MODTRAN4: Multiple Scattering and Bi-Directional Reflectance Distribution Function (BRDF) Upgrades to MODTRAN

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ABSTRACT

Radiance multiply scattered from clouds and thick aerosols is a significant component in the short wave IR through the visible region of the electro-optical (EO) spectrum. In MODTRAN, until very recently, multiple scattering predictions could not vary with the azimuth of the line-of-sight (LOS), although the single scattering component of the radiance did take the azimuthal variation into account. MODTRAN has now been upgraded to incorporate the dependence of multiple scattering (MS) on the azimuth of the LOS. This was accomplished by upgrading the interface between MODTRAN and DISORT, which is used as an MS subroutine in MODTRAN. Results from the upgraded MODTRAN are compared against measurements of radiance in a cloudy sky in the 1.5-2.5 μm region. Furthermore, taking advantage of DISORT, the upgraded version of MODTRAN can accommodate parameterized BRDFs (Bi-Directional Reflectance Distribution Functions) for surfaces. Some results, which demonstrate the new MODTRAN capabilities, are presented. Additionally, MS results from MODTRAN are compared to results obtained from a Monte-Carlo model.

Keywords: MODTRAN, DISORT, multiple scattering, azimuth-dependence, BRDF, Monte Carlo

1. INTRODUCTION

Measurements from nadir-viewing spectrometers provide information about the atmosphere and the surface of the earth, as well as data to validate atmospheric radiance codes such as MODTRAN (MODerate resolution atmospheric TRANsmittance and radiance code).[1-8] MODTRAN, a 2 cm^{-1} resolution band-model code, developed jointly by Spectral Sciences, Inc. and the Air Force Research Laboratory/Space Vehicles Directorate (AFRL/VS), has been widely used for the analysis of AVIRIS data,[9] and for other remote sensing applications due to its ability to model molecular and aerosol/cloud emission plus scattered radiance and atmospheric attenuation efficiently and accurately.

Descriptions, including recent enhancements, of MODTRAN can be found in recent papers and reports.[1-8] MODTRAN uses a spherically symmetric atmosphere, consisting of homogeneous layers, each of which is characterized by the layer boundary specification of temperature, pressure and atmospheric species concentrations; it uses Snell's law to refract a line-of-sight (LOS). To illustrate the accuracy of the band model transmittance approach, MODTRAN4 and FASCODE transmittances are compared at 5 cm^{-1} resolution (FWHM) between 1600 and 2500 nm in Figure 1. FASCODE[10] itself has been extensively validated directly against measurements and has an accuracy of better than 1% for atmospheric optical depth, based on a Voigt line shape. The comparisons are then based on conversion of these optical depths to transmittances, subsequently degraded to MODTRAN resolution. In regions of moderate transmittance, differences between FASCODE and MODTRAN

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predictions fluctuate about the zero line with maximum deviations of approximately 0.03. The radiance algorithms in MODTRAN employ a linear-in-tau approximation, common to other radiative transfer algorithms.[6,11,12]

Recently, several new scattering upgrades have been introduced into MODTRAN for more accurate radiances under cloudy and heavy aerosol loading conditions, and for modeling the bi-directional reflectance functions (BDRFs) of surfaces and adjacency contribution to pixel radiances. A recent paper[13] describes some of these upgrades, including those relating to specification of cloud profiles and spectral properties, and incorporation of a correlated-k (CK) algorithm which significantly improves the accuracy of fluxes, particularly for multiple scattering in spectral regions containing strong molecular line absorption.

This paper focuses on recent upgrades to MODTRAN in the computation of multiply scattered (MS) solar (or lunar) radiance; it touches upon the inclusion of BRDF.[14] The MS upgrade accounts for the dependence of the multiply scattered solar term on the LOS azimuth. Up to now MODTRAN could not model this component, although the azimuth-dependence of the single scattering (SS) was always included.

Under the reasonable assumption of randomly oriented scatterers, the only angle that affects scattering is the scattering angle. For the very first scattering event between a solar photon and the atmosphere, this angle is that between the LOS and the external source; i.e., the sun or the moon. This angle varies with the *relative* azimuth of the LOS and the external source. The SS component has a strong and direct relationship with this angle. The MS component, being the result of photons getting scattered several times, is less strongly dependent on the relative azimuth. Nevertheless, this dependence is highly discernible, particularly for aerosols where the scattering is mostly forward-peaked. The azimuth-dependence of MS is accommodated by more fully using the capabilities of the DISORT (DIScrete Ordinate Radiative Transfer)[15,16] code which was already a subroutine in MODTRAN. Some calculations demonstrating the new capabilities are presented, and calculations are compared to data and new Monte-Carlo simulations.

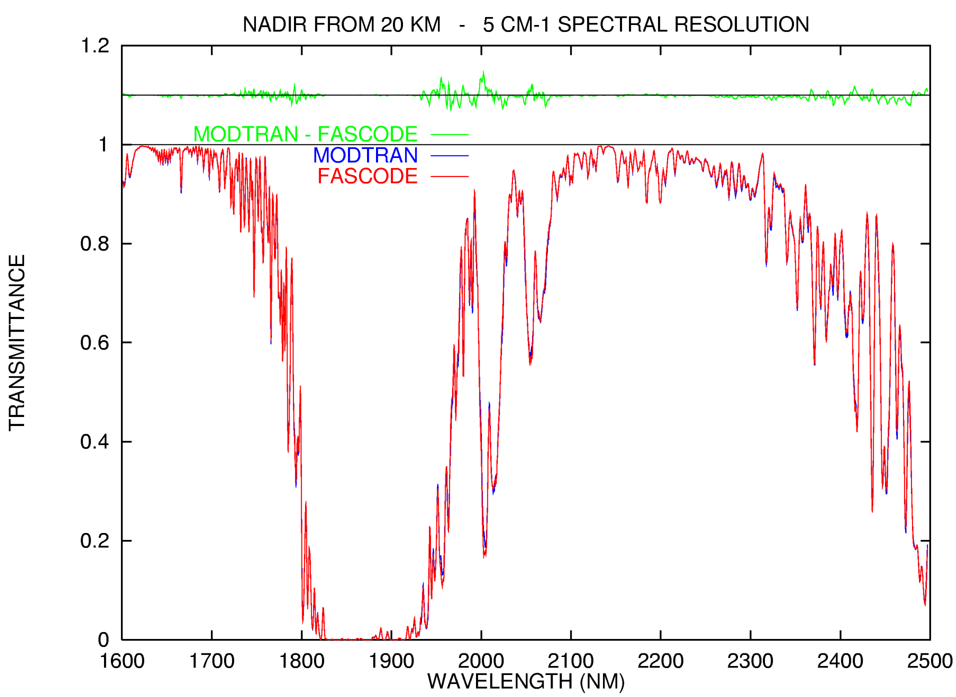

Figure 1. Comparison of MODTRAN4 to FASCODE 5 cm^{-1} Transmittances for a Nadir View through the U.S. Standard Atmosphere from 20 km Altitude. Differences between Model Predictions are Offset by 1.2.

2. ATMOSPHERIC SCATTERING OF THERMAL AND EXTERNAL SOURCE

Thermal emission aside, the major contribution to path radiance comes from scattering of radiation originating from other layers or external sources. Both thermal (skyshine and earthshine) and solar (or lunar) radiation are scattered by the earth's surface and by atmospheric particulates such as aerosols, water and ice cloud particles, and boundary layer fogs. Molecular or Rayleigh scattering is more important at shorter wavelengths (below 1 μm in the Near IR and UV/VIS) where the solar contribution dominates. MODTRAN models the SS solar radiation accounting for the top-of-the-atmosphere (TOA) solar spectrum,[17,18] the curvature of the earth, refractive geometry effects, and a general scattering phase function. MS, which is more difficult to treat accurately, is described with a plane-parallel atmosphere approximation and a Henyey-Greenstein phase function. The Henyey-Greenstein functions are acceptable for modeling fluxes, but less accurate for radiant intensities. MODTRAN provides two models for evaluating the scattered thermal and multiply scattered solar radiances: a simple but relatively faster 2-stream model[19,20] and a more accurate but slower DISORT N-stream method. Neither the Isaacs method nor the original DISORT-MODTRAN integration can account for the dependence of the MS solar contribution on the azimuth angle of the LOS. This paper describes the new DISORT-MODTRAN interface that successfully implements the azimuth-dependence of MS solar radiance.

3. THE NEW MODTRAN-DISORT INTERFACE

DISORT, in contrast to MODTRAN, uses a plane-parallel layered atmosphere without refraction. DISORT is mainly intended to be used as a subroutine which receives scattering and extinction optical depths, and phase functions for each layer as input from a driver program. The LOS and solar angles and the TOA solar irradiance are also required inputs. The usual outputs from DISORT are LOS radiances and fluxes at each layer boundary. If the TOA solar irradiance is set to zero, DISORT only performs a thermal calculation which consists of thermal emission plus thermal scattering terms. Similarly, DISORT is capable of performing a solar-only calculation by turning off the Planck function.

The total path radiance in MODTRAN is obtained by summing up the radiance contribution of each layer segment. The contribution of a segment bounded by layer boundaries *a* (nearer to the sensor) and *b* (farther from the sensor) is given by:

$$\Delta I = \int_{T_b}^{T_a} J\,dT = \bar{J}(T_a - T_b) = T_a \bar{J}(1 - T_L) = T_a \int_{T_L}^{1} J\,dT \qquad (1)$$

where T_a and T_b are transmittances from the observer to the layer boundaries along the LOS, T_L is the transmittance of the layer, and the integration is along the LOS. Here J is the total source term including the solar MS (J_{MS}) and thermal scattering components. The thermal component, unlike the solar component, is azimuth-independent. For notational simplicity, the explicit dependence of I, J and T on the bandwidth of the band model is omitted in Eq. (1). This equation is exact for monochromatic radiation which obeys Beer's Law ($T_b = T_a T_L$), and is the starting premise for band model formulations; in both cases, the problem is to determine the appropriate transmittances and sources. The factor T_a is the foreground transmittance from the observer to the front of the layer, and $\bar{J}(1-T_L)$ is the 'self-radiance' of the layer segment. Thus, the total path radiance (excluding surface terms) is simply the sum of the self-radiance of each layer segment weighted by the foreground radiance.

In addition to J_{MS}, the MS source term, and the thermal scatter source term, the total source, J, consists of two additional terms as shown below in the expression for self-radiance of layer L:

$$\int_{T_L}^{1} J\,dT = Thermal + Single\ Scatter\ Solar + Multiple\ Scatter\ Solar + Thermal\ Scatter \qquad (2)$$

$$Thermal = (1 - \omega_L) \int_{T_L}^{1} B(\Theta)\,dT \qquad (3)$$

$$Single\ Scatter\ Solar = \omega_L P(\theta) I_0 \int_{T_L}^{1} (T_0 / T)\, dT \tag{4}$$

Here ω_L is the layer single scattering albedo (ratio of the scattering optical depth to the total extinction optical depth); $B(\Theta)$ is the Planck function at the layer temperature, Θ; I_0 is the solar irradiance at the top of the atmosphere (TOA); $P(\theta)$ is the scattering phase function, dependent on the scattering angle, θ; T_0 is the transmittance from the sun/moon via the scattering point (on the LOS) to layer *a* along the LOS; and finally, T is transmittance from the scattering point to layer *a* along the LOS. For Beer's Law transmittances, T_0/T is simply the transmittance to the sun. Since the scattering point moves along LOS, T_0 varies along the LOS; therefore, T_0 cannot be taken outside the integral. θ is a virtual constant along the LOS. The variation in $P(\theta)$ is not due to change in the scattering angle; instead, $P(\theta)$ varies from layer to layer due to changes in the atmosphere's constitution.

The original DISORT-MODTRAN interface[16] provided MS solar and thermal source terms, both of which were independent of the solar azimuth angle. This interface was fast, but it did not take advantage of DISORT's full capability to compute azimuth-dependent LOS intensity. This capability is used in the new interface to compute an azimuth-dependent J_{MS}. The azimuth-symmetric scattered thermal source function is still computed using the original interface, by setting the solar irradiance to zero.

Therefore, there are now twice as many calls to DISORT for each frequency interval. (If C-K is used, DISORT is called twice for each k within the frequency loop). The first call is computationally fast, uses the original interface and initiates the thermal multiple scattering source term. The second call uses the new interface for computing the azimuth-dependent solar MS scattering term; it takes longer CPU time because it uses the full capability of DISORT.

To understand how J_{MS} is backed out from DISORT, it is necessary to compute the self-radiance term of a layer using the output of DISORT. The quantity returned from DISORT is $u(\tau_L)$ (u_L, for brevity), where τ_L is the accumulated nadir optical depth at the layer boundary *L* (0 being the TOA), and u_L is the radiance as seen by a sensor located at the layer boundary, *L*, and staring at either the space (for an up-looking path) or the ground (for a down-looking path), in the direction of the LOS. Given u_L, the self-radiance of a layer is given by

$$\int_{T_L}^{1} J\, dT = u_{Front} - u_{Back} T_L \tag{5}$$

Here *Front* and *Back* refer to front and back layer boundaries of the layer (from the view-point of the sensor). Previous formulas for thermal emission and single scattering terms are used to isolate the MS solar plus thermal scattering contributions. The total scattering source is then obtained by division by $(1-T_L)$. Finally, J_{MS} is obtained by subtracting out the thermal scattered source term (from the previous call to the original DISORT interface).

Once the source terms are obtained from DISORT, using its plane parallel atmosphere and lack of refraction, they are used by MODTRAN to compute layer radiances using MODTRAN's spherical atmosphere and radiative transport, which does take the refraction of the LOS into account.

4. CAVEATS AND REFINEMENTS

The new interface takes 6-10 times longer for typical 8 and 16-stream calculations if it is used in single precision. Double precision increases CPU time by an additional 20-40%. However, a recent refinement that reduces the number of atmospheric layers makes it unnecessary to use double precision. The relayering scheme, which is automatically performed, also eliminates numerical problems associated with subtraction of small numbers of comparable value. At each frequency, optically thin layers are combined beginning from the TOA; thus the relayering scheme is different for each frequency. On average, the number of layers is reduced by half. To speed up the new interface further, several other options are under consideration. First, one could use DISORT only up to a certain height in the atmosphere, since MS is negligible above, say, 15 km. Exceptions might include high cirrus, polar stratospheric clouds, and volcanic aerosol intrusions. Second, since the solar MS contribution beyond wavelengths greater than 5 μm is negligible, one could avoid calling DISORT to obtain the solar contribution to MS. Similarly, the thermal scattering can be ignored for wavelengths shorter than 2 μm.

If speed is a problem, the user has the option of choosing the earlier azimuth-independent MODTRAN-DISORT option which has been retained.

MODTRAN, being a single LOS code, is not designed to benefit from DISORT's inherent advantage, namely, its ability to compute radiances of several LOSs that have the same zenith angle but varying azimuth angles with little additional time than it would take for a single LOS. DISORT has some restrictions on the zenith angle of the LOS and the sun. The LOS cannot point directly at the sun; also, if the sun is below the horizon no solar twilight contributions are calculated; and finally, the solar and viewing angles cannot equal one of the quadrature angles used for integrating fluxes. The last problem is likely to occur when DISORT is used with 2-streams when the quadrature angle is 60 degrees. If this problem occurs, an easy solution is to change the number of streams.

5. BRDF IMPLEMENTATION

Until recently, MODTRAN only allowed a lambertian surface, a surface with angularly uniform reflectance, ρ. MODTRAN now has several parameterized BRDF representations.[14] For many purposes it is necessary to accommodate angularly varying bi-directional reflectance distribution functions (BRDFs). In principle, the reflectance can be a function of four angles – the zenith and azimuth angles, (θ_s, φ_s), of the incident (solar) beam and the corresponding angles, (θ_v, φ_v), from the viewer or sensor direction. For many situations encountered in practice, radiance is not altered if the surface is rotated around the surface normal; therefore, BRDFs of such surfaces depend on the relative azimuth, (φ_v-φ_s), only, not on φ_s and φ_v separately. This is not true of non-homogenous surfaces with striations or manmade landscapes such as farms with rows of corn plants. Currently, only the BRDFs which depend on the relative azimuths of the external beam and the viewer are accommodated.

The BRDFs can be used as lower boundary conditions for DISORT, which entails computation of the azimuth moments of the BRDF and its directional reflectance integrals. The full implementation of BRDFs into MODTRAN is in a 'research version' of the code. The officially released version does not use BRDFs for DISORT MS calculations; however, in this release of MODTRAN, BRDFs are used for all other non-MS purposes such as the calculation of directly reflected solar radiance. The BRDF implementation is available with the Isaacs 2-stream model for solar scattering.

6. VALIDATION OF DISORT USING TYPICAL MODTRAN INPUTS

Our initial validation tests DISORT's performance against a Direct Simulation Monte Carlo (DSMC)[21] code using typical MODTRAN inputs. Figure 2 compares DISORT and DSMC MS-only calculations for a nadir view (where azimuth angles are irrelevant). Apparent reflectance (which is essentially radiance normalized by solar irradiance) for two different surface reflectances (the surface with zero reflectance does not scatter any radiation off the ground) are plotted as a function of the 550 nm vertical optical depth. The calculations were done using a plane parallel mid-latitude summer (MLS) atmosphere of 500 layers with a solar zenith angle of 20^o. Since the new DISORT-MODTRAN interface is intended for retrieving a MS solar source function, only the MS apparent reflectance is shown in the figure. The asymmetry factor chosen for the aerosol was 0.7, which is typical of rural aerosols; the asymmetry factor for Rayleigh scattering is 0. The apparent reflectance increases with increased optical depth because the number of scatterers increases. Clearly, for these typical MODTRAN inputs, the agreement between DISORT and DSMC is excellent. Since DISORT and DSMC are two completely different approaches to the same problem (with identical inputs), this figure serves to cross-validate DISORT and the DSMC method, ultimately leading to further confidence in MODTRAN scene simulations.

7. 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,[22] and predictions from MODTRAN with the original and the new DISORT interface. The measurements were performed by the ONERA and CELAR research agencies (France) from an aircraft using the SICAP circular variable filter cryogenic spectrometer (2% resolution).

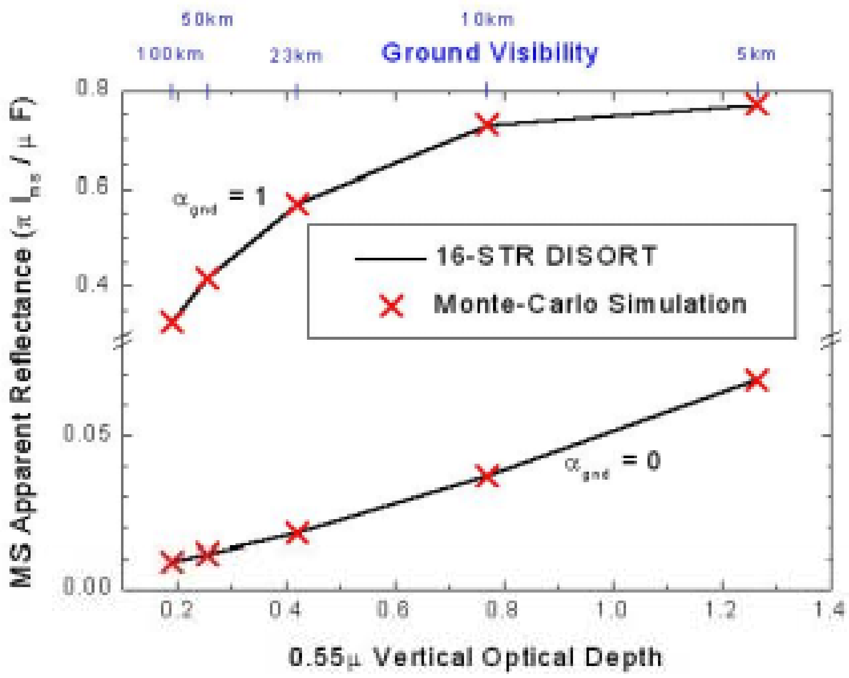

Figure 2. Validation of DISORT using MODTRAN Inputs; 20 km Nadir View, 20^o Solar Zenith.

Two typical measurement spectra are shown in Figure 3. The aircraft is at 3 km altitude, the cloud top altitude is 2.5 km and the solar zenith is 48^o. For the lower measurement, the sensor LOS zenith angle is 104^o, and the relative azimuth angle is 137^o. 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^3 from 0.1 to 2.5 km altitude. Water droplet single scattering albedos[23] for a mean spherical particle radius of 8µm were entered at a 0.05µm spectral resolution. Original DISORT-MODTRAN results (4-stream) at 10 cm^{-1} spectral resolution (0.2% at 2000 nm) are shown and are in good agreement with the data, although the data appear to be offset by 10 to 20 nm. Similar results are obtained using the newer DISORT-MODTRAN interface.

Figure 3 also shows an additional SICAP data-model comparison (the upper measurement curve) but with an LOS zenith angle of 95^o and, more importantly, a solar relative azimuth angle of 11^o. In this forward scattering case, the older DISORT-MODTRAN interface under-predicts the measurements by about a factor of two because the MS model averages over the azimuthal dependence. The older interface 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 newer DISORT-MODTRAN interface result is also shown; it is a considerable improvement because it models the azimuthal distribution of radiation in its MS source function. As is intuitive, the two azimuthally-symmetric calculations are ‘sandwiched’ by the two azimuth-dependent calculations. This is because the two viewing geometries are, roughly speaking, forward-viewing (11^o-azimuth) and backward-viewing (137^o-azimuth) scenarios. Note that for nadir-viewing geometries, such as AVIRIS,[13] solar azimuth geometry effects are minimized**.**

8. FURTHER VALIDATION OF DISORT AZIMUTH-DEPENDENCE

In Figure 4, the MODTRAN MS azimuth dependence is validated against DSMC. Solar calculations were performed at 550 nm for a 40^o sun viewed in the principle plane (sun, surface pixel and sensor all coplanar; that is, the relative azimuths are either 0^o (forward viewing), where the sun is in the front of the sensor, or 180^o (backward viewing), where the sun is directly behind the sensor). Without azimuth dependence, the MS radiance in the forward and backward directions are identical (the symmetrical curve). Radiance increases with increasing nadir angle because the column amount and, therefore, the number of scatterers is increasing. When the azimuth dependent DISORT calculations are performed, the multiple scattering radiance is greatest in the forward direction, as one expects due to the aerosol scattering. The results are in full agreement with the DSMC calculations.

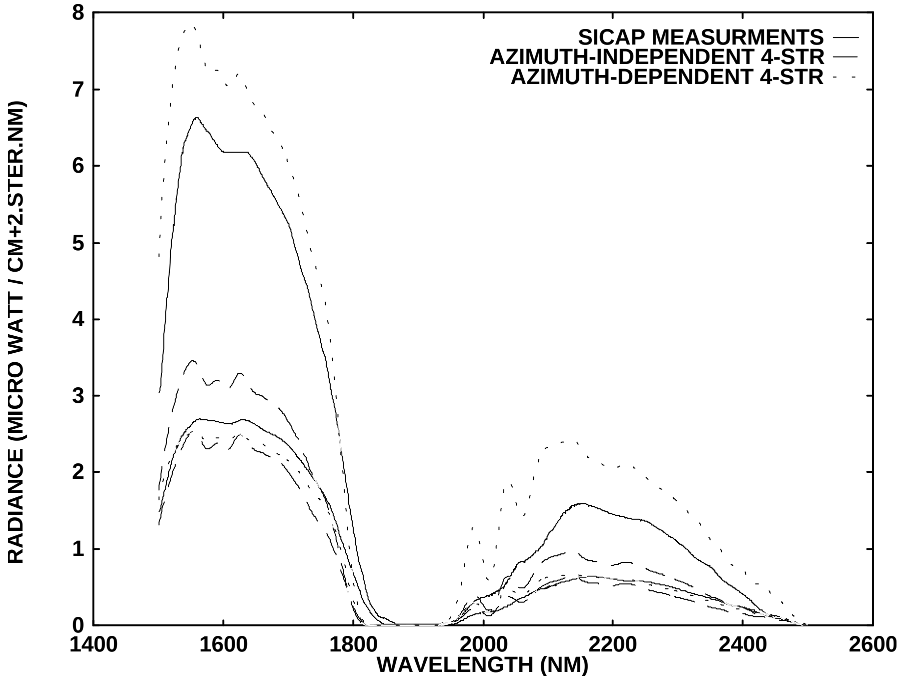

Figure 3. A Comparison Between SICAP Measurements and Model Predictions for a Solar Illuminated Cumulus Cloud Top with 11° and 137° Relative Solar Azimuth and 95° and 104° LOS Zenith Angles.

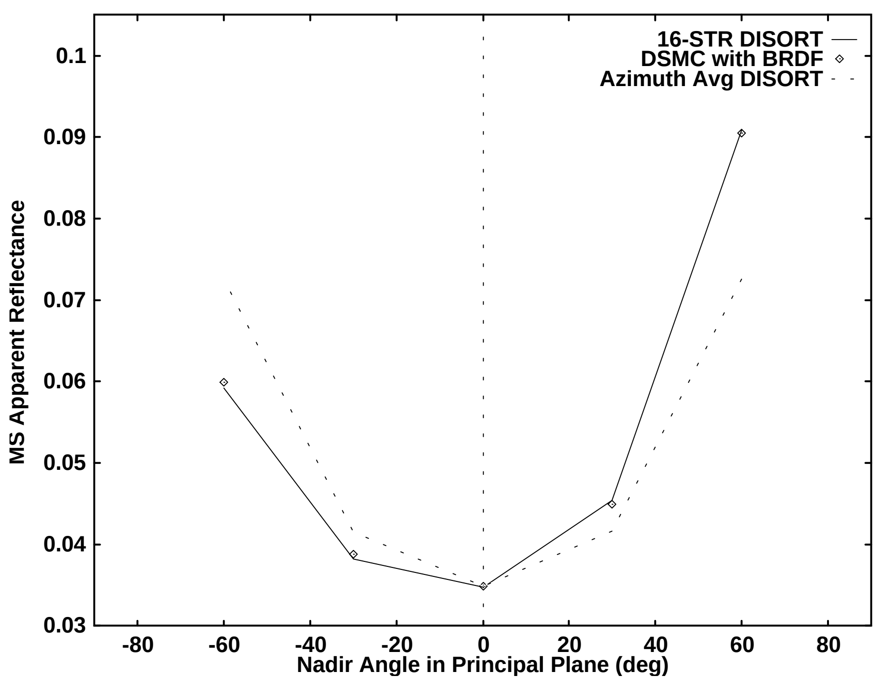

Figure 4. Validation of DISORT Azimuth-Dependence Using DSMC Calculations. 20 km Sensor Altitude, 23 km Visibility with 40° Solar Zenith.

9. SUMMARY

Several upgrades to MODTRAN have been developed which lead to improvements in the calculation of radiation scattering from clouds, aerosols, and surfaces. The multiple scattering calculation is now dependent on the relative solar-azimuth as is more physically correct. A relayering scheme allows DISORT to be used in single precision in MODTRAN. Several BRDFs are included in the latest version of MODTRAN for improving contribution of specified object surfaces to path radiance. Several results are presented which validate DISORT against data and Monte Carlo simulations.

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