calculation, effective species-averaged values for $\gamma_L$ and $\gamma_D$ and a first-guess value for $n$, the effective number of equivalent lines, are determined. $n$ is then adjusted and the K's recalculated until the CK transmittance matches the band model value.

The resulting single-layer K's are combined assuming perfect spectral correlation among the subintervals to give the total path transmittance as shown in Eq. (14):

$$T = \sum_{i=1}^{iM_{\text{max}}} \Delta g_i e^{-\sum \varepsilon_{ij} \phi_{ij}} \quad (14)$$

where $j$ denotes the sum over layers. This approach eliminates the need to model the optical path as an equivalent homogeneous layer using Curtis–Godson averaging.

Comparisons performed to date between MODTRAN4 and FASCODE for vertical paths indicate that MODTRAN4’s transmittance accuracy is comparable to that of MODTRAN3.7, consistent with proper matching of a single-layer band model transmittances by the CK approach. Additional comparisons over a wider range of geometries are planned.

**DATA-MODEL COMPARISONS FOR A SUNLIT CLOUD**

As part of the initial validation of MODTRAN’s multiple scattering algorithms, comparisons were made between spectral measurements of a sunlit cumulus cloud top (Malherbe et al., 1995), predictions from MODTRAN4, and calculations from another radiative transport code, NAULUM (Malherbe et al., 1995). The measurements were performed by the ONERA and CELAR research agencies (France) from an aircraft using the SICAP circular variable filter cryogenic spectrometer (1500–5500 nm, 2% resolution).

A typical spectrum is shown in Figure 3. Here the aircraft is at 3.0 km altitude, the cloud top altitude is 2.5 km, the sensor line-of-sight (LOS) zenith angle is 104°, and the solar zenith and relative azimuth angles are 48° and 137°, respectively. The CELAR cloud characterization was adopted for the MODTRAN simulations. The cumulus cloud was modeled with a homogeneous liquid water droplet density of 0.68 g/m$^2$ from 0.1 km to 2.5 km altitude. Water droplet single scattering albedos (Hansen et al., 1970) for a mean spherical particle radius of 8 $\mu$m were entered at a 0.05 $\mu$m spectral resolution. MODTRAN4 results at 10 cm$^{-1}$ spectral resolution (0.2% at 2000 nm) using the two-stream multiple scattering model (Isaacs et al., 1986; 1987; Meador and Weaver, 1980) are shown and are in good agreement with the data, although the data appear to be offset by 10–20 nm. Similar results were obtained with MODTRAN3.7 and with the discrete ordinates model DISORT (Stamnes and Swanson, 1981; Stamnes et al., 1988) run with eight streams over a limited spectral subregion. In addition, Figure 3 shows a calculation using ONERA’s NAULUM code (Malherbe et al., 1995), which is also in good agreement with the data and MODTRAN results; NAULUM assumes a plane parallel atmosphere, appropriate for this case but not for general applications.

Figure 4 shows an additional SICAP data-model comparison, but with a LOS zenith angle of 95° and, more importantly, a solar relative azimuth angle of 11°. In this forward scattering case, MODTRAN4 underpredicts the measurements by about a factor of two because the multiple scattering model averages over the azimuthal dependence. MODTRAN does account for the relative azimuth angle in single scattering, but single scattered radiation accounts for less than 20% of the total radiance in this example. The NAULUM calculation is an im-

![Figure 3](image-url)
improvement over MODTRAN4 because it models the azimuthal distribution of radiation in its plane-parallel discrete ordinates multiple scattering algorithm. DISORT can also model azimuthal variations, but currently only for plane-parallel atmospheres (Stamnes, personal communications, 1996); the development and integration into MODTRAN of a curved-Earth, refractive path DISORT routine which models solar azimuth dependencies is being pursued. For nadir-viewing geometries, such as AVIRIS, solar azimuth geometry effects are minimized.

APPLICATIONS TO AVIRIS MEASUREMENTS

The primary focus of AVIRIS is characterization of the Earth’s surface using nadir and near-nadir views. For many such applications, the upgrade from MODTRAN3.7 to MODTRAN4 will have only a minor effect on the data analysis. Under clear sky or thin cirrus conditions, differences between MODTRAN3.7 and MODTRAN4 down-looking radiances from 20 km in the 400–2500 nm spectral region are generally small. However, when multiple scattering is a sizable fraction of the total radiance, the differences can be significant in absorption bands. For example, Figure 5 shows down-looking radiances predicted by MODTRAN3.7 and MODTRAN4 in the center of the 1.9 μm H_2O band. These calculations were performed with a 1-km-thick cirrus cloud at 10 km altitude (0.14 vertical extinction at 550 nm), a solar zenith angle of 75°, and using the MODTRAN grass (Vegetation A) surface albedos (Mustard, 1991). Within the 1.9 μm band region, MODTRAN3.7 radiances exceed those from MODTRAN4 by up to 10%.

For views of solar-illuminated opaque clouds, the MODTRAN4 upgrades are more critical. In Figure 6, MODTRAN3.7 and MODTRAN4 mid-IR and near-IR radiances are compared for a nadir view of the MODTRAN model altostratus cloud (ICLD=2). The observer is at 20 km altitude and the solar zenith angle is again set to 75°. The cloud/rain model upgrade was used to introduce finer layering near the cloud top (12 layers were placed between 3.0 km and 3.5 km altitude). Inaccurate fluxes result from the multiple scattering algorithms if the original coarser layering is used. Even with the finer layering, MODTRAN3.7 radiances exceed those from MODTRAN4 by up to 20%.

SUMMARY

Several upgrades to MODTRAN have been developed which lead to improvements in the calculation of radia-

Figure 4. A comparison between SICAP measurements (Malherbe et al., 1995) and model predictions for a solar illuminated cumulus cloud top with a 11° relative solar azimuth angle.

Figure 5. A comparison between MODTRAN3.7 and MODTRAN4 radiances for nadir viewing of the Earth through a cirrus cloud with a 75° solar zenith angle. The differences between MODTRAN radiances are plotted offset by 0.08 μW sr⁻¹ cm⁻²/μm.

Figure 6. A comparison between MODTRAN3.7 and MODTRAN4 radiances for nadir viewing of the MODTRAN model altostratus cloud with a 75° solar zenith angle. The differences between MODTRAN radiances are plotted offset by 7 μW sr⁻¹ cm⁻²/μm.
tion scattering from clouds and aerosols. The cloud/aerosol models now allow for generalized layering and specification of physical and optical properties. A new CK radiative transfer model leads to more accurate multiple scattering calculations, particularly in spectral regions containing strong molecular line absorption. It has been shown that multiple scattering contributions can be important even for an optically thin solar-illuminated cirrus cloud in the near-IR through visible spectral regions; thus, these MODTRAN upgrades will lead to improved FASCODE3 spectral simulation. In *Proceedings of the 1996 Meeting of the IRIS Specialty Group on Targets, Backgrounds, and Discrimination*. Vol III, pp. 249–248.


Lacis, A. A., and Oinas, V. (1991), A description of the corre-


