MODTRAN CLOUD AND MULTIPLE SCATTERING UPGRADES WITH APPLICATION TO AVIRIS

A. Berk, L. S. Bernstein, D. C. Robertson, and P. K. Acharya
Spectral Sciences, Inc., 99 South Bedford St.,
Burlington, MA 01803

G. P. Anderson and J. H. Chetwynd
Phillips Laboratory, Geophysics Directorate
Hanscom AFB, MA 01731

1. INTRODUCTION

Characterization of surface properties from AVIRIS measurements is hampered by atmospheric attenuation and path radiances. MODTRAN (Berk et al., 1989), the Air Force PL/Geophysics Directorate moderate spectral resolution (2 cm^{-1}) background radiance and transmission model, is often used to account for the atmospherics in AVIRIS measurements. It rapidly predicts the molecular and aerosol/cloud emissive and scattered contributions to observed radiances along with the atmospheric attenuation. MODTRAN has been extensively validated against both measurements and the high spectral resolution FASCODE (Clough et al., 1988) model.

MODTRAN4, currently under development, contains two new features which greatly improve predictive capabilities under cloudy and/or heavy aerosol loading conditions. It allows a user to explicitly define water and ice cloud vertical profiles and spectral data either by scaling the default model clouds or by defining a new model cloud. MODTRAN4 also introduces a Correlated-*k* (CK) capability which significantly improves the accuracy of the multiple scattering radiance calculations. In the following sections, a discussion of the MODTRAN4 upgrades and an initial validation by comparison to airborne measurements of a solar illuminated cumulus cloud top are presented. Finally, the effect of the CK approach for two AVIRIS scenarios is demonstrated.

2. MODTRAN CLOUD/RAIN MODELS UPGRADE

The MODTRAN cloud/rain models have been upgraded (Berk, 1995) and now allow for generalized specification of layering and optical and physical properties as well as the presence of multiple overlapping and non-overlapping clouds. The cloud models affected are all of the cumulus and stratus type clouds, both with and without rain. This includes MODTRAN cloud/rain models 1 through 10. The cirrus models 17-19 only required improved layering. The cloud model upgrades include:

- adjustable cloud parameters,
  - thickness, altitude, vertical extinction, column amounts, humidity, and scattering phase functions,
- decoupling of the clouds from aerosols,
- introduction of ice particles,
- user-defined water droplet, ice particle and rain rate profiles,
- user-defined cloud spectral properties, and
- output of cloud/rain profiles and spectral data to tape6 (NOPRT = -1).

The decoupling of the cloud and aerosol models has a number of implications. Clouds and aerosols can co-exist at a single altitude, or clouds can be modeled with no aerosol profiles included. When clouds and aerosols co-exist, the cloud water droplets, cloud ice particles and aerosol particles may all have different scattering phase functions. The single scatter solar contribution of each component is properly combined. However, for multiple scattering a single effective phase function is defined based on a scattering optical depth weighted Henyey-Greenstein asymmetry factor; this is the same approach that is used to combine the aerosol and molecular scattering contributions.

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.

3. ADDITION OF A CORRELATED-*k* CAPABILITY TO MODTRAN

Addition of a CK capability to MODTRAN (Bernstein et al., 1995) provides an accurate and fast means for evaluation of the effects of clouds and heavy aerosol loading on retrievals (both surface properties and species concentration profiles) and on atmospheric radiative heating/cooling calculations. These radiative transfer computations require coupling the effects of gaseous molecular absorption due primarily to water vapor, carbon dioxide, and ozone, with particulate multiple scattering due to volcanic aerosols, ice crystals, and water droplets. The molecular absorption band model used in MODTRAN is not suitable for interfacing with standard multiple scattering algorithms. This is because the scattering models require a monochromatic representation of the molecular transmission (i.e., Beer's law), whereas molecular band models which represent the transmission for a finite spectral interval do not follow Beer's law. In order to adapt a band model approach for use in scattering calculations it is necessary to express the band model transmission function in terms of a weighted sum of Beer's law exponential terms. Thus, a method for determining the weighing factors and monochromatic absorption coefficients for the MODTRAN band model is required. An abbreviated discussion of the CK approach as tailored for integration into MODTRAN is given below; for a more complete discussion of the CK method the reader is referred to Lacis and Oinas (1991).

For simplicity, consider the problem of determining the average transmittance, as defined by Beer's law, for a homogeneous path over a finite spectral interval. The generalization to inhomogeneous paths is straightforward and is also described below. The path transmittance can be exactly determined through evaluation of

$$T(u) = \frac{1}{\omega_2 - \omega_1} \int_{\omega_1}^{\omega_2} d\omega \, \exp(-k(\omega) u) \quad , \tag{1}$$

where ω is frequency, $k(\omega)$ is the monochromatic absorption coefficient, and u is absorber column density. The basis of the CK approach is that evaluation of T(u) by integration over frequency can be replaced by an equivalent integration over the distribution of absorption coefficient values f(k) in the spectral interval

$$T(u) = \int_0^\infty dk \, f(k) \, \exp(-ku) \quad . \tag{2}$$

The difficulty in evaluation of T(u) via Equation (2) is the necessity of first determining f(k); the advantage is that $k(\omega)$ is typically a highly repetitive function of ω (i.e., there are many nearly equivalent values of a given k in a spectral interval) and thus numerical evaluation of Equation (2) requires far fewer grid points than Equation

(1). Note that $f(k) = 0$ above the maximum k_{max} and below the minimum k_{min} absorption coefficients in the spectral interval. The probability distribution $f(k)$ can be determined directly from $k(\omega)$ by binning the k's into selected Δk sub-intervals.

The distribution function $f(k)$ is not smooth or monotonic; it generally consists of a series of sharp spikes which reflects the sharp line structure of $k(\omega)$. It then becomes more computationally convenient to work with the smooth and monotonic cumulative probability distribution function

$$g(k) = \int_0^k dk' f(k') \quad . \tag{3}$$

Physically, $g(k)$ is the fraction of absorption coefficients below k within the finite spectral interval ω_1 to ω_2. It assumes the values $g = 0$ at $k = k_{min}$ and $g = 1$ at $k = k_{max}$. The transmittance is related to g by

$$T(u) = \int_0^1 dg \exp(-k(g)u) \quad , \tag{4}$$

where $k(g)$ is given by the inverse of $g(k)$, $k(g) = g^{-1}(k)$. In practice, the evaluation of Equation (4) proceeds via summation according to

$$T(u) = \sum_{i=1}^{imax} \Delta g_i \exp(-\bar{k}_i u) \quad , \tag{5}$$

where the Δg_i's and $\bar{k}_i$'s are the sub-interval weighting factors and effective absorption coefficients necessary for the MODTRAN band model. The maximum number of intervals i_{max} and the specific selection of Δg_i interval boundaries (g_i, g_{i+1}) are chosen based on consideration of a number of factors including computational speed and accuracy, and the altitude and spectral ranges of interest. For multi-layer paths it is assumed that there is perfect spectral correlation among the sub-intervals of each layer, resulting in a total path transmittance given by

$$T(u) = \sum_{i=1}^{imax} \Delta g_i \sum_{j=1}^{jmax} \exp(-\bar{k}_{ij} u) \quad , \tag{6}$$

where j denotes the sum over layers.

The MODTRAN band model for a single species (multiple species are discussed later) is based on four parameters: (1) the integrated line strength S in a spectral interval $\Delta\omega$ ($\Delta\omega = 1\ cm^{-1}$ in MODTRAN), (2) the effective number of equivalent lines n (non-integer values of n are acceptable) in the interval, (3) the average pressure broadening Lorentz line width γ_L, and (4) the Doppler line width γ_D. These parameters are determined directly from the 1992 HITRAN parameter line compilation (Rothman et al., 1992). The molecular transmittance model is given by

$$T(u) = \left(1 - \frac{W(S_{sl} u, \gamma_L, \gamma_D)}{\Delta\omega}\right)^n \quad , \tag{7}$$

where S_{sl} = S/n is the strength for a single effective line, and W is the Voigt equivalent width of the line taking into consideration only the portion of the line shape which falls within the 1 cm^{-1} MODTRAN spectral interval. This functional form for the band model transmittance derives from the assumption that all the lines in the spectral interval are positionally uncorrelated and thus accounts for line overlap in a statistically average sense. The transmittance contribution due to the tails of lines which originate from outside the spectral interval are included as a single multiplicative Beer's law term. Detailed formulas for the equivalent width W can be found in Berk et al. (1989). As discussed elsewhere (Bernstein et al., 1995), the k-distribution g(k) for the band model can be determined from line-by-line (LBL) simulations which are physically constrained by the same assumptions used to derive Equation (7). The use of real time LBL simulation to derive g(k) during a MODTRAN run is much too slow to be of practical value; however, the approach adopted in MODTRAN4 is to use LBL simulation off-line to pre-compute a table of k-distributions which can be rapidly accessed and interpolated during a run.

4. INITIAL VALIDATION OF MODTRAN4 MULTIPLE SCATTER SOLAR

Development of MODTRAN4 was necessary because MODTRAN3 predictions of multiple scatter solar radiances in spectral regions where non-continuum molecular absorption is important are inaccurate. Unfortunately, this scenario cannot be validated by comparisons to FASCODE because FASCODE does not calculate solar path scattered contributions. Thus, initial validation of MODTRAN4 multiple scatter solar calculations were made directly to measurements.

Figure 1 illustrates a comparison of calculated radiance predictions to airborne measurements (Malherbe et al., 1995) performed by ONERA and CELAR using SICAP, a circular variable filter cryogenic spectrometer (1500 - 5500 nm, 2% spectral resolution). The aircraft altitude was 3.0 km, the cloud top was 2.5 km, the sensor line-of-sight (LOS) zenith angle was 104°, and the solar zenith and relative azimuth angles were 48° and 137°, respectively. Three sets of calculations are shown: (1) results from NAULUM (Malherbe et al., 1995), a new radiative transport model developed at ONERA, (2) MODTRAN calculations performed without the CK approach (labeled MODTRAN3), and (3) MODTRAN calculations performed with the CK approach (labeled MODTRAN4). The MODTRAN4 cloud model upgrade enabled the cloud profile and spectral data to be explicitly entered for both the MODTRAN3 and MODTRAN4 calculations. The cumulus cloud was modeled with a homogeneous liquid water droplet density of 0.68 g/m^3 from 0.1 to 2.5 km altitude. Water droplet single scattering albedos (Hansen et al., 1970) for a mean spherical particle radius of 8μm were entered at a 0.05μm spectral resolution. Both MODTRAN calculations were performed using a simpler two-stream multiple scattering model (Isaacs et al., 1987); the discrete ordinate model in MODTRAN, DISORT (Stamnes et al., 1988), was run with 8-streams over a limited spectral sub-region and produced similar results. Differences between MODTRAN3 (no CK) and MODTRAN4 are small because extinction is dominated by continuum sources.

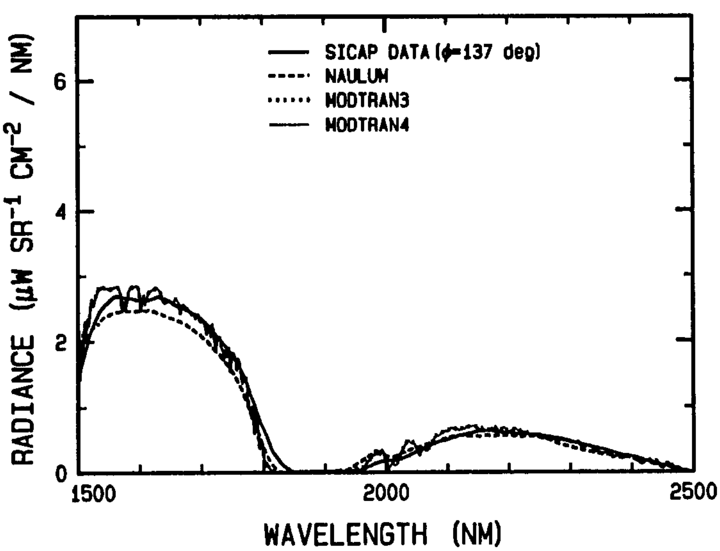

Figure 1. A Comparison Between SICAP Measurements (Malherbe et al., 1995) and Model Predictions for a Solar Illuminated Cumulus Cloud Top with a 137° Relative Solar Azimuth Angle.

Figure 2 illustrates an additional comparison of calculated radiances to SICAP, but with a LOS zenith angle of 95° and, more importantly, with a solar relative azimuth angle of 11°. In this forward scattering case, MODTRAN4 underpredicts the measurements by a factor of 2 because the multiple scattering model averages over the azimuthal dependence (MODTRAN does properly account for the relative azimuth angle in calculation of single scatter solar but single scatter solar is less than 20% of the total radiance in this example). The NAULUM calculation is an improvement over MODTRAN4 because it models the azimuthal distribution of radiation in its discrete ordinate multiple scattering calculation. A new version of DISORT has been developed which also models this azimuthal dependence, but this upgrade has not yet been ported to MODTRAN. For the nadir viewing geometries, such as AVIRIS, the neglect of the azimuthal dependence of the multiply scattered photons in DISORT is a reasonable approximation; similarly, the two-stream Isaac's model is also expected to yield good results.

5. APPLICATION OF MODTRAN4 TO AVIRIS

The primary focus of AVIRIS is the characterization of the Earth's terrestrial surface. For many applications, the upgrade from MODTRAN3 to MODTRAN4 will have only a minor effect on the analysis of AVIRIS data. Under clear sky or thin cirrus conditions, differences between MODTRAN3 and MODTRAN4 down-looking radiances from 20 km in the 400 to 2500 nm spectral region are generally small. This will be true whenever multiple scattering is only a small fraction of the total radiance, or whenever spectral variation of molecular absorption is small. However, these conditions are not always satisfied. Figure 3 illustrates differences between the down-looking radiances predicted by MODTRAN3 and MODTRAN4 in the center of the 1.9μm H_2O band. These calculations were performed with a 1km 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 surface reflectances (Mustard, 1991). Within the 1.9μm band region, MODTRAN3 radiances are too high by 0 to 10%.

For measurements of solar illuminated optically opaque clouds, MODTRAN4 upgrades are more critical. In Figure 4, MODTRAN3 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 was 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 and 3.5 km altitude). Inaccurate fluxes result from the multiple scattering algorithms if the original coarse layering is used. Even with the fine layering, MODTRAN3 overpredicts MODTRAN4 by approximately 0 to 20% in the center and on the wings of the H_2O molecular bands. This example demonstrates the importance of using MODTRAN4 when analyzing AVIRIS measurements of solar scatter off clouds.

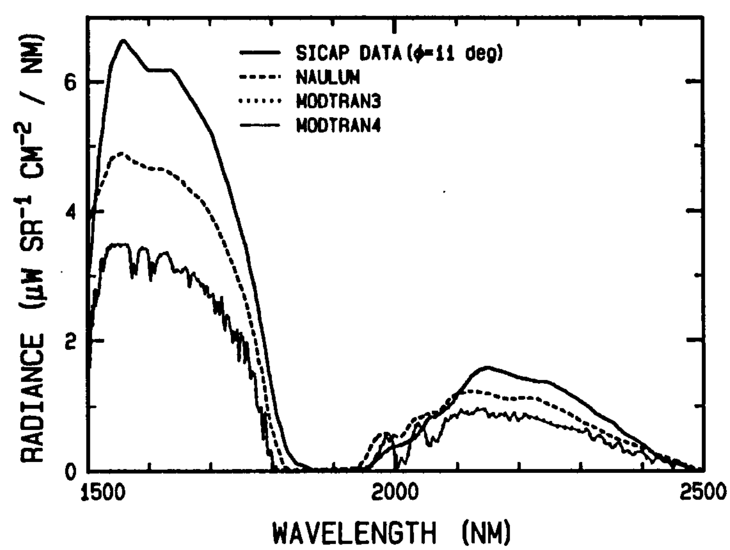

Figure 2. A Comparison Between SICAP Measurements (Malherbe et al., 1995) and Model Predictions for a Solar Illuminated Cumulus Cloud Top with a 11° Relative Solar Azimuth Angle.

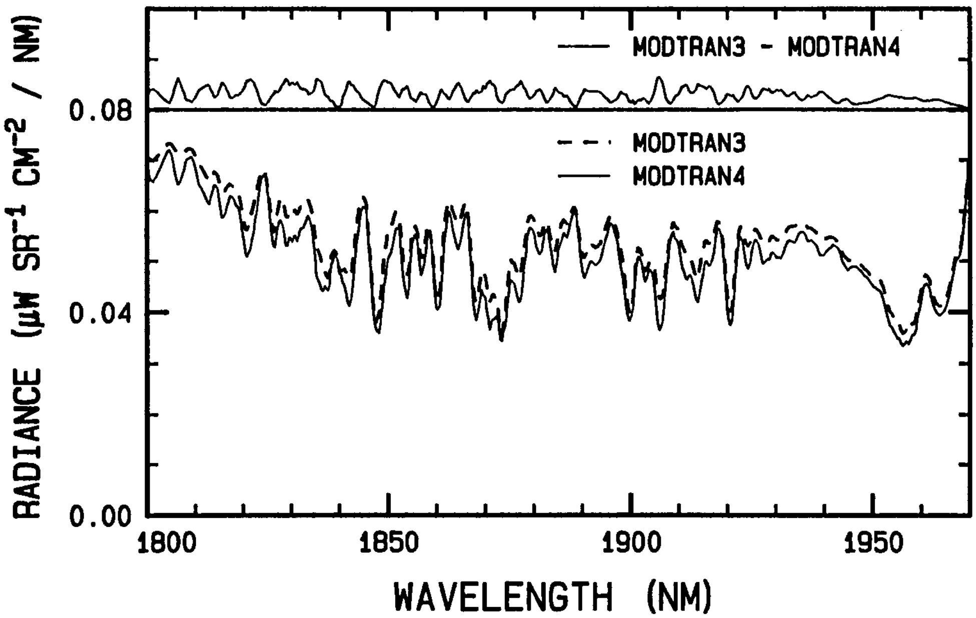

Figure 3. A Comparison Between MODTRAN3 and MODTRAN4 Radiances for Nadir Viewing of the Earth Through a Cirrus Cloud with a 75° Solar Zenith Angle. The differences Between MODTRAN3 and MODTRAN4 Are Offset by 0.08μW sr^{-1} cm^{-2} / nm.

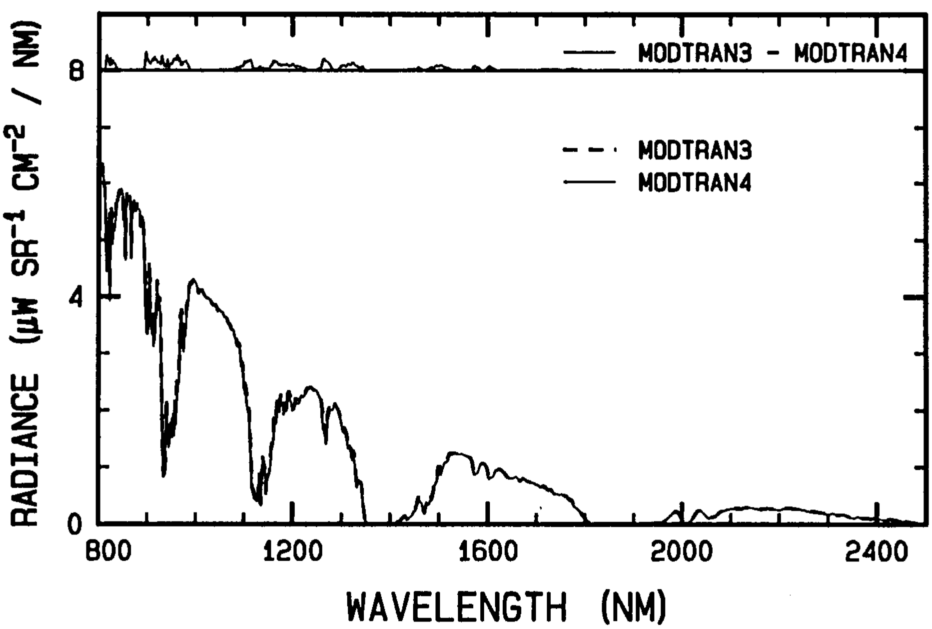

Figure 4. A Comparison Between MODTRAN3 and MODTRAN4 Radiances for Nadir Viewing of the MODTRAN Model Altostratus Cloud with a 75° Solar Zenith Angle. The differences Between MODTRAN3 and MODTRAN4 Are Offset by 8μW sr^{-1} cm^{-2} / nm.

6. SUMMARY

Major MODTRAN upgrades have been introduced which lead to significant improvements in the calculation of solar and thermal scattering from clouds and aerosols. The could/aerosol models now allow for generalized layering and specification of physical and optical properties. The new CK radiative transfer model leads to more accurate multiple scattering calculations, particularly in spectral regions containing strong molecular line absorption. It was shown that multiple scattering contributions can be important even for an optically thin solar illuminated cirrus cloud in the NIR-VIS spectral region; thus, these MODTRAN upgrades will lead to improved data analyses and atmospheric/surface property retrievals from down-looking sensors, such as AVIRIS, whose data are often "contaminated" by sub-visual clouds.

7. ACKNOWLEDGEMENTS

This work has been sponsored by the DOD/DOE/EPA interagency Strategic Environmental Research Program (SERDP) and funded through Air Force contracts F19628-93-C-0049 and F19628-91-C-0083 to Phillips Laboratory, Hanscom AFB, Bedford, Massachusetts. The authors express their appreciation to S. Miller (Geophysics Directorate, Phillips Laboratory) for technical and administrative oversight of this effort, to W. Cornette (Photon Research Associates) for insightful technical discussions, and to P. Simoneau (Office National d'Etudes et de Recherches Aerospatiales) for providing an advance copy of the Malherbe, et al., 1995 manuscript and for permission to include their measurements and calculations in this paper.

8. REFERENCES

Berk, A., 1995, "Upgrades to the MODTRAN Layer Cloud/Rain Models," Rpt. No. SSI-SR-56, Spectral Sciences, Inc., 99 S. Bedford St., Burlington, MA.

Berk, A., L. S. Bernstein, and D. C. Robertson, 1989, "MODTRAN: A Moderate Resolution Model for LOWTRAN7," Rep. GL-TR-89-0122, Air Force Geophys. Lab., Bedford, MA.

Bernstein, L. S., A. Berk, D. C. Robertson, P. K. Acharya, G. P. Anderson, and J. H. Chetwynd, 1996, "Addition of a Correlated-*k* Capability to MODTRAN," Proceeding of the 1996 IRIS Targets, Backgrounds, and Discrimination Mtg.

Clough, S. A., F. X. Kneizys, G. T. Anderson, E. P. Shettle, J. H. Chetwynd, L. W. Abreu, and L. A. Hall, 1988, "FASCODE3 Spectral Simulation" Proceedings of the International Radiation Symposium, Lenoble and Geleyn, Deepak Publishing.

Hansen, J. E. and J. B. Pollack, 1970, "Near-Infrared Light Scattering by Terrestrial Clouds," J. Atmos. Sci., *27*, 265 - 281.

Isaacs, R. G., W. C. Wang, R. D. Worsham, and S. Goldenberg, 1987, "Multiple Scattering LOWTRAN and FASCODE Models," Applied Optics, 26, 1272-1281.

Lacis, A. A., and V. Oinas, 1991, "A description of the Correlated K Distribution Method for Modeling Nongray Gaseous Absorption, Thermal Emission, and Multiple Scattering in Vertically in Homogeneous Atmospheres," J. Geophys. Res., 96, 9027 - 9063.

Malherbe, C., P. Simoneau, A. Boischot, G. Durand, J. Deschamps, and G. Gregoire, 1995, "Radiative Transfer Model in a Cloudy Atmosphere: A Comparison with Airborne Cumulus Measurement," Proceedings of the SPIE Conference on Passive IR Remote Sensing of Clouds and the Atmosphere III.

Mustard, J. F., 1991, "Distributions of Soil, Rock, and Grass in the Western Foothills of the Sierra Nevada," Proceedings of the Third Airborne Visible/Infrared Spectrometer (AVIRIS) Workshop, JPL Publication 91 - 28, 14 - 18.

Rothman, L. S. et al., 1992, "The HITRAN Molecular Database: Editions of 1991 and 1992," J. Quant. Spectrosc. Radiat. Transfer, 48, 469 - 507.

Stamnes, K., S. C. Tsay, W. J. Wiscombe, and K. Jayaweera, 1988, "Numerically Stable Algorithm for Discrete-Ordinate-Method Radiative Transfer in Multiple Scattering and Emitting Layered Media," Applied Optics, 27, 2502-2509.