SINGLE AND MULTIPLE SCATTERED
SOLAR RADIATION

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1. INTRODUCTION

For the past ten to fifteen years the Air Force Geophysics Laboratory (AFGL), Optical Physics Division has been developing the expertise to calculate radiative transfer (direct point-to-point transmittance and radiance) in the earth's atmosphere. At the focus of this research are two computer codes called LOWTRAN [Ref. 1] and FASCODE [Ref. 2,3,4]. LOWTRAN is a low spectral resolution code (typical resolution is 20 wavenumbers) that uses spectrally averaged and empirically derived direct transmittance functions for spherically symmetric and refractive model atmospheres that include aerosols. FASCODE uses the same spherical geometry and atmospheric models found in LOWTRAN, but retains the spectral resolution inherent in molecular and atomic line models. The developments described in this report concern solar/lunar scattering phenomena in the atmosphere and how such processes can be included in these two codes (mainly LOWTRAN in this study) which are under continual development at AFGL.

Mie calculations have been performed at AFGL for some time to obtain scattering and absorption coefficients for the various atmospheric aerosol models that have been developed. When scattering phenomena beyond zeroth order (attenuation only) are to be considered, the phase function must also be obtained from Mie calculations. Section 2 describes the complete Mie calculations which were done for all of the atmospheric aerosol models comprising the model atmospheres of LOWTRAN. The Mie code and aerosol models are described only briefly since they were developed by others and are well documented in the literature. The computed scattering data are parametrically defined and all unconventional approximations and assumptions are discussed. The format of the available data is described so that the
reader can more readily obtain access to it through AFGL.

Since LOWTRAN uses spherical geometry and spectrally averaged direct radiative transmission functions which do not obey Beer's law, there is no established method to compatibly calculate multiply scattered radiative fields due to solar/lunar illumination. As a first step toward including scattering in LOWTRAN, Section 3 develops a single-scattering calculation procedure compatible with LOWTRAN and describes its integration with a recent version of the LOWTRAN code, the result being designated LOWTRANSX. Example calculations made with the newly developed code are presented and the parametric range of all calculations performed to date is discussed. An independent verification of the code is also presented along with a discussion of the effects of spherical geometry and refraction on the single-scattering results.

Section 4 begins an analysis of multiple scattering in an atmosphere of unidirectional illumination from an external source like the sun. As an initial step along the difficult path to calculate multiple scattering in spherical atmospheres, an Adding/Doubling (A/D) computer code [Ref. 5,6,7] for plane-parallel media is modified to model radiation from external sources (the code was originally developed for infrared isotropic internal sources). A Fast Fourier Transform of the azimuth dependence of the phase function is taken and each Fourier component is used in a separate A/D run. The results are then inverse transformed to obtain intensity fields throughout the plane-parallel medium. The codes that perform these operations are described and the results are checked against other independent results for certain special values of the parameters (optical depth, albedo, and angular variables). A parallel but independent single-scattering code is developed, partly to check the A/D code in the limit of sufficiently small single
scattering albedoes. Appropriate intercomparisons are made between the A/D, LOWTRANSX, and plane-parallel single-scattering predictions to show their commonality and differences. The effects of spherical geometry, refraction, and multiple scattering are quantified within the context of the present codes. The A/D code is also used to study how spectral redundancy in realistic, inhomogeneous atmospheres may be used to reduce computational times for high resolution multiple scattering calculations.

Several appendices are used to present details of the codes and special mathematical developments that will be of interest only to the reader who must use the codes or their derivatives developed subsequently by AFGL.
2. AEROSOL PHASE FUNCTIONS

The model atmospheres contained in LOWTRAN 5 [Ref. 1] include a number of aerosol models for which Mie computations have been made to produce normalized aerosol scattering and absorption coefficients. When scattering (beyond zeroth order) is considered in the radiative transfer, the phase function must also be known. This chapter describes the complete Mie calculations carried out for all the aerosol models contained in LOWTRAN 5. Section 2.1 briefly delineates the aerosol models while Section 2.2 discusses the Mie code used, along with any pertinent assumptions. Appendix A describes a short code that will access the resulting data, and Section 2.3 discusses AFGL's plan to prepare a single, comprehensive aerosol-model report to guide the reader who may want to use the data. Details of how these Mie data were used in LOWTRAN can be found in Appendix C.

2.1 Aerosol Models

Molecular or Rayleigh scattering is well understood and accurately modeled by a simple empirical expression [Ref. 8]. Aerosol scattering properties, on the other hand, must be obtained numerically and models must be constructed that attempt to duplicate those found in the atmosphere. The aerosol models used here are identical to those described in LOWTRAN 5 [Ref. 1], which are revisions of those found in earlier versions of LOWTRAN [Refs. 9, 10]. Further details of their development can be found in References 11 and 12. Only a brief summary of these aerosol models will be given here to orient the reader.

The atmosphere is divided into four regions that contain distinct aerosol models as follows:

1) 0-2Km, Boundary or Mixing Layer; within this layer there are four
basic models, namely rural, urban, maritime, and tropospheric, each having properties specified at four different relative humidities. Two additional models represent light and heavy fog conditions which brings the total number of boundary layer aerosol models to eighteen.

2) 2-10 Km, Upper Tropospheric Layer; The model used in this region is identical to the boundary layer tropospheric model with 70% relative humidity.

3) 10-30 Km, Lower Stratospheric Layer; This region contains three models called background stratospheric, aged volcanic, and fresh volcanic.

4) 30-100 Km, Upper Atmospheric Layer; One meteoric dust model is used throughout this region.

There are, therefore, a total of 22 aerosol models. Each model is defined by a unique size distribution and composition. All models assume that the aerosols are spherical and homogeneous. The humidity dependent models, however, are actually two-component aerosols (a particulate surrounded by water) but are treated as a single substance using a method discussed below. Within each of the four altitude regions discussed above the model parameters are constant except for an altitude dependent loading or effective density, which does not affect the Mie calculations. The complex refractive index for each model has been tabulated [Ref. 11 and 12] for forty spectral points over the range from 0.2 to 40 μm.

2.3 Mie Calculations

The Mie [Ref. 13] code used here and called Mie 2 [Ref. 14] was developed specifically for use on the AFGL CDC-6600 computer system. It has
been modified to allow direct input of the desired scattering angle grid and to provide output in a form suitable for use in the LOWTRANSX code [see Section 3]. This Mie code handles only homogeneous aerosols but offers advantages of multiple run capability and improved computational time.

For aerosols containing water, an effective refraction index is formed by taking a volume weighted average of the refraction index of the substance and that for water [Ref. 11]. In addition, the rural and urban models each contain two distinct size distributions that lead to slightly different indices of refraction. These are sufficiently similar such that a simple numerical average is taken of the indices. The maritime model, on the other hand, has two distinct size distributions which are run through the Mie code separately. A combined phase function is then formed for the maritime model by forming a scattering-coefficient weighted average on these two phase functions. All the other aerosol models are homogeneous with a given size distribution.

The Mie code could be run at each of the forty spectral points with a fine scattering-angle grid for each of the twenty-two models. The data base would then be very large and the computational time excessive. Considerable discussion with the staff at AFGH led to the following spectral points (27) and scattering-angle grid (34) that is a compromise between accuracy and practicality.

a) Spectral points (μm): 0.2, 0.3, 0.55, 0.6943, 1.06, 1.536, 2.0, 2.5, 2.7, 3.0, 3.2, 3.3923, 3.5, 3.6, 4.0, 4.6, 4.7, 4.8, 5.0, 6.0, 7.2, 7.9, 8.7, 9.2, 10.6, 10.591, 12.5, 15.0, 17.2, 18.5, 21.3, 30.0, 40.0.

b) Scattering-angle Grid (degrees): 0° → 12° (increments of 2°), 12° → 40° (increments of 4°), 40° → 120° (increments of 10°), 120° → 180° (increments of 5°).
The data resulting from the 594 (22 models times 27 spectral points) Mie runs are quite extensive and was, therefore, divided into two parts. A truncated version of the output containing only the normalized phase function \( \int P(0) \, d\Omega = 1 \) at the 34 scattering angles was generated for direct use with LOWTRANSX (see Section 3). The full output file containing the wavelength, complex index of refraction, extinction and scattering coefficients, normalized phase matrix, and cosines for equal probability intervals was written in binary form to a disk file. A small separate program found in Appendix A is required to retrieve this data. A word of caution is necessary. Some of the early runs of the Mie code produced incorrect results for some of the data as a result of underdimensioned arrays. Fortunately the phase matrix was calculated correctly and this is what these calculations were for. The other quantities such as attenuation coefficients, albedos, and asymmetry parameters have been found previously. Because of computational costs, these calculations were not repeated. A full discussion of this problem is given in Appendix A.

2.3 Concluding Remarks

In an effort to reduce the size of the phase function data base, researchers at AFGL have recently performed a statistical analysis of the phase function data. While the details of this study have not yet been made public, early reports indicate that the number of aerosol-spectral models has been reduced from 594 to about 70. AFGL has also recognized the need for a single comprehensive reference describing all aspects of the aerosol models. Such a future report should contain refractive indices, attenuation coefficients, albedos, and asymmetry parameters as a function of wavelength, along with size distributions and normalized phase functions for each of the aerosol models.
3. LOWTRAN SINGLE SCATTERING MODEL

This section of the report develops a solar/lunar single scattering model based on LOWTRAN radiative transfer and outlines the new (LOWTRANSX) code structure. Subsection 3.2 presents the geometric perspective required to connect observer and illumination source locations to reference space and time coordinates on the earth. The code structure and users guide for LOWTRANSX are given in Appendices B and C, respectively, while Subsection 3.3 discusses an example calculation and independent verifications that the code functions properly. Finally, Subsection 3.4 contains concluding remarks and Appendix D contains a note on finding the subsolar point.

3.1 Radiative Transfer

The LOWTRAN code has been constructed to calculate point-to-point transmittance and observed thermal radiance along a line-of-sight in model spherical atmospheres made up of homogeneous layers. Refractive bending is computed and aerosol attenuation (zeroth order scattering and absorption) is included. Radiative transfer is calculated by way of spectrally averaged transmittance functions (resolution of about 20 wavenumbers) that are derived from experimental data and theoretical relationships. This code is extended here to include the source function due to single scattering within the atmosphere of the extraterrestrial sources, sun or moon. At the present time, reflection (scattering) off the earth's surface or other objects within the atmosphere is not considered. The observed scattering radiance is obtained by summing the properly attenuated scattering source function along any specified line-of-sight.
Before proceeding further, it will be helpful to introduce the following nomenclature:

**SUPERSSCRIPTS:**
- A: aerosol
- M: molecular

**SUBSCRIPTS:**
- e: extinction
- a: absorption
- s: scattering
- PS: primary solar path (sun to scattering point)
- OP: line-of-sight optical path (scattering point to observer)

**OTHER QUANTITIES:**
- $K$: monochromatic volumetric extinction, absorption, or scattering coefficient
- $T = e^{-KL}$: monochromatic transmittance over a homogeneous path length $L$, due to extinction absorption, or scattering
- $P(\gamma)$: scattering phase function of included angle $\gamma$
- $I_{\text{SUN}}$: solar extraterrestrial intensity

Note that the dependence of most quantities on the spectral frequency $\nu$ will be shown by a subscript $\nu$, although it will sometimes be suppressed for simplicity of notation when the concept is clear from context.

The monochromatic intensity (radiance) seen by an observer looking along a particular directional path is the sum of contributions from all sources lying along the line-of-sight. The sources are either primary sources
(infrared emission) or scattering sources. The scattering source function \( J \) for scattering points along the observer's line-of-sight can be expressed in terms of the local incoming intensity at each point \( I_{\nu}(\hat{n}') \) by

\[
J_{\nu}(\hat{n}) = \int I_{\nu}(\hat{n}') \left[ P_{\nu}^{A} K_{s}^{A} + P_{\nu}^{M} K_{s}^{M} \right] d\Omega'
\]

where \( \hat{n} \) is the unit vector directed toward the observer and \( \hat{n}' \) is to be summed over the solid angle denoted by \( \Omega' \). With only solar/lunar scattering included, the incident intensity \( I_{\nu}(\hat{n}') \) is given by

\[
I_{\nu}(\hat{n}') = I_{\nu}^{\text{SUN}} T_{e,ps} \delta(\hat{n}', \hat{n}_{s}')
\]

where \( \hat{n}_{s}' \) is the direction of the incident solar/lunar radiation at the scattering point. A schematic of the scattering geometry for a particular sun/observer orientation is displayed in Figure 3.1. The path that the sunlight/moonlight takes in passing through the atmosphere prior to being scattered at any scattering point \( P \) will be called the 'primary solar' path.

Other sources besides direct extraterrestrial illumination could of course contribute to the prescattered intensity \( I_{\nu}(\hat{n}') \). One might include other direct sources such as gaseous emission and boundary surface radiation plus previously scattered radiation, but only unscattered sunlight/moonlight is included in the present scattering source function. The resulting source function is found by using [3.2] in [3.1] to obtain

\[
J_{\nu} = I_{\nu}^{\text{SUN}} T_{e,ps} \left[ (P_{\nu}^{A}(\gamma) K_{s}^{A} + P_{\nu}^{M}(\gamma) K_{s}^{M}) \right].
\]
Figure 3.1 Schematic representation of the single scattering geometry.
A scattering point at $H1'$ is shown for an observer looking up from altitude $H1$. Both the optical paths and layer boundaries, which are shown to be straight lines, are slightly curved.
Note that \( P^A, P^M, K^M_s, \) and \( K^M_s \) vary with altitude (atmospheric density and composition) and are generally slowly varying functions of frequency. Note also that the included angle \( \gamma = \arccos (\hat{n} \cdot \hat{n}') \) would be constant (independent of the particular scattering point) along a line-of-sight in the absence of refractive bending. Both the primary solar path and the line-of-sight optical path actually bend somewhat, so that \( \gamma \) can be expected to vary by as much as a few degrees along the line-of-sight. The primary solar transmittance \( T_{e,ps}^{A+M} \) depends strongly on the optical path length of the primary solar path (prior to scattering), so that factor can be expected to vary considerably from one scattering point to the next.

The monochromatic intensity at the observer due to all of the single scattering sources within the line-of-sight is obtained by summing over the optical path the product of the source function and the transmission function which gives

\[
I^\text{SCAT}_\nu = \int J^\nu T_{e,op}^{A+M} \, dL_{op}
\]

\[
= I^\text{SUN}_\nu \int T_{e,ps}^{A+M} T_{e,op}^{A+M} (P^A K^A_s + P^M K^M_s) \, dL_{op} \quad (3.4)
\]

The scattering optical depth increment \( K_s \, dl_{op} \) can be expressed in terms of the incremental transmittance for both aerosol and molecular scattering as

\[
K_s^X \, dl_{op} = \frac{dT^X_{s,op}}{T^X_{s,op}} \quad (3.5)
\]

with \( X \) being either \( A \) or \( M \). The intensity can therefore be written as
which includes two separate integrals covering aerosol and molecular scattering effects. The above equation which provides for a monochromatic calculation at any frequency $\nu$ is now adapted for use with the molecular band transmission model used in LOWTRAN. The spectrally averaged intensity $I$ is formally defined in terms of a convolution of the spectral intensity with a triangular spectral shape function $g(\nu)$ taken over a spectral width of approximately $\delta\nu = 20 \text{ cm}^{-1}$, that is,

$$I_\nu = \frac{1}{\delta\nu} \int I_{\nu', g(\nu-\nu')} \, d\nu'. \quad (3.7)$$

The spectrally averaged, scattered intensity can be expressed in terms of known LOWTRAN quantities provided that only the molecular absorption transmittance is a rapidly varying function of frequency. All other quantities are assumed to be constant over the spectral interval $\delta\nu$. The result is

$$\tilde{I}_\nu^{\text{SCAT}} = \tilde{I}_\nu^{\text{SUN}} \int \tilde{T}_{e, ps + op} \left[ p_A \frac{dT_A}{T_{s, op}} + p_M \frac{dT_M}{T_{s, op}} \right]. \quad (3.8)$$

The quantity $\tilde{T}_{e, ps + op}^{A+M}$ represents the spectrally averaged transmittance that is calculated in LOWTRAN. Therefore, the molecular band models and aerosol models of LOWTRAN provide a direct means of calculating the path transmittance required for each of the scattering points. In order to maintain compatibility
with the spherical shell atmosphere of LOWTRAN, the integral over the path of scattering sources is replaced by a layer-by-layer sum along the line-of-sight. For an optical path traversing \( N \) layers in an upward or downward direction this process gives

\[
\int \frac{I_{\text{SCAT}}}{I_{\text{V}}} = \sum_{j=1}^{N} \left[ \frac{T_{\text{A}}^{A+M}}{T_{\text{A}}^{A, \text{op}}} \right] \Delta T_{\text{s}, \text{op}, j} + \left[ \frac{T_{\text{M}}^{A+M}}{T_{\text{M}}^{A, \text{op}}} \right] \Delta T_{\text{s}, \text{op}, j} \right].
\]

(3.9)

The quantity \( \Delta T_{j} \) is the change in molecular or aerosol scattering transmittance in passing through layer \( j \) and \( \langle \rangle_{j} \) denotes an average value for that layer. The terms \( \Delta T_{j} \), \( T_{\text{ps}+\text{op}} \), and \( T_{\text{op}}^{x} \) are quantities available within LOWTRAN.

The layer-by-layer sum for the singly scattered solar or lunar intensity is computed simultaneously with the existing direct thermal radiance. The sum is evaluated starting with the point of lowest altitude along the line-of-sight and proceeding up through successive layers. Long paths which pass through a tangent or minimum height are handled with a special set of transmittances in the same way, again following the radiance calculation already in LOWTRAN. Equivalent absorber amounts are computed separately for the two path legs (primary solar and line-of-sight) corresponding to each scattering point by a modified geometry program which is described in the next section.

3.2 Single Scattering Geometry

The existing LOWTRAN geometry tracks a single optical line-of-sight from...
an observer at altitude $H_1$ to the path endpoint at $H_2$, which can be above or below the observer. The path can be a short path directed up or down or a long slant path which passes through a minimum altitude point $H_{MIN}$, lower than both $H_1$ and $H_2$. The optical path will generally be curved by refractive bending since the atmospheric index of refraction has a finite vertical gradient. Although curved, the optical path remains in the fixed vertical plane containing the two path endpoints and passing through the earth's center. The refracted optical path can be described in a spherical coordinate system in terms of two path variables, usually the altitude and local zenith angle. The azimuthal orientation of this vertical plane, which contains the line-of-sight, must be separately specified or found in each case.

The new single-scattering geometry involves tracking two optical paths for each scattering source point. One path leg leads from the observer at $H_i$ to a scattering point at $H_i'$ along the line-of-sight. The other leg is traced from the scattering point toward the sun/moon and ends in space at $H_2'$ (presently taken to be 100 km). Note that each scattering source point defines two path legs and, therefore, two vertical planes, like the one described above (the new one contains the scattering point and the point where the sun's rays enter the atmosphere). With rather minor modifications to the existing geometry algorithm, LOWTRANSX tracks the altitude and zenith angle of both path legs for each scattering point. In addition, the path equivalent absorber amounts needed for transmittance, thermal radiance, and scattered radiance calculations are simultaneously summed by the same routines.

Aside from the in-plane tracking of each path leg, it is necessary to determine the angle of intersection of the two vertical planes, which is also the azimuthal angle separating the projections of the two path legs onto
the earth's surface. The projection of a path segment onto the earth forms part of a great circle on the earth, since a vertical plane always includes the earth center. The projected path segments for a typical geometrical configuration are shown in Figure 3.2 from a perspective above the earth's surface looking down. The relative azimuth angle $\psi_r$ between the projected path legs at the projected scattering point is calculated in LOWTRANSX by a new set of geometry subroutines. The method of calculation involves first computing the absolute azimuth angle for the observer-to-subsolr-point projection OS. The absolute line-of-sight azimuth $\psi_a, op$ is required as an input to the code, where absolute azimuth angles are measured from the local east direction with positive angles indicating north-of-east in this discussion. The user should note that azimuths in the code input card deck are specified in the clockwise sense from north, that is, positive east-of-north. A conversion from one convention to the other occurs within the code. The relative azimuth angle at the observer $\psi_r, o$ is calculated next. A transformation which reparameterizes the optical path is then made to facilitate the calculation of relative azimuth angles $\psi_r$ at each scattering point. This angle allows precise calculation of the scattering angle at each point.

The subsolar point and the projected observer position together define the great circle $\psi(\phi)$ which satisfies the condition

$$\tan \theta = A \cos \phi + B \sin \phi,$$  \hspace{1cm} (3.10)

where $\theta$ and $\phi$ are the standard latitude and longitude angles shown in Figure 3.3 and $A$ and $B$ are constants to be found. The case where the subsolar point and observer lie on the same longitude, $\tan \phi_s = \tan \phi_o$, is treated
Figure 3.2 Looking down on the scattering path. All points are projected on the earth and all line segments are parts of great circles. The relative azimuth can be seen to vary as one moves the scattering point along OP.
Figure 3.3 Latitude and longitude angles, where \( \phi = 0 \) passes through the Greenwich time base.
separately since \( \phi \) is fixed in this case and \( 0 (\phi) \) is indeterminate. Except for this special case, \( A \) and \( B \) are determined for the particular great circle passing through these two points by using the angular surface locations of the subsolar \( (0_s, \phi_s) \) and observer \( (0_o, \phi_o) \) points to obtain

\[
A = \frac{\tan 0_s \sin \phi_s - \tan 0_o \sin \phi_o}{\cos 0_s \sin \phi_s - \cos 0_o \sin \phi_o} \quad (3.11)
\]

and

\[
B = \frac{\tan 0_s \cos \phi_s - \tan 0_o \cos \phi_o}{\cos 0_s \sin \phi_s - \cos 0_o \sin \phi_o}. \quad (3.12)
\]

The absolute azimuth angle \( \psi_{a, os} \) for the plane containing the great circle segment \( OS \) can be written as

\[
\tan \psi_{a, os} = \frac{ds_{pl}}{ds_{pl}} = \frac{-1}{\cos 0} \frac{d0}{d\phi}, \quad (3.13)
\]

where \( d0/d\phi \) along this path is given by

\[
\frac{d0}{d\phi} = \frac{B \cos \phi - A \sin \phi}{1 + \tan^2 0}. \quad (3.14)
\]

The relations given in (3.13) can be derived from considerations based on Figure 3.3. Using the observer point location, the equations above are combined to obtain
\[
\tan \psi_{a, os} = \frac{A \sin \phi_o - B \cos \phi_o}{[1 + \tan^2 \phi_o] \cos \phi_o}
\]

\[
= \frac{\tan \phi_o \cos[\phi_s - \phi_o] - \tan \phi_s}{[1 + \tan^2 \phi_o] \cos \phi_o \sin[\phi_s - \phi_o]}
\]

(3.15)

The relative azimuth between the line-of-sight OP plane and the OS plane is then given by

\[
\psi_{r, o} = \psi_{a, os} - \psi_{a, op}
\]

(3.16)

Another useful angle to calculate is the angle \( \Lambda_o \) subtended at the earth center by radial lines from the sun and the observer. Using a dot product between position vectors on the unit sphere, it can be shown that

\[
\cos \Lambda_o = \cos \theta_s \cos \phi_s \cos \theta_o \cos \phi_o + \\
+ \cos \theta_s \sin \phi_s \cos \theta_o \sin \phi_o + \\
+ \sin \phi_s \sin \phi_o
\]

\[
= \cos \theta_s \cos \theta_o \cos[\phi_s - \phi_o] + \sin \theta_s \sin \theta_o
\]

(3.17)

The two angles \( \psi_{r, o} \) and \( \Lambda_o \) together with the multi-path altitude and zenith information specify the three dimensional single scattering geometry completely for any scattering source point. However, the angle \( \psi_{r, p} \) between the PS and OP planes is yet to be obtained.
It proves convenient to make a coordinate transformation so that the line-of-sight optical path is more easily parameterized. In the original configuration, the longitude and latitude of each scattering point are not known and cumbersome to calculate. The transformation used moves the subsolar point and observer location on the sphere so that the line-of-sight runs east from an observer on the equator at $(\hat{\theta}_0' = 0, \hat{\phi}_0' = 0)$. The angles $\psi_0$ (short notation for $\psi_{\hat{r},0}$) and $\Lambda_0$ are left invariant by the transformation so that the relative position of the sun in the sky is the same for the observer. No physical changes or approximations are introduced through this transformation. As one can see from Figure 3.4 by using (3.14) and (3.17) for the new coordinates, this transformation must satisfy the following equations for $\theta_0'$ and $\Lambda_0$:

$$\tan \theta_0' = \tan \psi_0 \sin \phi_0'$$  \hspace{1cm} (3.18)

and

$$\cos \Lambda_0 = \cos \theta_0' \cos \phi_0' .$$ \hspace{1cm} (3.19)

These conditions, when inverted, pinpoint the latitude $\theta_s'$ and longitude $\phi_s'$ of the new subsolar point in terms of the fixed angles $\psi_0$ and $\Lambda_0$, that is

$$\tan \phi_s' = - \tan \Lambda_0 \cos \psi_0$$ \hspace{1cm} (3.20)

and

$$\sin \theta_0' = \sin \Lambda_0 \sin \psi_0 .$$ \hspace{1cm} (3.21)
Figure 3.4 Looking down on the transformed scattering geometry. The line-of-sight lies on the equator. The sub-solar point at $(0^\prime_s - \phi^\prime_s)$ has the same relative position as in Fig. 3.2.
A line-of-sight scattering point \( P \) now has the new latitude and longitude coordinates \((\theta'_P = 0, \phi'_P = -\beta)\), where \( \beta \) is the angle subtended at earth center by radial lines to \( P \) and the observer 0.

It is now possible to compute the relative azimuth angle between two path legs, that is, between the vertical plane containing \( PS \) and the vertical plane containing \( OP \). The azimuth angle at \((0, -\beta)\) for the primary solar path connecting \((0, -\beta)\) and \((0', \phi')\) is given by

\[
\tan [\psi (\beta)] = \frac{\sin \Delta_o \sin \psi}{\cos \beta \sin \Delta_o \cos \psi - \sin \beta \cos \Delta_o}.
\]

(3.22)

It is also necessary to calculate the angle \( \Delta(\beta) \) subtended at the earth center by radial lines to the sun and the scattering point \((0, -\beta)\). This is given by

\[
\cos [\Delta(\beta)] = \cos \Delta_o \cos \beta - \sin \beta \sin \Delta_o \cos \psi,
\]

(3.23)

where in the absence of refractive bending \( \Delta(\beta) \) would be the zenith angle of the sun as viewed from the scattering point. In the presence of refraction \( \Delta(\beta) \) can be used as an initial guess for the actual zenith angle, and the primary solar path can be tracked iteratively to correct for refraction and obtain the correct zenith angle. The scattering point altitude \( Hl'(\beta) \) and approximate zenith angle \( \Delta(\beta) \) are used to specify the starting point of the primary solar path leg from \( P \) to space.

The set of angles which are discussed above is sufficient to track both legs of each L-shaped single scattering path. One additional angle, the included angle for single scattering \( \gamma(\beta) \) is needed for the phase function in
the scattering source term. That angle is given by

$$\cos \gamma = \hat{n}_{ps} \cdot \hat{n}_{op} ,$$  \hspace{1cm} (3.24)$$

where each path direction vector refers to the local direction at the scattering point. In terms of the two local zenith angles $\alpha_{ps}$ and $\alpha_{op}$ at the scattering point and the relative azimuth between vertical planes $\psi_p$, the included angle becomes

$$\cos \gamma (\beta) = \sin \alpha_{ps} \sin \alpha_{op} \cos \psi_p (\beta) +$$

$$+ \cos \alpha_{ps} \cos \alpha_{op} .$$  \hspace{1cm} (3.25)$$

The scattering angle $\gamma$ and the cumulative absorber and scattering amounts are computed for each scattering point which contributes to the intensity in the sum given by [3.9]. LOWTRANSX specifically uses as scattering source points the intersections of the line-of-sight with the model atmosphere layer boundaries. Equation (3.9) leads to the following expression for the scattered radiance as it is computed in LOWTRANSX using this set of $n$ single scattering source points.

$$\overline{I}_v^{SCAT} = \overline{I}_v^{SUN} \sum_{i=1}^{n-1} \sum_{X=(A,M)} \left[ \frac{1}{T_{s, op, i} - T_{s, op, i+1}} \right]$$

$$\frac{1}{2} \left[ \frac{T_{A+M}}{e_{ps, op, i} - e_{ps, op, i+1}} \right] \left[ \frac{T_{A+M}}{e_{ps, op, i+1}} + \frac{T_{A+M}}{e_{ps, op, i+1}} \right] .$$  \hspace{1cm} (3.26)$$

29
The layer average $< \cdot >_j$ has been evaluated using the properties of only the two scattering points which bound each layer path segment. The sum is taken over scattering points labelled by $i$ and this result applies to long slant paths as well as upward and downward trajectories. The observer position here coincides with $i = 1$ and the line-of-sight end point is $i = n$.

3.3 LOWTRANX Verification

Verification of this newly developed single-scattering code was done in several stages. On the most basic level, the individual subroutines described in Appendix B were driven artificially during the developmental phase, hand calculations and common sense were used to evaluate intermediate results, and overall trends for various inputs were checked. Once the routines were performing correctly, they were linked with each other and LOWTRAN to form the complete program. Because of the code's overall complexity, verification becomes a difficult task. Simple cases involving two or three scattering layers were approximated by hand calculations. This was done for a number of configurations, and agreement was found in all cases. Unfortunately as the number of scattering layers increases the number of calculations and the possibility of human error increases to the point that this approach become impractical. There are, however, two special cases that cover the entire atmosphere (32 scattering layers) that reduce analytically to easy solutions. These occur when the optical-solar path configurations are such that all scattering path lengths, absorber amounts, and transmittances are equal. This happens when the observer (on the ground in both cases) is looking directly at the sun and when the observer is looking away from the sun ($\psi = 180^\circ$) with a zenith angle of $45^\circ$ and the solar
zenith at 45°. Examination of an expanded version of the standard output file for these cases confirmed that the scattering path lengths, absorber amounts, and L-path transmittances were the same. The total scattered radiance reaching the observer was also equal to that given by hand calculations in each case. While this certainly illustrates the internal consistency of the code and supports the verification process, it does not establish the validity of the code in all modes of operation.

Further verification involving the entire atmosphere was made through comparisons with other single scattering codes. The unique band transmission functions and aerosol models found in LOWTRAN restricted such comparisons to other codes having similar data bases. Only one code called SPOT [Ref. 8] was found to have the necessary characteristics. It was developed by RRA of Fort Worth, Texas and used LOWTRAN 4 [Ref. 10] for its basic radiative transfer. Spot is a plane-parallel, single scattering code that calls LOWTRAN as a black box to find individual path transmittances. The L-path transmittances that arise in the calculation procedure are approximated as the product of the transmittances for each leg. This is incorrect since the LOWTRAN transmission functions do not obey Beer's law. The aerosol models and phase functions also differ from those found in LOWTRAN. Since the SPOT code was no longer available on the AFGL computer system, comparisons were limited to existing output. One such comparison is illustrated in Figures 3.5 and 3.6. Figure 3.5 shows the single scattering radiance and emission at predicted by LOWTRAN for an observer at 50 Km looking down at a zenith of 170°. The solar zenith angle is 60°, the relative azimuth angle is 10°, and a U.S. standard atmosphere with a rural aerosol model is used. Figure 3.6 shows the single scattering radiance and emission for a similar run of the SPOT code, i.e observer at 50 Km looking at 170° with a solar zenith...
Figure 3.5  LOWTRANSX thermal emission — and single scattered radiance ... for 1962 standard atmosphere with default aerosol models at 50 Km looking down with $\mu = 10^\circ$ and $\mu_0 = 60^\circ$. 
Figure 3.6 Plane-parallel, single scattering SPOT code at conditions equivalent to those in Fig. 3.5.
of 60°. The exact atmospheric and aerosol models for SPOT are not known, but they are similar. Take note that the vertical axes on these two figures have different units and the horizontal axes are scaled differently. Although comparison of these two figures indicates some slight differences in magnitude, they are well within the uncertainty of the atmosphere used in SPOT. Note that the spectral details in the single scattering and emission curves occur at identical wavenumbers in these two figures. While this is not a good comparison for checking details, it does serve to justify that the new algorithm is executing correctly.

A final verification of LOWTRANSX was made by using another single-scattering code developed under this contract and described in Chapter 4. Briefly, the code is based on a plane-parallel, monochromatic, multiple scattering code that requires optical depths, albedoes and phase functions for each layer. Since the LOWTRAN gaseous transmission functions do not obey Beer's law, the molecular band transmittances were "turned off" for this comparison. This was accomplished by setting the gaseous transmittances equal to one in the LOWTRANSX code. Statements were added to calculate and write total optical depths and albedoes based on the remaining attenuation mechanisms. This data was then used in the simple, plane-parallel single scattering code. Multiple runs of LOWTRANSX were made for comparison. Some of these results are presented in Table 3.1. The remainder of the results will be presented and discussed in Section 4 (Tables 4.9 and 4.10) where multiple scattering effects are examined. The numbers shown are the ratio of the single scattering radiance predicted by LOWTRANSX to that predicted by the single-scattering code for paths that are not affected by spherical geometry and refraction. The ratios are in good overall agreement and demonstrate that the LOWTRANSX code functions properly for these conditions. A discussion
Table 3.1 Ratio of LOWTRANSX To Single Scattering Plane-Parallel for Standard 1962 Atmosphere at 11 μm

<table>
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<tr>
<th>Top (100 Km)</th>
<th>g</th>
<th>0.0</th>
<th>0.8</th>
<th>Azimuthal angle relative to the sun</th>
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<td></td>
<td></td>
<td>0°</td>
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<td>1.0023</td>
<td>90°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0024</td>
<td>1.0020</td>
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(a)

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<td>1.000</td>
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<tr>
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<tr>
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(b)

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</tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>0.9957</td>
<td>0.9908</td>
<td>90°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(c)

All zenith angles are 12.95°

Radiation propagation

\[ g = \text{asymmetry factor} \]

\[ \tau = 0.183 \]
of the effects of spherical geometry and refraction, which are not included in the plane-parallel, single-scattering code, is presented in Chapter 4.

The versatility of the LOWTRANS code leads to further verification problems. Various input combinations, path types, and unique geometric situations make the list of possible test cases exceedingly large. Briefly, the following situations are possible and have been addressed in the development of the code:

1. Optical path - up or down, short or long (through a tangent height)

2. Specification of the observer-solar orientation
   (a) $\theta_o, \phi_o, \theta_s, \phi_s$
   (b) $\theta_o, \phi_o$, time, day
   (c) $\alpha_s, \Psi_s$ at observer

3. Unique Geometries
   (a) Arbitrary azimuth
   (b) Observer at pole (north or south)
   (c) Partially shaded path (end or center)
   (d) Long sun paths

The verification problem has been made more difficult by the parallel development of LOWTRAN6 at AFGL that required the continuous integration of the single-scattering algorithm. In some cases this involved only straightforward replacement of code, while others involved changes in coding logic, which opens the possibility for the introduction of errors.

Every attempt has been made to verify the code at each stage of development. All the situations listed above have been verified individually. Errors arising as a result of a rare combination of parameters occurring simultaneously
are unlikely, but still possible. The user should keep this in mind.

3.4 Concluding Remarks

The code constructed here (also see Appendices) using a recent LOWTRAN version and called LOWTRANSX is the one delivered to AFGL. The staff at AFGL is in the process of developing a LOWTRAN version (LOWTRAN6) that will contain the present single scattering model along with other modifications. Consequently, LOWTRANSX will not be available to the user in the form described here, although its capability will be. The reader should direct any inquiries concerning LOWTRANSX to the staff at AFGL.
4. MULTIPLE SCATTERING

The previous section discussed the procedure necessary to include the single scattering approximation in a LOWTRAN code [Ref. 1]. The spherical geometry and non-monochromatic (spectrally averaged) transmission functions found in LOWTRAN made single scattering difficult compared to the monochromatic, plane-parallel approach. These difficulties become insurmountable when multiple scattering is considered. At this time there is no multiple scattering formulation that can accept spherical geometry and LOWTRAN'S transmission functions. Monte Carlo codes are available [Refs. 16 through 18] that calculate monochromatic multiple scattering in spherical atmospheres. Such codes have a reputation for being computationally slow (expensive). Several monochromatic multiple scattering formulations and highly developed codes are available for the plane-parallel geometry that are computationally fast [Refs. 19 and 20]. Unfortunately plane-parallel codes predict intensity fields that are totally wrong for low sun angles and long, horizontal observation paths.

To overcome the present impasse, multiple scattering calculations must be developed that will accept spectrally averaged radiative properties (and therefore, spectrally averaged direct transmission functions) such that numerous monochromatic executions do not have to be made over the highly structured spectral domain caused by gaseous absorption and emission. The subject of how to deal with the spectral aspects of radiative transfer has always been an area of research in the field. Perhaps the most obvious and consequently the most common solution to this problem is to average or model the medium's spectral properties before the radiative transfer calculations are performed. This approach certainly has been useful, but has certain
unavoidable limitations. It is rare that one can determine (without approximations) how modeled or lumped photons are transported through the medium. That is, what is the governing equation? Consequently the errors involved are often unknown and uncontrollable. Furthermore, such calculations are limited to predicting spectrally averaged dependent variables, e.g., the intensity. In summary this approach lacks generality. The other approach to this spectral problem, and the one under research in this section, exploits the concept that monochromatic radiative transfer calculations over a highly structured spectral region are redundant. Therefore, only a relative few monochromatic calculations are necessary to represent the radiative transfer at all points in the spectral region. The research on this approach is neither as prodigious nor coherent as for the first approach and is associated with studies of the absorption or opacity distribution function, in homogeneous atmospheres in most cases. The work on exponential-sumfitting of the direct transmission function is also relatable to this latter approach.

To investigate spectral redundancy, a monochromatic multiple scattering code is required. Section 4.1 documents such a code [Refs. 5 through 7 and 20] for general plane-parallel media that is computationally fast. To check this code in a simple limit and to compare with LOWTRANSX, a plane-parallel, single-scattering code is described in section 4.2 that is compatible with the parametric inputs to the multiple-scattering code. Section 4.3 presents single versus multiple scattering results for a range of parameters to show when and by how much multiple scattering is important. The basic study of spectral redundancy or spectral degrading (averaging) in multiple scattering calculations is developed in section 4.4 along with some initial
results. Finally, section 4.5 is a discussion of further work that must be done to allow multiple scattering to be incorporated into codes like LOWTRAN and FASCODE.

4.1 Adding/Doubling, Multiple-Scattering Code

This multiple-scattering code was originally developed to handle internal, isotropic radiative sources (thermal radiation) for completely general media and boundary surfaces. Until now, Adding/Doubling (A/D) was used mostly for problems driven only by external, unidirectional (sun) sources. The formulation supporting the code is available in the open literature [Refs. 5 through 7] and the resulting code well documented in a Ph.D. thesis [Refs. 20]. The reader is assumed to be familiar with these references because only a brief discussion of the changes made will be presented here.

Because the present A/D code is general, well documented, and can handle thermal sources, all of which are of general interest to AFGL, it makes sense to modify the code to accept unidirectional, external illumination. This requires performing a Fourier decomposition (already inherent in the original development) of the radiative transfer process. That is, each monochromatic run is done for each Fourier component and the results are then recombined (inverse Fourier Transform) to obtain the intensity fields. Note that each run contains all possible sun and observer angles. To retain as much computational speed as possible, a Fast Fourier Transform (FFT) code was used.

A natural starting point in an A/D computation is to find the Fourier coefficients \( P_{n} \) in the cosine Fourier expansion of the phase function \( P \) in the form (note that this report uses both \( t \) and \( \tau \) for the optical depth)

\[
P = \sum_{j=0}^{J} P_{j}(\phi, \phi', \mu, \mu') \cos j(\phi - \phi'),
\]  

(4.1)
where $P$ is normalized as

$$
\int_{4\pi} P \, d\Omega' = 4\pi \quad (4.2)
$$

Here $\theta (\mu = \cos \theta)$ and $\phi$ are the zenith and azimuthal angles, respectively, and $d\Omega'$ is the differential solid angle. Each $P_j$ forms an $n \times n$ array or matrix, where $n$ is the number of gaussian quadrature points used in the system (normally seven in the basic code). The $P_j$'s each produce their own Fourier component for the dependent scattering functions which can be summed to obtain the final desired quantity. Note that if the radiative flux is wanted, the zeroth Fourier component is the only one required.

The $P_j$'s in Eq. (4.1) are found by the FFT routine described in Appendix F. Due to the details of how FFT codes work, Fourier analysis (forward) and Fourier synthesis (inverse) must be done by compatible routines. As discussed in Appendix F, the externally driven A/D code is made up of three parts. The first part finds the Fourier coefficients for the given phase function and passes the results to the radiative transfer part. After each Fourier component has been processed through the radiative transfer code, these results are passed back to an FFT code for synthesis to obtain the radiative fields throughout the medium. The FFT code is rather straightforward, but the changes made to the existing A/D code will now be described.

The A/D code calculates several sets of diffuse scattering functions that represent intensity fields for Green's function type problems of different complexity. The functions of interest here are symbolized as $S_{P_j}^{ij}$ and $T_{P_j}^{ij}$ that represent how an internal fundamental source is diffusely transmitted to the boundaries. Through reciprocity, these functions are directly related
to the $\tilde{S}^\pm_S$ and $\tilde{T}^\pm_S$ functions that relate external sources to internal responses, the problem that is being solved. These functions of the two variables $\mu_o$ (illumination) and $\mu$ (response) appear as $n \times n$ matrices. Reciprocity [Ref. 21] says that

$$\tilde{T}^+_{F'} = \tilde{T}^+_{F}$$

$$\tilde{S}^-_{F'} = \tilde{S}^-_{F}$$

where $\tilde{\cdot}$ over a matrix means transpose. For a plane parallel medium with no boundary surfaces, the dimensionless (divided by driving intensity) diffuse radiative intensity $I$ at any optical depth $t$ is given by

$$I^+_D (t, \mu, \phi) = \frac{1}{4\pi\mu} \tilde{S}^-_F (\mu, \phi, t; \mu_o, \phi_o)$$

and

$$I^-_D (t, \mu, \phi) = \frac{1}{4\pi\mu} \tilde{T}^+_F (\mu, \phi, t; \mu_o, \phi_o),$$

where the $\tilde{S}^-_F$ and $\tilde{T}^+_F$ are Fourier synthesized from $\tilde{S}^-_F$ and $\tilde{T}^+_F$. The superscripts $+$ and $-$ on intensities denote propagation up and down, respectively. The same superscripts on the scattering functions have a different meaning that need not be discussed here [see Refs. 5 and 20]. The angles $\mu$ and $\phi$ are those for the observer while subscript zero on these denote angles for the illumination.

Appendix E contains the original user's manual for the A/D code that was developed in Ref. 20. This plus a copy of Sharma's thesis [Ref. 20] will enable one to understand the basic A/D code. The surface scattering (or reflection), thermal sources, and heat transfer options in this code are turned off in the modified version by setting logical parameters. They could be
reactivated with some modification of control and input functions of the present code.

4.2 A Plane-Parallel Single Scattering Code

A simple plane-parallel, monochromatic, single scattering computer code is described in this section. This code is used to study the following items: (1) The Adding/Doubling multiple scattering code becomes single scattering in the limit of sufficiently small single scattering albedoes and can therefore be checked against the present independent and simple code. (2) Within the limitations imposed by the plane-parallel geometry, one can compare multiple and single scattering results to find the accuracy of the single scattering assumption for various parametric values. (3) LOWTRANSX can be verified by comparisons with the present simple code for appropriately chosen spectral regions (having no significant line structure) and geometric configurations (with vertical-like solar and observation paths). (4) By using other path configurations, the same comparison will show the effects of the spherical geometry on single scattering intensities.

The nomenclature used here, which is the same as that used in the adding/doubling code, is shown in Figure 4.1. In this context the radiative transfer equation is

\[ \mu \frac{dI(3, \phi)}{d\tau} = I - J(0, \phi), \quad (4.6) \]

where \( \theta \) and \( \phi \) are the zenith and azimuth angles respectively. The monochromatic intensity is given by \( I \), the direction cosine is \( \mu = \cos \theta \), and the vertical optical depth parameter, as measured from the top surface and based on the extinction coefficient, is \( \tau \). Scattering sources are represented by
Figure 4.1 Plane-parallel geometry and nomenclature
the source function $J$ defined by

$$J(0, \phi) = \frac{\omega}{4\pi} \int I(\theta', \phi') P(0, 0', \phi - \phi') \, d\Omega',$$  \hspace{1cm} (4.7)$$

where $\omega$ is the single scattering albedo and $\Omega'$ measures solid angle. The phase function $P$ is normalized according to

$$\int P(\theta, 0', \phi - \phi') \, d\Omega' = 4\pi.$$  \hspace{1cm} (4.8)$$

To solve (4.6) for the solar driven problem, it is customary to break up the radiative intensity into direct and diffuse parts. With the direct solar intensity at any point $1$ given by ($I_o^{\text{SUN}}$ being the solar intensity at the top of the atmosphere)

$$I^{\text{SUN}} = I_o^{\text{SUN}} \, e^{-\frac{\theta}{\mu_o}} \, \delta(\mu - \mu_o, \phi - \phi_o),$$  \hspace{1cm} (4.9)$$

the source function becomes

$$J(0, \phi) = \frac{\omega}{4\pi} \int I(\theta', \phi') P(0, 0', \phi - \phi') \, d\Omega'$$

$$+ \frac{\omega}{4\pi} I_o^{\text{SUN}} \, e^{-\frac{\theta}{\mu_o}} P(0, 0', \phi - \phi_o).$$  \hspace{1cm} (4.10)$$

where $I_o$ now represents the diffuse radiative field (as obtained from (4.6) with boundary conditions of zero incident diffuse intensity) and $\delta$ is the Kronecker delta function. For single scattering, only the second term on the right hand side of (4.10) is retained in solving (4.6) and this gives
the downward (-) intensity

\[ I_\downarrow (t, 0, 0, \phi - \phi_0) = \frac{1}{4\pi} \int_0^1 \frac{w}{\mu} \left[ \int_0^{\mu} \frac{w}{\mu} \text{SUN} P e^{-\gamma'/\mu} e^{-(\gamma - \gamma')/\mu} d\gamma' \right] d\mu, \]

(4.11)

and upward (+) intensity

\[ I_\uparrow (t, 0, 0, \phi - \phi_0) = \frac{1}{4\pi} \int_0^1 \frac{w}{\mu} \left[ \int_0^{\mu} \frac{w}{\mu} \text{SUN} P e^{-\gamma'/\mu} e^{-(\gamma - \gamma')/\mu} d\gamma' \right] d\mu, \]

(4.12)

where all values of \( \mu \) and \( \mu_0 \) are now positive (angles measured from the normal in the appropriate hemisphere).

For inhomogeneous atmospheres, which are modelled with an atmosphere composed of \( N \) homogeneous layers, the above expressions can be integrated analytically. Let \( \tau_j \) \((j = 1, 2, \ldots, N + 1)\) denote the optical depth from the top to any layer boundary \((\tau_0 = 0)\) and \( w_j \) and \( P_j \) the properties of the layer which lies below \( j \). Equations (4.6) and (4.7) then take the form

\[ I_j \downarrow = \frac{1}{4\pi} \frac{w_0}{\mu - \mu_0} e^{-\tau_j/\mu} \sum_{i=1}^{j-1} w_i P_i \left[ e^{-(\tau_i/\mu) - (\tau_j/\mu)} \right] \]

\[ I_{j+1} \uparrow = e^{\tau_j/\mu} \sum_{i=1}^{j+1} w_i P_i \left[ e^{-(\tau_i/\mu) - (\tau_j/\mu)} \right] \]

\( (4.13) \)
for \( j > 1 \) and

\[
\frac{i_{j}^{+}}{I_{0}} = \frac{1}{4\pi} \frac{\mu_{o}}{\mu + \mu_{o}} e^{\sum_{i=j}^{N-1} \frac{\mu_{i}}{\mu_{i} - \mu_{o}} \left[-\frac{1}{\mu_{i}} \left(\frac{1}{\mu_{i} + 1} + \frac{1}{\mu_{o}}\right) + \frac{1}{\mu_{i}} \left(\frac{1}{\mu_{i} + 1} + \frac{1}{\mu_{o}}\right)\right]}
\]

for \( j < N + 1 \).

One can get a somewhat more physical understanding of (4.13) and (4.14) by rearranging terms slightly. Let \( P_{\text{B}}(\mu, \mu_{o}, \phi) \) denote backward scattering upward (\(+\)) and forward scattering downward (\(-\)) phase functions, that is for \( \theta \) less (\(+\)) or greater (\(-\)) than 90 degrees. Both the upward and downward intensities contain similar expressions for what might be called the single layer "discrete source" terms defined by

\[
S_{\pm}^{(i, \mu, \mu_{o}, \phi)} = \frac{\mu_{0} \mu}{\mu \pm \mu_{0}} \frac{1}{\mu} \frac{1}{\mu_{o}} e^{-\frac{i}{\mu_{o}}} \left[1 - \exp \left[-(i+1 - i) \left(\frac{1}{\mu_{o} \pm 1} \frac{1}{\mu}\right)\right]\right],
\]

except for the forward scattering case \( \mu = \mu_{o} \) where

\[
S_{-}^{(i=\mu_{o}, \phi)} = \frac{1}{\mu_{o}} e^{\frac{-i}{\mu_{o}}} P_{\text{F}}^{-} [i+1 - i].
\]

Using these "discrete sources," the complete downward and upward intensities at level \( j \) are

\[
I_{j}^{-}(i, \mu, \mu_{o}, \phi) = \sum_{i=1}^{j-1} S_{-}^{(i, \mu, \mu_{o}, \phi)} e^{-\frac{(i - i)}{\mu}}
\]

(4.17)
and
\[
I_j^+ (\eta_j, \mu, \nu_0, \phi) = \sum_{i=j}^{N} S_i^+ (\mu, \nu_0, \phi) e^{-\frac{(i - j)}{\mu}} \tag{4.18}
\]

Physically, the sums include contributions from all of the scattering layers, which in the case of the downward intensity \( I_j^- \) includes all layers above level \( j \), while all layers below \( j \) contribute to \( I_j^+ \). The upward single layer "discrete source" \( S_i^+ \) represents all of the singly scattered intensity at level \( i \) due to scattering in the layer immediately below it. Similarly,
\[
S_i^- e^{-\frac{(i+1 - i)}{\mu}}
\]
represents the intensity at level \( i+1 \) due to scattering in the layer just above this level (the \( i' \)th layer).

The code takes the following steps in calculating the single scattering intensities at each observer level (layer boundary) for each set of angles:

1. The upward and downward "discrete source" terms \( S_i \) are first computed for the top layer, for all pairs of zenith quadrature points and a single azimuth angle.

2. The contribution to the intensity at each level which comes from these terms is computed and added to the total intensity for that level.

3. This process is repeated for each successive scattering layer, producing upward and downward intensities for all possible zenith angles at all levels.

4. The entire calculation is repeated for each new azimuth angle if the scattering is anisotropic.
This algorithm allows a completely different phase function to be specified for each layer. The phase function, expressed in terms of the quadrature zenith angles and azimuth, is computed from the phase function of the included angle of scattering by ADNGFFT. The Fourier transform is not required and is therefore bypassed within ADNGFFT in the case of single scattering (user sets INOFT=1). All other code input data are identical in content and format with that for Adding/Doubling code, and the reader is referred to Appendix F for these details.

4.3 Intercomparison of Radiative Transfer Results

Since LOWTRANSX only includes single-scattering, it is important to know how the error produced by this approximation varies parametrically. Unfortunately, multiple scattering results are not available for refracting and spherical atmospheres. To investigate this error question, a comparison is made between results for single and multiple scattering in homogeneous, plane-parallel atmospheres. Such information gives a good deal of insight for the same problems when the geometry is spherical. To further bridge the conceptual differences between these two situations, comparisons are made for single scattering results from LOWTRANSX (spherical and refracting atmospheres) and the plane parallel formulation of Section 4.2 for a realistic example atmosphere.

The first intercomparison to be discussed is that between plane-parallel single and multiple scattering. For simplicity only homogeneous model atmospheres are used. The parameters involved, namely $\tau_0$ (optical depth), $\omega$ (single scattering albedo), $g$ (phase function asymmetry factor), $\gamma$ (position of observer), and $\phi-\psi_0$ (azimuthal angle between observer and sun), are quite numerous. The only parameter that is functionally well understood is $\omega$, since order of scattering expansions go asymptotically in powers of $\omega$.

*Radiative parameters are constant throughout the atmosphere.
(everything else held fixed). The effect of the other parameters will be found numerically.

The first set of data is for isotropic scattering \((g = 0)\) and consequently \(\phi - \phi_0\) is no longer a parameter. The data is presented as a ratio of multiple scattering over single scattering intensities (ratio is always greater than one) in 7 x 7 arrays representing combinations of sun and observer zenith angles.* The optical depth and single scattering albedo are varied as well as the observer location. To understand these results one should note that the top layers in the atmosphere will have scattering source functions that are closer (than those in deeper layers) to those predicted by the single scattering approximation, and as the sun approaches grazing angles such single scattering type layers will be found only at the very top of the atmosphere. The overall view, therefore, is one of scattering source functions becoming more effected by multiple scattering as one goes from the top to the bottom of the atmosphere.

With the above discussion in hand, the data in Table 4.1 for \(t = 1.0\) and \(\psi = 0.3\) makes physical sense. At the top of the atmosphere the intensity ratio for \(0_0 = 12.95^\circ\) decreases from 1.21 to 1.13 as the observer angle varies from 12.95° to 88.54°. The improvement is caused by the fact that the scattering source function is more single scattering in the top most layers seen by the more grazing view angles. Still looking at up intensities, the ratio gets larger (more multiple scattering) as \(t\) increases, again because these intensities see source functions deeper in the medium.

In all cases, except for the top of the atmosphere, the ratios get larger (note that all ratios greater than \(10^3\) are printed as \(10^3\)) as the sun angle goes towards grazing (read from left to right on the tables). The intensities out of the top are unique since the ratios become smaller as the sun angle

*See the last page of this section for a list of the angles used.
increases, for any observer angle. This must be caused by the fact that
at grazing sun angles less flux is entering the atmosphere and, therefore,
less backscattering flux from the larger $i's$ is available to cause multi-
ple scattering effects in the top most portion of the atmosphere. The angle
and $\tau$ effects discussed above also hold as other parameters are varied.

Table 4.2 is also for $\tau_o = 1.0$ (as is Table 4.1) but now $\omega = 0.6$. Since
these intensity ratios vary from unity approximately linearly with the single
scattering albedo (for $\omega < 1$), the multiple scattering effects are about doubled
by going from Table 4.1 to Table 4.2. The effect of total optical depth is
not as simple and can be seen by comparing Table 4.1 with Table 4.3, the
latter table is for $\tau_o = 2.0$. This comparison keeps $\omega$ constant and doubles
the optical depth. The ratios in Table 4.3 are all larger than those of
Table 4.1 and this becomes much more pronounced as both sun and observer
angles increase. Note again the rather unique properties of the intensities
exiting the top. Comparing 4.2 with 4.4, where $\tau_o$ goes from 1.0 to 0.5 while
$\omega$ remains constant at 0.6, shows that for the smaller view and sun angles
the multiple scattering effect is almost linear in $\tau_o$ and would become more
so as $\tau_o$ decreases further. However, this is not true for the larger view and
sun angles of 82° and 88°.

The influence of changing the asymmetry parameter is shown in Tables
4.5 through 4.8 where the cases of Tables 4.1 through 4.4 are repeated for
$g = 0.8$ (forward scattering peak). The results are now given for $\phi-\phi_o$ of 0°,
90°, and 180°. The most important overall effect is that the corresponding
ratios are now larger for forward scattering and, therefore, multiple scat-
tering is stronger. However, this is not true for intensities that view or
depend mostly on only the top of the medium. These portions now become closer
to the single scattering results because the forward scattering reduces the
backscattering that leads to less diffuse flux up into the top of the medium to cause multiple scattering effects. The multiple scattering effects are slightly larger (larger ratios) for out of plane ($\phi-\phi_0$ of 90° and 180°) viewing than when $\phi-\phi_0$ is 0. Also note that the linearity in $\omega$ observed previously for $g = 0$ does not hold as well in the present cases for $g = 0.8$. However, theory says that as $\omega$ goes to zero this linear effect must again hold.

To use the plane-parallel multiple over single scattering ratios discussed above to evaluate the accuracy of the single scattering approximation in LOWTRANSX, the influence of spherical geometry and refraction must be understood. To accomplish this a comparison has been made between LOWTRANSX and comparable plane-parallel, single-scattering results. LOWTRANSX was executed for a vertical path with all gaseous band transmittances set equal to one. It then returned the layer-by-layer absorption and scattering coefficients for the remaining mechanisms. This data was then used in the single-scattering, plane-parallel code and the results compared with runs made by LOWTRANSX for specified observer locations and view angles. The sun angle was also varied, and the Henyey-Greenstein phase function asymmetry factors were either 0 (isotropic) or 0.8. Each run with LOWTRANSX is for only one set of sun and observer angles and observer location, while a plane-parallel run produces results for all sun angles, observer angles, and observer locations. Therefore, these comparisons were restricted to a few angle and location choices. Table 4.9 presents the ratio of LOWTRANSX to plane-parallel intensities (both single scattering) for sun (view) angles of 12.95°, 82.57° and 88.54° for $g = 0.0$ at three locations (top, bottom and 2 km). The first thing to note is that the view angles of 82° and 88° at the top of the atmosphere represents tangent paths for LOWTRANSX and the ratios are extremely small. Plane-parallel results are completely erroneous for such cases. However, at 2 km and the bottom the
upper 2 x 2 part of the arrays show that geometry effects are 10% or less. In general (keeping away from tangent paths), geometry and refraction effects are weak until view and or sun angles are greater than 82°. The same comparison is repeated in Table 4.10 for g = 0.8 where the azimuthal angle is now present and also shown. The discussion for Table 4.9 also holds here and the only effect of changing the asymmetry factor was to increase the ratios slightly (geometry and refraction effects are slightly stronger for forward scattering aerosols).

The above two comparisons are of general interest in radiative transfer, but the important conclusion for present purposes is that the plane-parallel multiple versus single scattering study can be used to estimate the accuracy of the LOWTRANSX results for sun and view angles of 82° or less as long as tangent paths are not allowed.

The zenith angles used in Tables 4.1 through 4.10 are fixed by the Gaussian quadrature used in the Adding/Doubling code. For the present results, seven quadrature angles were used and the angles are as follows:

12.95°
29.45°
45.34°
60.00°
72.72°
82.57°
88.54°
Table 4.1 through 4.8 are ratios of multiple to single scattering intensities in plane parallel media for the conditions shown. The solar and observer zenith angles are 12.95°, 29.45°, 45.34°, 60.00°, 72.72°, 82.57° and 88.34°.

<table>
<thead>
<tr>
<th>TABLE 4.1</th>
<th>TOT. OPT. DEPTH = 1.0</th>
<th>ALBEDO = 0.3</th>
<th>G = 0.0</th>
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### SOLAR ZENITH ANGLE INCREASING ---

#### RATIO OF INTENSITIES UP

<table>
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<tr>
<th>Observer TAU = 0.000</th>
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<tr>
<td>1.2124e 1.21117 1.20830 1.20249 1.19036 1.16624 1.13334</td>
</tr>
<tr>
<td>1.21117 1.20977 1.20669 1.20049 1.18778 1.16308 1.12998</td>
</tr>
<tr>
<td>1.20830 1.20669 1.20316 1.19620 1.18232 1.15654 1.12310</td>
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<tr>
<td>1.20249 1.20049 1.19620 1.18793 1.17219 1.14485 1.11101</td>
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<tr>
<td>1.19036 1.18778 1.18232 1.17219 1.15412 1.12521 1.09121</td>
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<tr>
<td>1.16624 1.15654 1.14485 1.13334 1.11101 1.09120 1.06246</td>
</tr>
<tr>
<td>1.13334 1.12310 1.11101 1.09120 1.06246 1.03001 1.00000</td>
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#### RATIO OF INTENSITIES DOWN

<table>
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<th>Observer TAU = 0.250</th>
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#### RATIO OF INTENSITIES UP

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| 1.24908 1.25125 1.25654 1.26963 1.31292 1.63736 100 +++
| 1.24874 1.25081 1.25780 1.26835 1.31065 1.62781 100 +++
| 1.24792 1.24862 1.25449 1.26619 1.30775 1.60771 100 +++
| 1.24624 1.24777 1.25139 1.26148 1.29633 1.57085 928.044466 |
| 1.24374 1.24532 1.24875 1.25318 1.27830 1.50539 739.32300 |
| 1.23949 1.23208 1.23165 1.23287 1.24652 1.40144 460.22192 |
| 1.21708 1.21564 1.21297 1.20958 1.21156 1.29634 186.51082 |

#### RATIO OF INTENSITIES DOWN

<table>
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<th>Observer TAU = 0.250</th>
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<tbody>
<tr>
<td>1.17735 1.17699 1.16627 1.15255 1.13620 1.11366 1.10015</td>
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### Table 4.1 (Cont.)

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<th>ALBEDO = 0.3</th>
<th>G = 0.0</th>
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[SOLAR ZENITH ANGLE INCREASING ——> ]

**RATIO OF INTENSITIES UP**

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**RATIO OF INTENSITIES DOWN**

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**RATIO OF INTENSITIES UP**

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**RATIO OF INTENSITIES DOWN**

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### Table 4.1 (Cont.)

**TOT. OPT. DEPTH = 1.0**  
**ALBEDO = 0.3**  
**G = 0.0**

[SOLAR ZENITH ANGLE INCREASING ———]

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**TABLE 4.2**

TOT. OPT. DEPTH = 1.0  ALBEDO = 0.6  G = 0.0

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TABLE 4.2 (CONT.) TOT. OPT. DEPTH = 1.0  

[SOLAR ZENITH ANGLE INCREASING ----- ]

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TABLE 4.2 (CONT.)  
TOT. OPT. DEPTH = 1.0  
ALBEDO = 0.6  
G = 0.0

[SOLAR ZENITH ANGLE INCREASING ----: ]

RATIO OF INTENSITIES UP  

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RATIO OF INTENSITIES DOWN  

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TABLE 4.3  
T.O.T. OPT. DEPTH = 2.0  ALBEDO = 0.3  $G = 0.0$

[SOLAR ZENITH ANGLE INCREASING ———— ]

RATIO OF INTENSITIES UP  

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TABLE 4.3 (CONT.)  
TOT. OPT. DEPTH = 2.0  
ALBEDO = 0.3  
G = 0.0  

[SOLAR ZENITH ANGLE INCREASING ----- ]  

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61
### Table 4.3 (Cont.)

**T"ABI,** \( \text{TOT. OPT. D'PTH} = 2.0 \)** \ ALBEDO = 0.3 \ G = 0.0

[SOLAR ZENITH ANGLE INCREASING ---\-

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[SOLAR ZENITH ANGLE INCREASING ----> ]

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**RATIO OF INTENSITIES UP**

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TABLE 4.4 (CONT.)  TOT. OPT. DEPTH = 0.5  ALBEDO = 0.6  G = 0.0

[SOLAR ZENITH ANGLE INCREASING ----> ]

RATIO OF INTENSITIES UP


RATIO OF INTENSITIES DOWN


RATIO OF INTENSITIES UP

|       | 1.38782 | 1.39477 | 1.41123 | 1.45027 | 1.57268 | 2.57024 | 1000 ++++ | 1.38790 | 1.39485 | 1.41129 | 1.45030 | 1.57261 | 2.56905 | 1000 ++++ | 1.38800 | 1.39707 | 1.41145 | 1.45029 | 1.57248 | 2.56639 | 1000 ++++ | 1.38850 | 1.39540 | 1.41177 | 1.45057 | 1.57220 | 2.56083 | 1000 ++++ | 1.38942 | 1.39627 | 1.41251 | 1.47106 | 1.57152 | 2.54787 | 1000 ++++ | 1.39223 | 1.39892 | 1.41474 | 1.45222 | 1.56934 | 2.50863 | 1000 ++++ | 1.40422 | 1.41000 | 1.42369 | 1.45611 | 1.55693 | 2.33580 | 1000 ++++ |

RATIO OF INTENSITIES DOWN

TABLE 4.4 (CONT.) TOT. OPT. DEPTH = 0.5 ALBEDO = 0.0 G = 0.0

[SOLAR ZENITH ANGLE INCREASING -----]

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### Table 4.5

**SOLAR ZENITH ANGLE INCREASING -----**

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| Solar Zenith Angle Increasing --- | }

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TABLE 4.5 (Cont.)  
TOT. OPT. DEPTH = 1.0  
ALBEDO = 0.3  
G = 0.8
TABLE 4.5 (CONT.)

| TOT. OPT. DEPTH = 1.0 | ALBEDO = 0.3 | G = 0.8 |

[SOLAR ZENITH ANGLE INCREASING ----> ]

**RATIO OF INTENSITIES UP**

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**RATIO OF INTENSITIES UP**

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TABLE 4.5 (CONT.)  TOT. OPT. DEPTH = 1.0  ALBEDO = 0.5  G = 0.8

[SOLAR ZENITH ANGLE INCREASING -----> ]

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[SOLAR ZENITH ANGLE INCREASING ---- ]

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| SOLAR ZENITH ANGLE INCREASING ---> | |

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| TOTAL OPT. DEPTH = 2.0 | ALBEDO = 0.3 | G = 0.8 |

[SO\'AR ZENITH ANGLE INCREASING ----> ]

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[SOLAR ZENITH ANGLE INCREASING ---- ]

RATIO OF INTENSITIES UP  

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### TABLE 4.7 (CONT.)  
**TOT. OPT. DEPTH = 2.0**  
**ALBEDO = 0.3**  
**G = 0.8**

[SOLAR ZENITH ANGLE INCREASING ———— ]

#### RATIO OF INTENSITIES UP

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[SOLAR ZENITH ANGLE INCREASING ----> ]

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TABLE 4.7 (CONT.)

| TOT. OPT. DEPTH = 2.0 | ALBEDO = 0.3 | G = 0.8 |

[SOLAR ZENITH ANGLE INCREASING -- --] |

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<td>ALBEDO = 0.3</td>
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[SOLAR ZENITH ANGLE INCREASING ---> ]

**RATIO OF INTENSITIES UP**

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**RATIO OF INTENSITIES UP**

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**RATIO OF INTENSITIES DOWN**

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### Table 4.7 (Cont.)

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[SOLAR ZENITH ANGLE INCREASING ---]

#### Ratio of Intensities Up

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#### Ratio of Intensities Down

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**Ratio of Intensities Up**

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**Ratio of Intensities Down**

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**Ratio of Intensities Up**

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**Ratio of Intensities Down**

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### Table 4.8 (Cont.) 

**Total Opt. Depth** = 0.5  
**Albedo** = 0.6  
**G** = 0.8  

[Solar Zenith Angle Increasing ——— ]

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### Table 4.8 (Cont.)

**Total Opt. Depth = 0.5, Albedo = 0.6, G = 0.8**

[Solar Zenith Angle Increasing -->]

#### Ratio of Intensities Up

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#### Ratio of Intensities Down

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#### Ratio of Intensities Up

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**RATIO OF INTENSITIES UP**

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**RATIO OF INTENSITIES DOWN**

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[SOLAR ZENITH ANGLE INCREASING ———— ]

**RATIO OF INTENSITIES UP**

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**RATIO OF INTENSITIES DOWN**

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### Table 4.9: Ratio of LowTransx to Plane Parallel Intensities for the Case of Isotropic Scattering Using 1962 Standard Atmosphere at 11 μm (Single Scattering)

[Observer and Solar Zenith Angles...... 12.95, 82.57, 88.54]

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<td>Observer angles</td>
<td>ISOTROPIC</td>
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<tr>
<td>Observer angles</td>
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<td>Observer at 100 km</td>
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### Table 4.10 (Cont.)

[Observer and Solar Zenith Angles..... 12.95, 82.57, 88.54]

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101
4.4 Spectral Redundancy

For high resolution, plane-parallel, multiple scattering radiative transfer in inhomogeneous media, the gaseous absorption causes the radiative properties to be highly dependent on frequency. Such complex spectral structure requires the monochromatic calculations to be done on a fine frequency grid over the entire spectrum. Computational times are consequently large and procedures to decrease them are sought. Two rather distinct approaches have evolved to deal with this spectral problem. The first, and more highly developed method, is to spectrally model or average the extinction coefficient in some manner and then attempt to use such averaged properties in an appropriately modified radiative transfer equation or its solution. The literature on this approach is too extensive to discuss in detail and shows successful applications for many specific problems [Refs. 22 and 23]. The major limitations of this method are 1) the modeling or averaging is not general, 2) the radiative transfer using averaged properties is almost always an approximation, and 3) that only spectrally averaged quantities can be predicted. In other words this approach lacks generality and has unknown and uncontrolled errors.

The second method of dealing with the spectral problem, and the one pursued in this section, exploits the idea that monochromatic radiative transfer calculations can be highly redundant over a spectral region containing many gaseous absorption/emission lines. Therefore, only a relative few monochromatic multiple scattering calculations are required to represent radiative transfer at all points in the spectral region. Prior research on this approach has taken several forms using the nomenclature of the K or opacity distribution function [Refs. 24 through 27], and is well developed.
only for homogeneous atmospheres or when scattering is neglected. The work on exponential-sum fitting of the direct transmission function [Ref. 28 and 29] can also be related to this method. The research proposed here builds on this previous work and presents the method in a more general manner using the properties of the diffuse transmission functions associated with the adding/doubling computational method for multiple scattering. This different viewpoint makes it easier to understand when and how spectral redundancy can be used to advantage.

To study the spectral redundancy for multiple scattering radiative transfer in the generality being proposed, a general and fast radiative transfer computational code is required. The method of Adding/Doubling has been developed over a period of time by several research groups and is now able to solve any monochromatic, multiple scattering problem in plane-parallel media [Refs. 5, 6, 7, 30, 31 and 32]. Although the particular adding/doubling algorithm to be used here, and developed by one of the authors, is general (internal and external radiative sources, inhomogeneous and non-isothermal media, arbitrary scattering properties of medium and surfaces) and computationally rather fast (5 to 10 CPU seconds on an IBM 370/158 per monochromatic run), it is not fast enough to allow high resolution, point-by-point calculations to be done over the entire spectrum in a realistic gaseous medium for all of the various conditions encountered in modeling engineering and atmospheric environments. Therefore, the following scheme is one possible approach to decrease computational times for obtaining both the total energy flux and the spectral intensity emerging from, or found within, a multiple scattering medium. The concept is rather simple. The approximation is made that all spectral points having the same total optical
depth also have the same, or very similar, direct and diffuse transfer or transmission functions. This is not true in the general case, and the research discussed here is to find out through analysis and numerical experiments the accuracy of this approach in simulating radiative transfer in realistic atmospheres and what further parameters may be required.

As a simple example, consider the problem of radiative transfer through an inhomogeneous medium illuminated by solar radiation. The monochromatic intensity $I_{\nu} (\nu$ denotes frequency) exiting the top and bottom of the medium of total optical depth $t_{\nu}$ can be written as [Ref. 5]

$$I_{\nu}^+ (0, \mu, \phi) = \frac{I_{\nu 0}}{4\pi} \frac{S_s R_s (t_{\nu 0}, \mu, \phi)}{\mu}$$

and

$$I_{\nu}^- (t_{\nu 0}, \mu, \phi) = I_{\nu 0} \left\{ \exp (-t_{\nu 0} /\mu) \delta (\mu-\mu_0, \phi-\phi_0) \right. + \frac{T_s R_s (t_{\nu 0}, \mu, \phi)}{4\pi \mu} \right\} .$$

(4.20)

Here the diffuse transmission functions $S_s R_s$ and $T_s R_s$ are calculated by the Adding/Doubling method and have been modified (superscript R) for any reflecting surface located at $t_{\nu 0}$. $I_{\nu 0}$ is the solar intensity at the top of the atmosphere in the direction of $\mu_0$ ($\cos \nu_0$), $\phi_0$, where $\theta$ and $\phi$ are the zenith and azimuthal angles, respectively. The direct solar beam is angularly turned on by the Dirac delta function $\delta$. The optical depth $t_{\nu}$ is based on the extinction coefficient $k_{\nu}$ by
\[ t_{\nu} = \int_{0}^{x} K_{E_{\nu}}(x) \, dx \]

where \( x \) is the perpendicular distance measured down from the top of the medium, while upward (downward) hemispheric intensities are labeled with a \( +(-) \) superscript. Also note that the full functional arguments for \( S_{S} \) and \( T_{S} \) are not given, and they are calculated for a solar flux of 4 W/m².

If one is concerned with only the direct radiative transfer, the spectral variation of the incident solar flux is usually considered to be smooth and the spectrally summed intensity can be written as

\[
T_{\nu}^{-}(x_{0}, \mu_{0}, \phi_{0}) = 1_{0} \int_{\Delta \nu} \exp(-t_{\nu_{0}} / \mu_{0}) \, dv.
\] (4.21)

The spectrally averaged direct transmission function is the integral in the equation, and it is often approximated by a sum of exponentials as discussed at length in several references [see Refs. 28 and 29]. The exponential sum fitting method is also directly related to the K-distribution method where the spectrally averaged, direct transmission function is written as (for an homogeneous medium)

\[
T(U) = \frac{1}{\Delta \nu} \int_{\Delta \nu} \exp(-K_{E_{\nu}} \, U) \, dv = \int_{0}^{\cdots} f(K_{E}) \exp(-K_{E} \, U) \, dK_{E},
\] (4.22)

where \( U \) is the gas amount and \( f(K_{E}) \) is the K distribution function. This function weights the spectrum according to how often the extinction coefficient has values between \( K_{E} \) and \( K_{E} + dK_{E} \). Such a function can then be used in several different ways [Ref. 26]. The common factor in these constructs
is that all spectral points with the same \( K_e \) or \( t_o \) should be grouped and would then constitute a single monochromatic radiative transfer calculation.

The more general approach is to include the diffuse transmission (scattering) or transfer functions \( S^{R-}_s \) and \( T^{R-}_s \). An intensity spectral sum would then appear as

\[
I^+ = \frac{1}{4\pi} \int_{\Delta v} S^{R-}_s(t_{\nu_0}, \mu, \phi) d\omega .
\]  

(4.23)

Now one must ask for what parametric values does one obtain the same \( S^{R-}_s \). For this, the complete functional dependence of \( S^{R-}_s \) is required and can be expressed as

\[
S^{R-}_s = S^{R-}_s(t_{\nu_0}, \mu, \phi; \omega_{\nu_0}(t_{\nu_0}), P_{\nu}(t_{\nu}), \mu_0, \phi_0).
\]  

(4.24)

Here \( \omega_{\nu_0} \) and \( P_{\nu} \) are the single scattering albedo and phase function, respectively. To make this more explicit, it can be rewritten as

\[
S^{R-}_s = S^{R-}_s \left( \int_{0}^{x_{\nu}} K_{E_{\nu}}(x) dx, \mu, \phi; \frac{K_{S_{\nu}}(x)}{K_{E_{\nu}}(x)}, P_{\nu}(x), \mu_0, \phi_0 \right).
\]  

(4.25)

where \( K_{S_{\nu}} \) is the scattering coefficient. When the medium is homogeneous and one assumes \( K_{S_{\nu}} \) and \( P_{\nu} \) are spectrally smooth, the only remaining spectral parameter is \( t_{\nu_0} \), or

\[
S^{R-}_s = S^{R-}_s(t_{\nu_0})
\]  

(4.26)
and \( S^R_S \) calculations can be grouped into \( t_0 \) bins in the same way as discussed above for direction transmission.

For a given homogeneous medium, the procedure is conceptually straightforward and without physical approximations. A line-by-line algorithm like HIRACC [Ref. 33] which is contained in FASCODE [Ref. 4] would be used to produce the required \( t_0 \) over the spectral region of interest. Using these results, one would then perform a mapping of all frequencies with common \( t_0 \) values. This mapping is retained. The monochromatic multiple scattering code (Adding/Doubling) is then run for a small number of \( t_0 \)'s each of which represent many different values of frequency. The results of these calculations are then used to perform the spectral sums as expressed in Eq. (5), which now takes the form

\[
I^+ = \int_0^\infty S_S^R(t_0) f(t_0) dt_0. \tag{4.27}
\]

The function \( S_S^R(t_0) \) and the extinction or opacity distribution function \( f(t_0) \) are smooth functions so the integral can be evaluated accurately using only a few carefully selected values of \( t_0 \). In addition the high resolution spectral intensity given by Eq. (4.19) can be constructed by an inverse mapping of \( t_0 \) results back to their associated frequency values.

For the realistic situation of an inhomogeneous atmosphere under discussion here, the redundancy for radiative transfer with scattering is more complex. Referring back to the general functional form given by Eq. (4.25) and making the reasonable assumption that \( K_{S,v}(x) \) and \( L_{v}(x) \) are known in \( x \) and spectrally smooth over the spectral region of interest, then
progress can be made with the redundancy concept for inhomogeneous media. The remaining spectral parameter besides $t_{o}$ is $K_{E_{v}}(x)$ that with $K_{s}(x)$ makes up the single scattering albedo. If $K_{E}(v, x)$ could be written as $K_{E}(t_{o}, x)$ when $t_{o} = t_{o}(v)$, then redundancy would be valid and such a situation is called the correlated opacity approximation. For certain simple line models such as equally spaced overlapping lines of equal strength the above parameterization of $K_{E_{v}}$ is valid and redundancy is an exact approach. For realistic inhomogeneous atmospheres it will be shown that the line absorption is not exactly correlated but progress can be made by working with an average (over the $v$'s associated with a given $t_{o}$) $K_{E_{v}}$ or equivalently an appropriately averaged single scattering albedo.

The above theoretical arguments and functional relations can be made clear by an example calculation. This will also give some initial results that will show how successful the redundancy approximation can be for inhomogeneous atmospheres. This initial calculation is not sufficient, however, to say that redundancy will work for all model atmospheres over their entire spectral region.

Although a theoretical argument can and has been made for spectral redundancy, its accuracy and usefulness can only be demonstrated by numerical experiments with realistic model atmospheres. For an initial experiment, a small spectral region was chosen from a standard atmosphere (Model six) of FASCODE (Ref. 4). The total transmittance for this atmosphere, which did not include aerosols, is shown in Fig. 4.2 over the narrow spectral region from 4950 to 4954 cm\(^{-1}\) that contains a mixture of CO\(_{2}\) (uniformly mixed gas) and H\(_{2}\)O (nonuniformly mixed gas) lines. A part of this atmosphere was chosen to work with and was made up of 12 layers that extended from ground to 30 Km. The upper part of the atmosphere from 30 to 100 Km was
Figure 4.2 Spectral total transmittance for FASCOD standard atmospheric model six.
not used since it contributed little to the optical depths. For a total transmittance of 0.40 (optical depth $t_o$ of 0.9163), there are fourteen corresponding frequencies in this spectral region. For each of these frequencies the optical depths of each of the 12 layers were found along with the average (over frequency) optical depth for each layer. In this initial sample calculation, aerosols were added to each layer by assuming the scattering optical depth was $1/9$ of the average absorption optical depth. This gave an average single scattering albedo in each layer of 0.1. A single scattering albedo distribution over the 12 layers was then computed for each of the 14 frequencies by using the actual molecular optical depth in each layer, again for each frequency under study. Note that $1/\omega$ averaged over the frequencies gives the value of 10 for each layer.

To use this data in the multiple scattering Adding/Doubling code, it is convenient to reduce the 12 layers to six layers, five of which have optical depths of 0.127 and the bottom layer has an optical depth of 0.3825.* The new single scattering albedoes were formed from the originals by optical depth weighted averages.† The data from this optical depth and albedo modeling are given in Table 4.11 (note that Ref. doesn't mean average of the albedoes given).

Each of the 14 different frequencies along with their unique single scattering albedo distributions were used in Adding/Doubling multiple scattering calculations for the flux exiting the top and bottom of the atmosphere. The results of these runs were averaged and compared with the one Adding/Doubling run using averaged layer properties. The results are presented in Figs. 4.3 and 4.4 for three sun angles.

*The physical layers therefore become frequency dependent, but this doesn't affect the present calculations.
†Because layers have been merged, the albedoes listed in Table 4.11 no longer give an average (as $1/\omega$) over frequency of 10.
Table 4.11 Layer optical depth, and albedoes for the fourteen spectral points corresponding to the total transmittance of 0.4.

<table>
<thead>
<tr>
<th>POINT</th>
<th>OPTICAL DEPTH BY LAYER FROM TOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3468 0.2211 0.1405 0.0903 0.0527 0.0289 0.0164 0.0093 0.0052 0.0028 0.0026 0.0006</td>
</tr>
<tr>
<td>2</td>
<td>0.4127 0.2356 0.1290 0.0689 0.0355 0.0183 0.0096 0.0053 0.0029 0.0015 0.0014 0.0003</td>
</tr>
<tr>
<td>3</td>
<td>0.4623 0.2494 0.1165 0.0518 0.0209 0.0092 0.0042 0.0022 0.0012 0.0006 0.0006 0.0001</td>
</tr>
<tr>
<td>4</td>
<td>0.4453 0.2389 0.1123 0.0506 0.0220 0.0120 0.0078 0.0059 0.0030 0.0010 0.0004 0.0002</td>
</tr>
<tr>
<td>5</td>
<td>0.3638 0.2293 0.1377 0.0827 0.0467 0.0259 0.0139 0.0075 0.0039 0.0021 0.0019 0.0004</td>
</tr>
<tr>
<td>6</td>
<td>0.3561 0.2365 0.1375 0.0841 0.0478 0.0265 0.0147 0.0077 0.0041 0.0022 0.0019 0.0004</td>
</tr>
<tr>
<td>7</td>
<td>0.3114 0.2208 0.1532 0.0985 0.0597 0.0316 0.0181 0.0106 0.0055 0.0031 0.0029 0.0007</td>
</tr>
<tr>
<td>8</td>
<td>0.3112 0.2224 0.1508 0.1001 0.0590 0.0334 0.0192 0.0106 0.0061 0.0032 0.0031 0.0007</td>
</tr>
<tr>
<td>9</td>
<td>0.3550 0.2124 0.0737 0.0294 0.0134 0.0076 0.0052 0.0038 0.0027 0.0021 0.0019 0.0011</td>
</tr>
<tr>
<td>10</td>
<td>0.5786 0.2207 0.0742 0.0273 0.0114 0.0052 0.0026 0.0013 0.0009 0.0003 0.0003 0.0001</td>
</tr>
<tr>
<td>11</td>
<td>0.3549 0.2292 0.1439 0.0650 0.0491 0.0253 0.0137 0.0076 0.0040 0.0022 0.0020 0.0005</td>
</tr>
<tr>
<td>12</td>
<td>0.3693 0.2254 0.1374 0.0827 0.0481 0.0272 0.0144 0.0077 0.0042 0.0021 0.0020 0.0004</td>
</tr>
<tr>
<td>13</td>
<td>0.3804 0.2290 0.1345 0.0789 0.0442 0.0229 0.0122 0.0068 0.0034 0.0018 0.0017 0.0004</td>
</tr>
<tr>
<td>14</td>
<td>0.4532 0.2424 0.1201 0.0585 0.0263 0.0130 0.0064 0.0032 0.0018 0.0009 0.0008 0.0002</td>
</tr>
</tbody>
</table>

AVERAGE: 0.4072 0.2295 0.1259 0.0705 0.0383 0.0205 0.0113 0.0064 0.0036 0.0021 0.0022 0.0007

<table>
<thead>
<tr>
<th>POINT</th>
<th>ALBEDO BY LAYER FROM BOTTOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.07389 0.08222 0.09071 0.10341 0.10433 0.11541</td>
</tr>
<tr>
<td>2</td>
<td>0.10877 0.09893 0.09773 0.09700 0.09832 0.09860</td>
</tr>
<tr>
<td>3</td>
<td>0.15167 0.10332 0.09276 0.09276 0.09825 0.08914</td>
</tr>
<tr>
<td>4</td>
<td>0.12665 0.11239 0.09734 0.09644 0.09283 0.09223</td>
</tr>
<tr>
<td>5</td>
<td>0.08498 0.08839 0.09291 0.10006 0.10228 0.11061</td>
</tr>
<tr>
<td>6</td>
<td>0.06266 0.06793 0.09351 0.09733 0.09953 0.11273</td>
</tr>
<tr>
<td>7</td>
<td>0.06677 0.07538 0.08567 0.09832 0.10353 0.12532</td>
</tr>
<tr>
<td>8</td>
<td>0.06506 0.07214 0.08489 0.09804 0.10286 0.12525</td>
</tr>
<tr>
<td>9</td>
<td>0.18983 0.12617 0.10719 0.08322 0.07538 0.07538</td>
</tr>
<tr>
<td>10</td>
<td>0.21106 0.11507 0.10357 0.07658 0.07253 0.07253</td>
</tr>
<tr>
<td>11</td>
<td>0.08286 0.06596 0.09017 0.10012 0.10191 0.11307</td>
</tr>
<tr>
<td>12</td>
<td>0.08228 0.08881 0.09429 0.10163 0.10345 0.10914</td>
</tr>
<tr>
<td>13</td>
<td>0.09184 0.09250 0.09627 0.10020 0.10230 0.10630</td>
</tr>
<tr>
<td>14</td>
<td>0.13461 0.10433 0.09556 0.09518 0.09132 0.09077</td>
</tr>
</tbody>
</table>

REF: 0.10000 0.10000 0.10000 0.10000 0.10000 0.10000
Figure 4.3 Transmittance diffuse flux for a total molecular transmittance of 0.4 at each of the fourteen corresponding frequencies (case #')s 2 thru 15) and for average layer properties (case #1).
Reflective diffuse flux for a total molecular transmittance of 0.4 at each of the fourteen corresponding frequencies (case #2 through #15) and for averaged layer properties (case #1).

\[ \theta_0 = 12.9^\circ \]

\[ \theta_0 = 60^\circ \]

\[ \theta_0 = 88.5^\circ \]
The diffusely transmitted flux out of the bottom with sun angles of 12.9°, 60° and 88.5° for each frequency (case number) is shown in Fig. 4.3. Case number one is the run using averaged layer properties and the bar denotes the averages of all the other cases (2 through 15). For the more overhead (lower angles) sun angles the cases show small amounts of variance, while grazing sun angles produce more variance. This variance says that the total optical depth does not control the multiple scattering radiative transfer problem. On the other hand, the averaged property run agrees quite well with the average over frequencies or case number. For example, when the sun is at 88.5° the run using averaged properties gives $Q^{-} \times 10^4 = 0.914$ while the average of all runs gives $Q^{-} \times 10^4 = 0.940$. This results in a 2.8% error and the smaller sun angles produce even less error. The result of this experiment is that the total optical depth and layer properties averaged over all corresponding frequencies for this optical depth can be used in a single multiple scattering run to predict the radiative flux with good accuracy.

The diffusely scattered flux out of the top of the atmosphere for the same conditions discussed above is presented in Fig. 4.4. Here the case by case variance is larger since the reflected flux is more sensitive to the albedo distribution than the diffusely transmitted flux. Again the greatest variance is observed at the more grazing sun angle of 88.5°. For this sun angle, the calculation using the averaged layer properties gives $Q^{+} \times 10^3 = 0.991$ while the average of all calculated cases results in $Q^{+} \times 10^3 = 1.108$. Here the error is 10%, but do note that when the sun angle is 12.9° this error reduces to 2%. Although the error introduced by the redundancy argument is greater for diffusely scattered radiation than for diffusely transmitted radiation and the grazing sun angles produce the
maximum errors, there does appear to be a great deal of spectral redundancy
in multiple scattering radiative transfer.

4.5 Recommendations For Further Research

The need to reduce the number of spectral-like, multiple-scattering cal-
culations was discussed at the beginning of this section. The spectral re-
dundancy concept subsequently developed along with an initial numerical ex-
periment is one logical approach that does reduce the number of multiple
scattering calculations required to obtain radiative fluxes. However, more
theoretical and numerical work is required before spectral redundancy is re-
duced to a practical and useful method. More (different line features) and
larger spectral regions have to be analyzed to find out if redundancy argu-
ments remain valid. This will require a fair number of numerical experiments.

The final goal of spectral redundancy studies is to produce a set of
spectrally averaged (over a specified spectral resolution) atmospheric
properties that can be used in any monochromatic multiple scattering cal-
culation (Adding/Doubling, Monte Carlo, two-stream Delta Approximation, etc.)
to produce accurate radiative transfer predictions. This will not be an
easy or simple task, but it is basic to all other so called alternative
approaches that have been proposed.
REFERENCES


27. Ackerman, T.P., private communication.


APPENDIX A: MIE DATA ACCESS CODE

As mentioned in Chapter 2, the complete output of the MIE calculations was much too large for continuous online storage. Therefore, the data was stored in binary format on a magnetic tape at the AFGL computer center. The volume serial number of the tape is CC-0366, and the file name is MIEOUTPUT10. This file is actually composed of 39 records each containing the results for a particular model at many (up to 27) wavelengths. A summary of the records follows:

<table>
<thead>
<tr>
<th>RECORD #</th>
<th>AEROSOL MODEL</th>
<th>WAVELENGTHS (um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RURAL 0% RH*</td>
<td>0.2 - 1.06</td>
</tr>
<tr>
<td>2</td>
<td>&quot; *</td>
<td>1.536 - 5.0</td>
</tr>
<tr>
<td>3</td>
<td>&quot;</td>
<td>6.0 - 40.0</td>
</tr>
<tr>
<td>4</td>
<td>RURAL 70% RH*</td>
<td>0.2 - 1.536</td>
</tr>
<tr>
<td>5</td>
<td>&quot; *</td>
<td>2.0 - 3.392</td>
</tr>
<tr>
<td>6</td>
<td>RURAL 80% RH*</td>
<td>0.2 - 3.392</td>
</tr>
<tr>
<td>7</td>
<td>RURAL 99% RH</td>
<td>0.2 - 40.0</td>
</tr>
<tr>
<td>8</td>
<td>URBAN 0% RH*</td>
<td>0.2 - 5.0</td>
</tr>
<tr>
<td>9</td>
<td>&quot;</td>
<td>6.0 - 40.0</td>
</tr>
<tr>
<td>10</td>
<td>URBAN 70% RH*</td>
<td>0.2 - 5.0</td>
</tr>
<tr>
<td>11</td>
<td>&quot;</td>
<td>6.0 - 40.0</td>
</tr>
<tr>
<td>12</td>
<td>URBAN 80% RH</td>
<td>0.2 - 5.0</td>
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<tr>
<td>13</td>
<td>&quot;</td>
<td>6.0 - 40.0</td>
</tr>
<tr>
<td>14</td>
<td>URBAN 99% RH</td>
<td>0.2 - 40.0</td>
</tr>
<tr>
<td>15</td>
<td>OCEANIC 0% RH*</td>
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<tr>
<td>16</td>
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<td>17</td>
<td>OCEANIC 70% RH*</td>
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<tr>
<td>18</td>
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<td>6.0 - 40.0</td>
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<tr>
<td></td>
<td>OCEANIC 80% RH*</td>
<td></td>
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<tr>
<td></td>
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<td>39</td>
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<td></td>
</tr>
</tbody>
</table>

*This data was generated by a version of the code that had underdimensioned arrays. Data other than the normalized phase matrix may be incorrect and should be used with caution.

The data for these two models at wavelengths from 5.0 to 40.0 μ were not saved.

+It has recently been discovered that these records were generated using incorrect refractive index data. The reader is referred to Eric Shettle of AFGL, who has recalculated these phase functions using the correct data.
The data can only be accessed with the FORTRAN program (called RDTPIOB) listed below:

```fortran
PROGRAM RDTPIOB(INPUT, OUTPUT, TAPE5, TAPE6)
C
C THIS PROGRAM IS USED TO READ THE BINARY OUTPUT
C OF THE MIE CALCULATIONS STORED ON "TAPE5" AND
C WRITE THE OUTPUT TO "TAPE6".
C
C PLEASE CONSULT APPENDIX A OF THE LOWTRAN SINGLE
C SCATTERING REPORT REGARDING THE VALIDITY OF
C SOME OF THE DATA.
C
NTHETA IS THE NUMBER OF SCATTERING ANGLES, = 34
C
NTHETA IS THE NUMBER OF COSINES FOR EQUAL PROBABILITY
C INTERVALS, EQUALS 25 OR 36.
C
THE CONTENTS OF THE ENTIRE FILE ARE COPIED, I.E. THE
C PHASE-FUNCTION DATA FOR A GIVEN AEROSOL MODEL AT
C UP TO 27 WAVELENGTHS. REFER TO THE CHAPTER 2 OF
C THE SINGLE SCATTERING REPORT FOR A SUMMERY OF THE
C FILE CONTENTS
C
COMPLEX PM
DIMENSION TH(34), PHAS1(34), PHAS2(34), PHAS3(34),
1 PHAS4(34), CMOP(36)
C
950 FORMAT(//" INDEX OF REFRACTION WAVELENGTH 4 KEXT "
1 ' K SIT")
960 DO 10 I=1,27
970 WRITE(6,960)
980 PM, IROB, WAVE, CEXT, SCSR0, NTHETA, NFANG
990 IF (I>35) 200, 5
100 5 : JAD(3) (TH(I), I=1, NTHETA),
1 (PHAS1(I), I=1, NTHETA), (PHAS2(I), I=1, NTHETA), (PHAS3(I),
2 I=1, NTHETA), (PHAS4(I), I=1, NTHETA), (CMOP(I), I=1, NFANG)
105 WRITE(6,910) PM, WAVE, CEXT, SCSR0
106 WRITE(6,920)
107 920 FORMAT(" WAVELENGTH 4 KEXT")
108 DO 10 I=1,27
109 WRITE(6,910)
110 PM, IROB, WAVE, CEXT, SCSR0, NTHETA, NFANG
111 IF (I>35) 200, 5
112 5 : JAD(2) (TH(I), I=1, NTHETA),
1 (PHAS1(I), I=1, NTHETA), (PHAS2(I), I=1, NTHETA), (PHAS3(I),
2 I=1, NTHETA), (PHAS4(I), I=1, NTHETA), (PHAS5(I), I=1, NTHETA),
3 (PHAS6(I), I=1, NTHETA), (PHAS7(I), I=1, NTHETA), (PHAS8(I),
4 I=1, NTHETA), (CMOP(I), I=1, NFANG)
116 WRITE(6,910) PM, WAVE, CEXT, SCSR0
117 WRITE(6,920)
118 920 FORMAT(" COSINES FOR EQUAL PROBABILITY INTERVALS")
119 DO 10 I=1,27
120 WRITE(6,910)
121 PM, IROB, WAVE, CEXT, SCSR0, NTHETA, NFANG
122 IF (I>35) 200, 5
123 5 : JAD(2) (TH(I), I=1, NTHETA),
1 (PHAS1(I), I=1, NTHETA), (PHAS2(I), I=1, NTHETA), (PHAS3(I),
2 I=1, NTHETA), (PHAS4(I), I=1, NTHETA), (PHAS5(I), I=1, NTHETA),
3 (PHAS6(I), I=1, NTHETA), (PHAS7(I), I=1, NTHETA), (PHAS8(I),
4 I=1, NTHETA), (CMOP(I), I=1, NFANG)
126 WRITE(6,910) PM, WAVE, CEXT, SCSR0
127 WRITE(6,920)
128 920 FORMAT(" WAVELENGTH")
129 DO 10 I=1,27
130 WRITE(6,910)
131 PM, IROB, WAVE, CEXT, SCSR0, NTHETA, NFANG
132 IF (I>35) 200, 5
133 5 : JAD(2) (TH(I), I=1, NTHETA),
1 (PHAS1(I), I=1, NTHETA), (PHAS2(I), I=1, NTHETA), (PHAS3(I),
2 I=1, NTHETA), (PHAS4(I), I=1, NTHETA), (PHAS5(I), I=1, NTHETA),
3 (PHAS6(I), I=1, NTHETA), (PHAS7(I), I=1, NTHETA), (PHAS8(I),
4 I=1, NTHETA), (CMOP(I), I=1, NFANG)
136 WRITE(6,910) PM, WAVE, CEXT, SCSR0
137 WRITE(6,920)
138 920 FORMAT("")
139 121
```

The program reads one record from "TAPE5" (the binary data file) and writes the information to "TAPE6" for examination, cataloging, etc. While this program is capable of operating directly on the magnetic tape, it is not recommended. The binary data file should be copied (in binary) from the tape to a mass storage disk file. This allows interactive execution of the program and avoids the possibility of repeated tape mounts in the event that problems arise.

The following example should clarify the use of the program. Assuming that a compiled version of RDTP10B is local file LGO and the binary data file is local file DATATP, the following commands could be used to retrieve the aged volcanic data in record number 32.

```
COPYBR, DATATP, DUMMY, 31
COPYBR, DATATP, TAPE5
REWIND, TAPE5
LGO
```

The first three commands copy the data in record number 32 to TAPE5 and then rewind it. The last command executes the program. A copy of the contents of file number 32 would appear in coded format in local file TAPE6. A portion of the output that would result from the above sequence will is shown below:

The headings above the output are self-explanatory. The first line of output consists of the complex index of refraction, wavelength, extinction coefficient, and scattering coefficient. This is followed by six columns of data. Each column has 34 entries, one for each scattering angle. The first column lists the scattering angles. The next four columns are the four Stokes parameters, and the last column the phase function for unpolarized light (i.e. the numerical average of the first two Stokes parameters). The final portion of output is
a single column containing the cosines for equal probability intervals. Similar sets of output would be repeated for each of the remaining 26 wavelengths.
<table>
<thead>
<tr>
<th>INDEX OF REFRACTION</th>
<th>WAVELENGTH</th>
<th>K EXT</th>
<th>K SST</th>
</tr>
</thead>
<tbody>
<tr>
<td>158000785.01 - 270030785.01</td>
<td>203007795.01</td>
<td>115954380.01</td>
<td>61653820.01</td>
</tr>
</tbody>
</table>

### CASING FOR EQUAL PROBABILITY INTERVALS

- 0.01: 0.00
- 0.05: 0.00
- 0.10: 0.00
- 0.15: 0.00
- 0.20: 0.00
- 0.25: 0.00
- 0.30: 0.00
- 0.35: 0.00
- 0.40: 0.00
- 0.45: 0.00
- 0.50: 0.00
- 0.55: 0.00
- 0.60: 0.00
- 0.65: 0.00
- 0.70: 0.00
- 0.75: 0.00
- 0.80: 0.00
- 0.85: 0.00
- 0.90: 0.00
- 0.95: 0.00
- 1.00: 0.00
- 1.05: 0.00
- 1.10: 0.00
- 1.15: 0.00
- 1.20: 0.00
- 1.25: 0.00
- 1.30: 0.00
- 1.35: 0.00
- 1.40: 0.00
- 1.45: 0.00
- 1.50: 0.00
- 1.55: 0.00
- 1.60: 0.00
- 1.65: 0.00
- 1.70: 0.00
- 1.75: 0.00
- 1.80: 0.00
- 1.85: 0.00
- 1.90: 0.00
- 1.95: 0.00
- 2.00: 0.00
- 2.05: 0.00
- 2.10: 0.00
- 2.15: 0.00
- 2.20: 0.00
- 2.25: 0.00
- 2.30: 0.00
- 2.35: 0.00
- 2.40: 0.00
- 2.45: 0.00
- 2.50: 0.00
- 2.55: 0.00
- 2.60: 0.00
- 2.65: 0.00
- 2.70: 0.00
- 2.75: 0.00
- 2.80: 0.00
- 2.85: 0.00
- 2.90: 0.00
- 2.95: 0.00
- 3.00: 0.00
APPENDIX B: LOWTRANSX STRUCTURE

This section of the report describes the structure of the single scattering portions of the LOWTRANSX code. A complete description of the original LOWTRAN code can be found in Reference [1]. Changes made in the original LOWTRAN routines are described first. Next a discussion and flow chart is presented for each of the newly introduced subroutines. Finally, a list of new variables and their definitions is provided.

B.1 Changes in Original LOWTRAN Routines

1. In the main routine LOWEM, the control parameter ISCTTR and control card 2A were added to the input data file to provide for specification of the single scattering control parameters. The definitions of the new control parameters can be found in the comments at the beginning of the code and also in Appendix C of this report. Additional blank common areas have been added to provide space for the new single scattering quantities. The only major change in program flow was the addition of a CALL SSGEO statement. Subroutine SSGEO is a new driving routine which will be discussed along with all other new routines in Section B.2.

2. Subroutine TRANS has been modified to perform two, rather than one transmittance calculations at each scattering point along the line-of-sight. The first calculation is for the L-shaped path from the extraterrestrial source to the scattering point on the optical path, then along the optical path to the observer. The second transmittance calculation is for the path from the scattering point to the observer. After each transmittance calculation subroutine SSRAD (a new routine) is called to either save the transmittances (during the first call) or perform the single scattering intensity calculation (during the second call).
3. Subroutine RFPATH has been modified to save the earth centered angle increment DBETA, and the path zenith angle THETA, in arrays ADBETA and ATHETA, respectively. These quantities are necessary for specifying the scattering point-to-sun paths and the scattering angles.

No other significant changes have been made to the original LOWTRAN routines.

B.2 New Subroutines

1. Subroutine SSGEO drives the single-scattering geometry calculations. If ISCTTR = 1, (i.e. the single scattering calculation is desired) SSGEO is called immediately after GEO is called for the optical path geometry calculations. SSGEO first saves all path quantities such as H1, H2, ANGLE, etc., along with the arrays WLAY, WPATH and TBBY. This is done to avoid losing the information during subsequent GEO calls for the scattering point to sun amounts. Next, SSGEO calls subroutine PSIDEL to determine the values of PS10 (the relative azimuth between the optical path and the sun's rays at the observer) and DEL0 (the angle subtended at the earth's center by the observer and the subsolar point). This is followed by the loop over the scattering points, during which SSGEO calls function PSI, DEL and SCTANG along with subroutine GEO (the LOWTRAN geometry routine) to determine the cumulative point to sun absorber amounts. These absorber amounts are then stored in the array WPATHS, which is analogous to the optical path absorber amount array WPATH. Upon completion of all geometry calculations, the optical path parameters and arrays are restored, and control is returned to LOWEM.

2. Subroutine PSIDEL computes and returns the values of PS10 and DEL0.
3. Function PSI returns the value of the relative azimuth angle between the line-of-sight and the direct solar path.

4. Function DEL returns the value of the angle subtended at the earth's center by the subsolar point and a scattering point. This is also the straight path approximation for the sun's zenith angle at the scattering point. An iteration of the geometry calculation is performed by SSGEO if the bending along the sun path is greater than one-tenth degree.

5. Function SCTANG determines the value of the included angle for single scattering, i.e., the angle between the sun's rays and the line-of-sight optical path.

6. Subroutine SSRAD is called by TRANS after each transmittance calculation. TRANS has been modified to perform two transmittance calculations at each scattering point along the optical path. When called following the first transmittance calculation, SSRAD saves the total transmittance for the L path. After the second call SSRAD uses the current optical path transmittance along with the previously saved L path transmittance to calculate the single scattering intensity contribution from the current layer.

7. Subroutine SOURCE contains the extraterrestrial source intensity data as a function of wavelength [34]. A correction factor accounts for the earth's elliptic orbit. Lunar intensities (when required) are based on the solar intensity and stored values of the wavelength dependent albedo [36, 37] and angle dependent phase function [38] of the lunar surface.

8. Subroutine SUBSOL determines the sub-solar point angles, that is the longitude and latitude where the sun is directly overhead.
9. Subroutine PHASEF returns the value of the aerosol phase function when the MIE data base is used. First the aerosol model number and the bounding angle, wavelength and humidity (if within the 0–2 Km boundary layer) indices are determined. Function PF is then called to obtain the appropriate data from the PFnn subroutines which contain the results of the MIE calculations described in Chapter 2. Subroutine INTERP is called to perform any necessary interpolations.

10. Function PF calls the appropriate PFnn data subroutine.

11. Subroutines PFnn(wherenn = 01 to 22) contain the phase function data for aerosol model nn.

12. Subroutine INTERP performs linear and logarithmic interpolation.

B.3 Flow Charts of New Subroutines

Figure B1 through B12 are flow charts of the subroutines described above.

B.4 New Variables and Their Definitions

Variables introduced in the development of LOWTRANSX are listed and defined below.

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>FIRST REFERENCE</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADBETA</td>
<td>MAIN</td>
<td>Optical path, earth-centered-angle increment array</td>
</tr>
<tr>
<td>AIT</td>
<td>MAIN</td>
<td>Scattering point altitude array</td>
</tr>
<tr>
<td>ALAM</td>
<td>PHASEF</td>
<td>Wavelength</td>
</tr>
<tr>
<td>ALL</td>
<td>SOURCE</td>
<td>Lunar albedo array</td>
</tr>
<tr>
<td>ALT</td>
<td>PHASEF</td>
<td>Altitude</td>
</tr>
<tr>
<td>ANG0</td>
<td>SSGEO</td>
<td>Optical path zenith</td>
</tr>
<tr>
<td>ANGF</td>
<td>MAIN</td>
<td>User supplied phase function scattering angle array</td>
</tr>
<tr>
<td>ANGLO</td>
<td>SSGEO</td>
<td>Straight line approximation of solar zenith</td>
</tr>
</tbody>
</table>
Figure B1 Flow chart of subroutine SSGEO.

129
Define HIST, ANGLST, LEN and DHR using data stored in arrays and calling functions PE1 and PE4.

HIST = HRRP or LEN = 1

Scattering point is at above
the top of the atmosphere and
LEN = 0; set absorber amount
equal to zero and continue

CRR = 0

ANGLST = ANGLE - CRR

LEN = 0

Call GPM

abs(CRR - BEMOR) = 1

CRR = BEMOR

Call SRTAM to determine
the scattering angle

molecular phase function

IPR = 0

vIPR = 1

Henyey-Greenstein
phrase function

User supplied
phrase function

Read SRTAM array

End of loop over scattering points

Restore optical path parameters and arrays

Return

Figure B1 (cont'd)
Figure B2 Flow Chart of subroutine PSIDEL
Figure B2 (cont'd)
Argument list
- PSIO - relative azimuth at the observer
- DELO - angle subtended at the earth's center by the observer and the subsolar point
- BETA - angle subtended at the earth's center by the observer and the scattering point
- IARS - arbitrary azimuth flag
  - 0 azimuth is not arbitrary
  - 1 azimuth is arbitrary
- IARBO - arbitrary initial azimuth flag
  - 0 azimuths are not arbitrary
  - 1 path azimuth is arbitrary
  - 2 solar azimuth is arbitrary
  - 3 both azimuths are arbitrary

Calculate DEL0 and BET0; the radian measure equivalents of DEL0 and BETA

PSIO = 0

IARS = IARBO

PSI = 180

Return

Figure B3 Flow chart of function PSI1
Argument list:
PS10 - relative azimuth at the observer
DELO - angle subtended at the earth's center by the observer and the subsolar point
BETA - angle subtended at the earth's center by the observer and the scattering point
IARRO - arbitrary initial azimuth flag
0 azimuths are not arbitrary
1 path azimuth is arbitrary
2 solar azimuth is arbitrary
3 both azimuths are arbitrary

Calculate PS1OR, BETAR, DELOR; the radian measure equivalents of PS10, BETA and DELO

Figure B4 Flow chart of function DEL

Argument list:
ANCLST - solar zenith angle
THRST - path zenith angle
PS1ST - relative azimuth
IAR - arbitrary azimuth flag
0 azimuth is non arbitrary
0 azimuth is arbitrary

Calculate S11ZEN and PHZEN; the radian measure equivalents of ANCLST and THRST

Calculate PSI; the radian measure equivalent of PS1ST

Figure 95 Flow chart of function SCTANG
Figure B6  Flow chart of subroutine SSRAD
The extraterrestrial source intensity is stored in ESUN(210) at the 210 wavelengths in VSUN(210). Lunar intensities are based on the solar intensity, the lunar albedo stored in ALB(29) and the lunar phase function stored in PHS(17).

\[ V = \frac{10000}{VV} \]

1. ISOURC = 1
2. ICALL = 1
3. FPHS = f(ANGLE)
4. FALB = f(V)
5. ICALL = 1
6. FORHIT = f(IDAY)
7. ICALL = 1
8. SS = f(V)
9. SS = SS · FORHIT
10. ISOURC = 1
11. SS = f(SS, FPHS, FALB)
12. Change intensity units from m-2 to cm-2
13. Return

Figure B7: Flow chart of subroutine SOURCE
Argument list:
- THETAS - subsolar latitude
- PHIS - subsolar longitude
- TIME - Greenwich time
- IDAY - day of the year

Declination angle and equation of time data are stored in DEC(25) and EQT(25) for the 25 days stored in NDAY(25)

EQTIME = f(IDAY)
DECANG = f(IDAY)

THETAS = DECANG

Convert EQTIME to minutes

PHIS = f(TIME, EQTIME)

PHIS < 0  \rightarrow  PHIS = PHIS + 360

Return

Figure B8 Flow chart of subroutine SUBSOL
Figure B9 Flow chart of subroutine PHASEF
Determine IANG1 and IANG2, the bounding scattering angle indices. If ANG corresponds exactly to one of the angles in ANG set IANG1 - IANG2.

Determine IWAV1 and IWAV2, the bounding wavelength indices. If ALAM corresponds exactly to one of the wavelengths in WAVE set IWAV1 - IWAV2.

- If IWAV1 = IWAV2, IANG1 = IANG2 → No interpolation necessary
- If IANG1 = IANG2, interpolate in angle
- Interpolate in both angle and wavelength
- Interpolate in wavelength

Check for humidity dependency
- ALT > 2 or NN > 17 or IRHLo = IRHH1

Repeat procedure at upper bounding humidity and call INTERP to determine the value at the desired humidity.

Figure B9 (cont'd)
Argument list
NN - aerosol model number, = 01, 02, ..., 22
I - wavelength index
J - scattering angle index

Call PFNN(ARG,I,J)
PF = ARG

Return

Figure B10 Flow chart of function PF

There are 22 subroutines of this form namely: PF01, PF02, ..., PF22
Argument list
ARG - desired phase function value
II - wavelength index
JJ - scattering angle index

Phase function data for aerosol model number NN is stored in array X(I,J)
of II wavelengths and JJ scattering angles

ARG = X(I,J)

Return

Figure B11 Flow chart of subroutine PFnn

Argument list
INTYPE - indicated interpolation method
* 1 for linear interpolation
* 2 for logarithmic interpolation
X - independent variable
X1 - lower bounding value of X
X2 - upper bounding value of X
F - desired function value at X
F1 - function value at X1
F2 - function value at X2

INTYPE = INTYPE
F1 ≤ 0 or F2 ≤ 0  ----> INTYPE = 1

INTYPE = 2
Logarithmic interpolation

Linear interpolation

Return

Figure B12 Flow chart of subroutine INTERP
<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>FIRST REFERENCE</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANGLE</td>
<td>SOURCE</td>
<td>Lunar phase angle</td>
</tr>
<tr>
<td>ANGLEM</td>
<td>MAIN</td>
<td>Same as &quot;ANGLE&quot; above</td>
</tr>
<tr>
<td>ANGLST</td>
<td>SSGEIO</td>
<td>Solar zenith</td>
</tr>
<tr>
<td>ARH</td>
<td>MAIN</td>
<td>Relative humidity array</td>
</tr>
<tr>
<td>ATHETA</td>
<td>MAIN</td>
<td>Optical path zenith angle array</td>
</tr>
<tr>
<td>AZ</td>
<td>SSGEIO</td>
<td>Layer boundary altitude array</td>
</tr>
<tr>
<td>BENDING</td>
<td>SSGEIO</td>
<td>Solar path bending</td>
</tr>
<tr>
<td>CORR</td>
<td>SSGEIO</td>
<td>Solar path bending correction</td>
</tr>
<tr>
<td>DELO</td>
<td>SSGEIO</td>
<td>Solar declination angle</td>
</tr>
<tr>
<td>DELO</td>
<td>SSGEIO</td>
<td>Angle subtended at the earth's center by the observer and the subsolar point</td>
</tr>
<tr>
<td>EQT</td>
<td>SUBSOL</td>
<td>Equation of time</td>
</tr>
<tr>
<td>ESUN</td>
<td>SOURCE</td>
<td>Extraterrestrial solar intensity array</td>
</tr>
<tr>
<td>F</td>
<td>MAIN</td>
<td>User supplied phase function array</td>
</tr>
<tr>
<td>FALB</td>
<td>SOURCE</td>
<td>Lunar albedo</td>
</tr>
<tr>
<td>FORBIT</td>
<td>SOURCE</td>
<td>Solar elliptic orbit factor</td>
</tr>
<tr>
<td>FPHS</td>
<td>SOURCE</td>
<td>Lunar phase function</td>
</tr>
<tr>
<td>G</td>
<td>MAIN</td>
<td>Asymmetry parameter, see user's guide</td>
</tr>
<tr>
<td>LANG1</td>
<td>PHASEF</td>
<td>Lower bounding angle index</td>
</tr>
<tr>
<td>LANG2</td>
<td>PHASEF</td>
<td>Upper bounding angle index</td>
</tr>
<tr>
<td>IARB</td>
<td>SSGEIO</td>
<td>Flag indicating arbitrary azimuth</td>
</tr>
<tr>
<td>IARBO</td>
<td>SSGEIO</td>
<td>Flag indicating arbitrary initial azimuth</td>
</tr>
<tr>
<td>IDAY</td>
<td>MAIN</td>
<td>Day of the year, see user's guide</td>
</tr>
<tr>
<td>IPARM</td>
<td>MAIN</td>
<td>Control parameter, see user's guide</td>
</tr>
<tr>
<td>IPATH</td>
<td>SSGEIO</td>
<td>Flag indicating straight or L-path</td>
</tr>
<tr>
<td>IPH</td>
<td>MAIN</td>
<td>Control parameter, see user's guide</td>
</tr>
<tr>
<td>IRH11I</td>
<td>PHASEF</td>
<td>Lower bounding relative humidity index</td>
</tr>
<tr>
<td>IRH1LO</td>
<td>PHASEF</td>
<td>Upper bounding relative humidity index</td>
</tr>
<tr>
<td>ISCTTR</td>
<td>MAIN</td>
<td>Control parameter, see user's guide</td>
</tr>
<tr>
<td>ISOURC</td>
<td>MAIN</td>
<td>Control parameter, see user's guide</td>
</tr>
<tr>
<td>ITZERO</td>
<td>TRANS</td>
<td>Flag indicating that scattering point is in the shade</td>
</tr>
<tr>
<td>IWAV1</td>
<td>PHASEF</td>
<td>Lower bounding wavelength index</td>
</tr>
<tr>
<td>IWAV2</td>
<td>PHASEF</td>
<td>Upper bounding wavelength index</td>
</tr>
<tr>
<td>NANGLS</td>
<td>MAIN</td>
<td>Control parameter, see user's guide</td>
</tr>
<tr>
<td>VARIABLE</td>
<td>FIRST REFERENCE</td>
<td>DEFINITION</td>
</tr>
<tr>
<td>----------</td>
<td>----------------</td>
<td>------------</td>
</tr>
<tr>
<td>NN</td>
<td>PHASEF</td>
<td>Aerosol model number</td>
</tr>
<tr>
<td>Pi</td>
<td>MAIN</td>
<td>Aerosol phase function array</td>
</tr>
<tr>
<td>PAL</td>
<td>SSRAD</td>
<td>Aerosol phase function at previous scattering point</td>
</tr>
<tr>
<td>PAER2</td>
<td>SSRAD</td>
<td>Aerosol phase function at current scattering point</td>
</tr>
<tr>
<td>PARM1</td>
<td>MAIN</td>
<td>Variable input parameter, see user's guide</td>
</tr>
<tr>
<td>PARM2</td>
<td>MAIN</td>
<td>Variable input parameter, see user's guide</td>
</tr>
<tr>
<td>PARM3</td>
<td>MAIN</td>
<td>Variable input parameter, see user's guide</td>
</tr>
<tr>
<td>PARM4</td>
<td>MAIN</td>
<td>Variable input parameter, see user's guide</td>
</tr>
<tr>
<td>PHFA1</td>
<td>PHASEF</td>
<td>Phase function at lower bounding relative humidity</td>
</tr>
<tr>
<td>PHFA2</td>
<td>PHASEF</td>
<td>Phase function at upper bounding relative humidity</td>
</tr>
<tr>
<td>PHI0</td>
<td>SSGEO</td>
<td>Observer longitude</td>
</tr>
<tr>
<td>PHI5</td>
<td>SSGEO</td>
<td>Subsolar longitude</td>
</tr>
<tr>
<td>PHS</td>
<td>SOURCE</td>
<td>Lunar phase function array</td>
</tr>
<tr>
<td>PMOL1</td>
<td>SSRAD</td>
<td>Molecular phase function at previous scattering point</td>
</tr>
<tr>
<td>PMOL2</td>
<td>SSRAD</td>
<td>Molecular phase function at current scattering point</td>
</tr>
<tr>
<td>PR</td>
<td>MAIN</td>
<td>Molecular phase function array</td>
</tr>
<tr>
<td>PS10</td>
<td>SSGEO</td>
<td>Relative azimuth at the observer</td>
</tr>
<tr>
<td>PS1PO</td>
<td>MAIN</td>
<td>Line of sight azimuth at the observer</td>
</tr>
<tr>
<td>PS1SO</td>
<td>SSGEO</td>
<td>Solar azimuth at the observer</td>
</tr>
<tr>
<td>PS1ST</td>
<td>SSGEO</td>
<td>Relative azimuth</td>
</tr>
<tr>
<td>RAT</td>
<td>SOURCE</td>
<td>Solar elliptic orbit factor array</td>
</tr>
<tr>
<td>RHD</td>
<td>SSGEO</td>
<td>Relative humidity array</td>
</tr>
<tr>
<td>RHPTS</td>
<td>PHASEF</td>
<td>Bounding relative humidities array</td>
</tr>
<tr>
<td>SANGLE</td>
<td>SSGEO</td>
<td>Scattering angle</td>
</tr>
<tr>
<td>SS</td>
<td>SOURCE</td>
<td>Extraterrestrial source intensity</td>
</tr>
<tr>
<td>SUMSSR</td>
<td>TRANS</td>
<td>Total scattering single-radiance at the observer</td>
</tr>
<tr>
<td>TASP1</td>
<td>SSRAD</td>
<td>Aerosol scatter transmittance at previous scattering point</td>
</tr>
<tr>
<td>VARIABLE</td>
<td>FIRST REFERENCE</td>
<td>DEFINITION</td>
</tr>
<tr>
<td>----------</td>
<td>----------------</td>
<td>------------</td>
</tr>
<tr>
<td>TASP2</td>
<td>SSRAD</td>
<td>Aerosol scatter transmittance at current scattering point</td>
</tr>
<tr>
<td>TEB1</td>
<td>SSRAD</td>
<td>Total extinction transmittance at previous scattering point</td>
</tr>
<tr>
<td>TEB2</td>
<td>SSRAD</td>
<td>Total extinction transmittance at current scattering point</td>
</tr>
<tr>
<td>THETAO</td>
<td>SS GEO</td>
<td>Observer latitude</td>
</tr>
<tr>
<td>THETAS</td>
<td>SS GEO</td>
<td>Subsolar latitude</td>
</tr>
<tr>
<td>TIME</td>
<td>MAIN</td>
<td>Greenwich time</td>
</tr>
<tr>
<td>TMSP1</td>
<td>SSRAD</td>
<td>Molecular scattering transmittance at previous scattering point</td>
</tr>
<tr>
<td>TMSP2</td>
<td>SSRAD</td>
<td>Molecular scattering transmittance at current scattering point</td>
</tr>
<tr>
<td>VSUN</td>
<td>SOURCE</td>
<td>Wavelength array corresponding to the solar intensity array ESUN</td>
</tr>
<tr>
<td>WPATHS</td>
<td>MAIN</td>
<td>Cumulative absorber amount array for the solar paths</td>
</tr>
</tbody>
</table>
APPENDIX C: LOWTRANSX USER'S GUIDE

The instructions for using LOWTRAN with single scattering are very similar to those for using LOWTRAN 5. The parameter ISCTTR has been added to the LOWTRAN input card 1. Control card 2A which contains all of the single scattering parameters (with the exception of ISCTTR) has also been added. The format of the new card sequence, definitions of new input parameters and a sample run are presented in this appendix.

C.1 Input Data and Format

The parameters required to specify a particular problem are contained on the four or five (if single scattering is included) input cards as follows:

CARD 1  MODEL, IHAZE, ITYPE, LEN, JP, IM, M1, M2, M3, ML, IEMISS, RO, THOUND, ISEASN, IVULCN, ISCTTR, VIS
       FORMAT (11I3, 2F10.3, 3I3, F10.3)

CARD 2  H1, H2, ANGLE, RANGE, BETA
       FORMAT (7F10.3)

The following card must be included if ISCTTR = 1

CARD 2A  PARM1, PARM2, PARM3, PARM4, TIME, PSIPO, ANGLEM, G, IPH, IDAY, ISOURC, IPARM
         FORMAT (8F7.2, 4I3)

CARD 3  V1, V2, DV
        FORMAT (3F10.3)

CARD 4  1XY
        FORMAT (I3)

If MODEL = 0 or 7 (user supplied meteorological data) the above card sequence and format for CARD 2 is changed. The user is referred to Reference 1 for a complete description of these cases.
C.2 Basic Instructions

It is assumed that the user is familiar with all of the earlier LOWTRAN control parameters as described in Reference 1. The following discussion deals only with the new parameters and their effect, if any, on the original ones.

CARD 1 Remains unchanged except for the addition of the parameter ISCTTR defined as follows:

\( ISCTTR = 0 \) The program runs in the usual transmission or emission mode. Single scattering effects are not included, and CARD 2A must be omitted.

\( ISCTTR = 1 \) The program must be run in the emission mode (IEMISS = 1). If the user has specified ISCTTR = 1 and IEMISS = 0 the program automatically sets IEMISS = 1 and continues. CARD 2A must be included in the input card sequence. Single scattering intensity calculations are performed, and the results are written on TAPE6 and TAPE7.

CARD 2 All parameters as defined in Reference 1.

CARD 2A PARM1, PARM2, PARM3, PARM4, TIME, PSIPO, ANGLEM, G, IPH, ISOURC, IDAY, IPARM

Definitions of PARM1, PARM2, PARM3, PARM4 determined by value of IPARM.

For IPARM = 0

PARM1 = observer latitude (-90 to +90)
Note if \( \text{ABS(PARM1)} \) is greater than 89.5 the observer is assumed to be at either the north or the south pole. In this case the path azimuth is undefined. The direction of the line-of-sight must be specified as the longitude that the path lies along. This quantity rather than the usual azimuth is read in.

PARM2 = observer longitude (0 to 360)

PARM3 = source (sun or moon) latitude, see note regarding sun angle

PARM4 = source (sun or moon) longitude
For IPARM = 1

(TIME must be specified, cannot be used with ISOURC = 1)

PARM1 = observer latitude (-90 to +90)
PARM2 = observer longitude (0 to 360)
PARM3, PARM4 are not required

For IPARM = 2

PARM1 = azimuthal angle between the observer's line of sight and the
observer-to-sun path, measured from the line of sight, positive
east of north, between -180 and 180
PARM2 = the sun's zenith angle
PARM3, PARM4 are not required

TIME = Greenwich time in decimal hours, i.e. 8:45 am is 8.75, 5:20 pm
is 17.33 etc).

PSIPO = path azimuth (degrees east of north, i.e due north is 0.0 due
east is 90.0 etc.

ANGLEM = phase angle of the moon, i.e. the angle formed by the sun,
moon and earth (required if ISOURC = 1)

G = asymmetry factor for use with H.G. phase function

IPH = 0 Henyey-Greenstein aerosol phase function
IPH = 1 user supplied aerosol phase function

The user supplied phase function data follows input card 2A and must
have the following format:

CARD 2B NPTF / FORMAT (15)
CARD 2C ANG(1), F(1, 1), F(2, 1), F(3, 1), F(4, 1) / FORMAT (5E10.3)
CARD 2C is repeated NPTF times

The variables are defined as follows:

NPTF - the number of scattering angles at which the phase function is
to be specified. NPTF < 50

ANG(I) - the I'th scattering angle at which the phase function is
specified. 0 < ANG(I) < 180 (in ascending order)
F(n, I) - the value of the phase function at the l'th scattering angle in altitude region n.

n = 1 0 to 2 km region
n = 2 2 to 10 km region
n = 3 10 to 30 km region
n = 4 30 to 100 km region

I - scattering angle index, I varies from 1 to NPTF

IPH = 2 MIE data base used for aerosol phase function
ISOURC = 0 extraterrestrial source is the sun
ISOURC = 1 extraterrestrial source is the moon
IDAY - day of the year; value from 1 to 365

IPARM indicates method of specifying the observer to source orientation
= 0 specify observer and subsolar longitude and latitude
= 1 specify observer longitude and latitude along with date and time
= 2 specify solar zenith and azimuth relative to observer

Note the following sign conventions:

Latitude is positive north of the equator.
Longitude is positive west of Greenwich, Eng.
Azimuth is positive east of north.

CARD 3 all parameters as defined in Ref. 1.
CARD 4 IXY

If ISCTTR = 0 the definition of IXY remains as in Ref. 1.
If ISCTTR = 1 cards 2 and 2A are treated as a unit as far as the IXY parameter is concerned.

IXY = 0 to end the program
IXY = 1 to select new cards 3 and 4
IXY = 2 to select an entirely new data sequence
IXY = 3 to select new cards 2, 2A and 4
IXY = 4 to select new cards 1 and 4
If the user specifies \( I_{XY} = 4 \) and \( ISCTTR = 0 \) on the original input card sequence, \( ISCTTR \) must remain unchanged since no \( CARD \ 2A \) has been or would be read in. Therefore, the only way to change from \( ISCTTR = 0 \) to \( ISCTTR = 1 \) is by specifying \( I_{XY} = 2 \) and supplying the entire data sequence. As an example, if the user desired to specify various geometrical configurations (optical paths and sun positions) the following card sequence could be used:

```
CARD 1
CARD 2
CARD 2A
CARD 3
CARD 4  I_{XY} = 3
CARD 2
CARD 2A
CARD 4  I_{XY} = 3
 .
 .
 .
CARD 4  I_{XY} = 0
```

The final \( I_{XY} \) card must be zero (or blank) to ensure proper termination of the program. There are no default conditions built into the single scattering routines of the LOWTRAN code.

### C.3 Solar and Lunar Sources

The extraterrestrial solar intensity is obtained from the data compiled by Thekaekara [Ref. 34]. The lunar extraterrestrial intensity is obtained by reflecting the solar intensity off of the moon's surface as [Ref. 35].

\[
I_{\text{moon}}(\lambda) = 2.04472 \times 10^{-7} \ I_{\text{SUN}}(\lambda) \ \alpha(\lambda) \ \rho(\gamma).
\]
Here $\alpha(\lambda)$ is the wavelength-dependent geometric albedo of the moon [Ref. 36 and 37], while $P(\gamma)$ is the moon's phase function giving the relative intensity as a function of the phase angle [Ref. 38]. Note that $P(\gamma = 0) = 1$ for a full moon.

C.4 LOWTRANSX Example Run

An example run of LOWTRANSX will serve to illustrate the structure and format of the input and output files. The input "file" consists of three records. The first record contains the job control language necessary to access, load, and execute the program. LOWTRANSX is structured to allow segmentation during loading to reduce central memory requirements. The structure of the segmented program is defined by the directives in the second record. The third record contains the input cards that describe the example run. The particular input file shown defines a line of sight from 2 Km to 5 Km altitude, at a zenith angle of 45 degrees and azimuth of 30 degrees. The observer is located at 40 north latitude and 160 degrees longitude, which the subsolar point is at 40 degrees north latitude and 240 degrees longitude. Details of the atmospheric composition and wavenumber region of interest are relatively unimportant and will not be described here. The output file is similar to the one produced by the original LOWTRAN code. Additional output pertaining specifically to the single scattering radiance calculation is clearly labelled and includes:

1. A summary of the single scattering control parameters following the standard LOWTRAN summary,

2. A summary of the geometric aspects of the scattering point to sun paths and,

3. Both scattered and total radiance as additional entries in the radiance table normally produced by LOWTRAN.

A listing of the example run output file is shown on the following pages.
C.5 Concluding Comments

Before executing the program in the single scattering mode, the user should be made aware of the following characteristics of the code:

1. Execution time can be expected to increase when operating in the single scattering mode. This is largely a result of the following:
   a) The code must be run in the emission mode.
   b) The geometry routines are called once for each scattering point to sun path (i.e. at each layer boundary contained in the optical path) in addition to the single call normally made for the optical path.
   c) The transmittance calculations are done twice (rather than once) for each scattering point along the optical path.

For most applications one can expect the run time to be about twice as long in the scattering-emission mode as in the emission mode alone.

2. To avoid unnecessary and misleading calculations the user should review Chapter 4 of this report regarding the validity of the single scattering assumption.

3. Depending upon his specific interests the user may or may not want intermediate results printed. For this reason modification of the printed output is left to the user.
LOWTRANSX Example Input File (CDC NOS/BE Operating System Only)

```
SCRAB - CM120047, DISK
ATTACH LWS, LOWXSSG; ID=MOOSE, MP=1
ATTACH GE0, LOWXSSG; ID=MOOSE, MP=1
ATTACH FNS; ID=MOOSE, MP=1
REQUEST, LOUT, DF.
REQUEST, TAPF, DF.
MAD, PART.
LOSET, PES=INDEX.
LOAD, P D; ID=MOOSE.
SELOAD.
EXIT: LOUT.
CATALOG FILE; ID=MOOSE.
REWIND, OUTPUT.
CATALOG, OUTPUT, LOUT.
EOR

LOWTRAN TEST LOMEM-NSSMOL, PROF, SSIO, EE, EXTENS)
LOWK GLOBAL CAO, ARR, CAR, CONTRL, TSTA, SLS, USER, IFIL, SAVE
NSSMOL INCLUDE NSMOL, PROF, SSIO, EE
HUTI CNC INCLUDE NSMOL, PROF, SSIO, EE
SSIO INCLUDE NSMOL, PROF, SSIO, EE
SSIO GLOBAL MODEL, PARMT, PERTH, SAVE
EXGIN INCLUDE EXGIN, EXTEND
TRANS TST: TRANS-NSMOL, PROF, SSIO, EE, PERTH, SAVE
TRANS-NSMOL, PROF, SSIO, EE, PERTH, SAVE
TRANS-NSMOL, PROF, SSIO, EE, PERTH, SAVE
TRANS-NSMOL, PROF, SSIO, EE, PERTH, SAVE

EOR

END LOMEM
```

```
   6 1 2 0
  2.300 6.000 45.000
  70.000 40.000 26.000
  1500.000 15000.000 20.000
```
LOWTRANX Example Output File (cont'd)

CASE 24: GIVEN H1, H2, ANGLE

SLANT PATH PARAMETERS IN STANDARD FORM

<table>
<thead>
<tr>
<th>H1 (km)</th>
<th>2.000</th>
<th>H2 (km)</th>
<th>5.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANGLE (deg)</td>
<td>45.000</td>
<td>PH1 (deg)</td>
<td>135.223</td>
</tr>
<tr>
<td>h1 (km)</td>
<td>1.000</td>
<td>L (km)</td>
<td>L (km)</td>
</tr>
</tbody>
</table>

CALCULATION OF THE REFRACTED PATH THROUGH THE ATMOSPHERE

<table>
<thead>
<tr>
<th>z (km)</th>
<th>1.000</th>
<th>1.000</th>
<th>1.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>T (km)</td>
<td>1.000</td>
<td>T (km)</td>
<td>T (km)</td>
</tr>
<tr>
<td>P (km)</td>
<td>1.000</td>
<td>P (km)</td>
<td>P (km)</td>
</tr>
<tr>
<td>H1 TO H2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.000</td>
<td>3.000</td>
<td>1.914</td>
</tr>
<tr>
<td>2</td>
<td>3.000</td>
<td>4.000</td>
<td>1.914</td>
</tr>
<tr>
<td>3</td>
<td>4.000</td>
<td>5.000</td>
<td>1.914</td>
</tr>
</tbody>
</table>

CUMULATIVE ABSORBED AMOUNTS FOR THE PATH FROM H1 TO H2

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<thead>
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<th>z (km)</th>
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<th>1.000</th>
<th>1.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>T (km)</td>
<td>1.000</td>
<td>T (km)</td>
<td>T (km)</td>
</tr>
<tr>
<td>P (km)</td>
<td>1.000</td>
<td>P (km)</td>
<td>P (km)</td>
</tr>
<tr>
<td>H1 TO H2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.000</td>
<td>3.000</td>
<td>1.914</td>
</tr>
<tr>
<td>2</td>
<td>3.000</td>
<td>4.000</td>
<td>1.914</td>
</tr>
<tr>
<td>3</td>
<td>4.000</td>
<td>5.000</td>
<td>1.914</td>
</tr>
</tbody>
</table>

SUMMARY OF THE SECRETRY CALCULATION

| h1 = | 2.000 km |
| H2 = | 5.000 km |
| ANGLE = | 45.000 deg |
| PH1 = | 135.223 deg |
| L = | 1.000 km |
| BENDING = | 1.914 deg |
| L (km) = | L (km) |
APPENDIX D: INPUT ANGLES FOR THE SUBSOLAR POINT

The user has the option of specifying the orientation of the sun by direct input of the subsolar longitude and latitude, i.e. that point on the earth where the sun is directly overhead. To find the subsolar point angles, the sun’s declination angle and the equation of time are required. The declination angle is defined as the longitude at which the sun is directly overhead at solar noon. The equation of time represents the difference between local (standard) time and true solar time. The American Ephemeris and Nautical Almanac published annually by the U.S. Government Printing Office contains precise values of the declination angle and equation of time for each day of each year. For illustrative purposes consider the sample data for a single year, taken directly from Reference 39 and shown in Table D1 and graphically in Figure D1. With this data, it is a simple task to determine the subsolar point angles. An example follows:

\[
\begin{align*}
\Theta_{\text{subsolar}} &= \text{the sun's declination angle} \\
\lambda_{\text{subsolar}} &= \text{subsolar longitude} = \text{STM} + 15^\circ (\text{ST} + \text{ET} - 12.0) \\
\end{align*}
\]

where,

- \text{STM} = the standard time zone meridian in degrees. The standard time zones for the continental U.S. are Pacific - 120, Mountain - 105, Central - 90, and Eastern - 75.
- \text{ST} = local (or standard) time in hours, expressed as a decimal number between 0.0 and 24.0 (i.e. 2:40 PM would be 14.66). Note, if a region is on daylight savings time the correct time is one hour earlier.
- \text{ET} = equation of time in hours.

As an example:

Determine the subsolar point angles on October 13 and 1:45 PM Central Standard Time.
Solution:

From Table D1 -

declination angle = -7 deg 29 min = -7.48 deg

equation of time = +13 min 30 sec = .225 hours

Therefore -

THETAS = -7.48

PHIS = 90 + 15*(13.75 + 0.225 - 12.0) = 119.63 degrees
<table>
<thead>
<tr>
<th>Date</th>
<th>Deg</th>
<th>Min</th>
<th>Sec</th>
<th>Date</th>
<th>Deg</th>
<th>Min</th>
<th>Sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan. 1</td>
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<td>Feb. 1</td>
<td>-17</td>
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<td>34</td>
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<tr>
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<td>35</td>
<td>- 0</td>
<td>Oct. 1</td>
<td>- 2</td>
<td>53</td>
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<td>10</td>
</tr>
<tr>
<td>Nov. 1</td>
<td>-14</td>
<td>11</td>
<td>+16</td>
<td>Dec. 1</td>
<td>-21</td>
<td>41</td>
<td>+11</td>
</tr>
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</tr>
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<td>29</td>
<td>21</td>
<td>21</td>
<td>11</td>
<td>29</td>
<td>23</td>
<td>17</td>
<td>34</td>
</tr>
</tbody>
</table>

Table D1 Tabular example of the equation of time.
Figure D1  Graphical equation of time.
1. INTRODUCTION

The ADDING code VERSION 8.2 computes the following scattering functions:

\[ S_s^\pm, T_s^\pm, S_F^\pm, T_F^\pm, \]
\[ c^\pm (a^- + a^+) \]
\[ f^\pm. \]

These functions are calculated from Equations (2.42)-(2.66) and (2.30) as described in Chapters II and III and Appendix 2 of Ajay Sharma's thesis. In addition, this program calculates the emerging intensities and one-sided heat fluxes for problems with given temperature profile (see Chapter IV of the thesis). The program is capable of calculating any Fourier component of the above quantities for plane-parallel, anisotropic scattering, inhomogeneous media bound by top and bottom surfaces with arbitrary specified bidirectional reflectivity or directional emissivity, at a given wavelength.

2. USER DEFINABLE FUNCTIONS

This version of ADDING code has FIVE subroutines and function subprograms that specify various media and surface conditions. The five are FUNCTION PHASFN (XMUL, XMU2), FUNCTION OMEGFUN (T), FUNCTION ASYFUN (T), FUNCTION TMPFUN(T) and SUBROUTINE SURINP. All these functions and subroutines must ALWAYS be included at run time although some of them may not be called or used. All of these can be replaced by the users to suit their needs. The function of these routines is as follows:

A. FUNCTION OMEGFUN (T)

This user defined function subprogram supplies the ADDING code with the single scattering albedo \( \omega \) as a function of the optical depth \( T \). Any arbitrary \( \omega \) profile can be specified. The function must set OMEGFUN = value of \( \omega \) at optical depth \( T \). This function is called ONLY if INHOMO is specified as being inhomogeneous by INHOMO parameter discussed in Section 5.
E. FUNCTION ASYFUN (T)

Should specify the value of asymmetry factor for the scattering phase function. The use of this function is linked to the use of Henyey-Greenstein phase function. The function is called only if inhomogeneous asymmetry factor is specified by INHOMO.

C. FUNCTION TMPFUN (T)

For a nonisothermal case, this function should return the medium temperature (degrees Kelvin) at optical depth T, to be used in intensity and heat flux calculations in direct problems.

D. FUNCTION PHASFN (XMU1, XMU2)

Can be replaced by the user to specify any scattering phase function other than H.-G., but associated parameters will have to be carefully checked.

E. SUBROUTINE SURINF

This routine can be replaced to specify any arbitrary reflecting, emitting or scattering bottom surface. The replacement routine must set function values as described in the comment cards at the beginning of the example SURINF routine supplied with the deck. NOTE that Black surfaces, surfaces with known emissivity and a "reflection, peakyness parameter", or surfaces with known bidirectional reflectivity can be handled by existing routines by specifying ISURF as 1, 2 and 3 respectively. See Section 6 of this manual for details.

3. EXTERNAL ROUTINES USED BY ADDING CODE.

The ADDING code uses five library routines - QA05AD, FP01AP, TMMDAT, CFUTIM and ERRSET. Their functions and need are described in the comment cards in the beginning of the MAIN program.

4. INPUT/OUTPUT FILES.

ADDING VERSION 8.2 uses many input/output files as described in the comment cards. The following is a description of the physical organization of these files:

NOTE: ICSRN means the FORTRAN 'Data Set Reference Marker' or Unit number in READ and WRITE statements.
DSRN 02: It is used through a READ(1,*) statement to enter a run label of up to 80 characters. The program also writes interactive messages on this file. It is strongly recommended that this file be the user TERMINAL.

DSRN 03: Is an INPUT file from which the program can read one card long equations defining OMSFUN, ANYPUN and TMTFUN, respectively, on three consecutive cards. These equation are used for INFORMATIVE OUTPUT ONLY and have no effect on computations.

DSRN 05: PRIMARY INPUT file for the program, used through a READ (5,CASE) input statement (using NAMELIST CASE) and for input of surface properties by SUR1NP/SUR1N2 routines as necessary. The inputs on this file are described in detail in Sections 5 and 6 of this document.

DSRN 06: PRIMARY OUTPUT file, used through many WRITE (6, ...) statements. This file should usually be attached to the line printer. The printing on DSRN 06 is controlled by the parameter I0CTL1.

DSRN 07: Is an OUTPUT file controlled by parameter I0CTL2 and would contain unformatted output records of the exiting intensities (see line numbers 21070-21130 in program). This should be a disk or a tape file to work right. Typically this output might be read by another program for plotting purposes.

DSRN 17: Is an input/output file controlled by I0CTL3 which should preferably be a disk file. The ADDING code uses this file to store and retrieve RESTART information, i.e., ADDING can write sufficient information on this file at the end of a run so that it can add DIFFERENT surfaces at the top and bottom of a particular medium, without computing medium properties all over again. This process is called RESTARTING in this document. The file is written in subroutines HEADER and OUTPUT (lines 17650, 21130-21230) and is read in subroutine INPUT (lines 4770-4890). The use of this file is purely internal to ADDING.

DSRN 13: ADDING writes all the functions computed on this file under control of I0CTL4. The output is unformatted and should be disk or tape resident. Typically this output can be read by another program for the purpose of comparing the adding technique with the results of another theory. Lines 21340-21390 in subroutine OUTPUT contain the WRITE statements for this file.
DCRN 14: This file is used by ADDING to write the generated S and a functions using unformatted WRITE. These functions can later be read by another program for printing or computing purpose. The output on this file is controlled by the IOCTL parameter. NOTE that this is the ONLY file on which these functions are written, ADDING does not write them on DSRN 06.

5. PRIMARY INPUT PARAMETERS

The following is a list of parameters together with their functions which are read in by ADDING using NAMELIST CASE from DSRN 5. If any of the parameters are omitted from the input data, they take the default values shown:

<table>
<thead>
<tr>
<th>NAME</th>
<th>RANGE</th>
<th>DEFAULT</th>
<th>FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASY</td>
<td>-1.0 to 1.0</td>
<td>0.0</td>
<td>ASY is the asymmetry factor &quot;g&quot; for the H.-G. phase function and is used only if ASY is specified to be HOMOGENEOUS by INHOMO as described below.</td>
</tr>
<tr>
<td>C</td>
<td>GAUSS</td>
<td></td>
<td>The C array contains the quadrature weights for the angle integrations. The default values result in a Gaussian quadrature. There should be N values for this array if the default is to be overridden.</td>
</tr>
<tr>
<td>DTMAX</td>
<td></td>
<td></td>
<td>Variable not for user modification.</td>
</tr>
<tr>
<td>DTSLR</td>
<td>0.0 to T01</td>
<td>1.0</td>
<td>Where T01 is the optical thickness (TWOTLR) for the first layer. This variable specifies the c function spacing desired. The program will pick DTR such that DTR = DTRL and DTR = T01 / (2 ** I) where I is an integer.</td>
</tr>
</tbody>
</table>
| IOCTL | 1,2,3,4,5 | 1       | Control parameter for primary output on DSRN 06. The effect of IOCTL is:  
=1 : All functions generated are printed after adding each layer.  
=2 : Only intensities and Heat Fluxes are printed after adding each layer.  
=3 : All functions are printed after adding up to the final optical thickness. |
Only Intensities and Heat fluxes are printed after adding up to final optical thickness.

=5: NO OUTPUT on DSRN 06 except the header page.

This parameter controls output on DSRN 11 as follows:
=0: NO output is written on this file.
=1: Output on this file after adding up to the final optical thickness.
=2 AND IOCTL1>3: Output on this file after adding each layer.

Controls output on DSRN 12 as follows:
=0: NO restart file is written or read.
=1: Restart file is written for later use by ADDING.
=2: ADDING runs to only add a surface to medium whose properties were last written on this restart file.

Causes output to be written on DSRN 13 if IOCTL4 = 1.

Controls a function writing on DSRN 14 as follows:
=0: NO output on DSRN 14.
=1: Only the c and f functions written after adding all the layers.
=2: The c, f and a functions written after adding ALL the layers.
=3: The c, f, and a functions are all written after adding each layer.

Specifies the medium as follows:
=0: HOMOGENEOUS medium, values of ASY and OMEGA are both used.
=1: Omega is inhomogeneous and values obtained from OMEGAFUN(T) are used, OMEGA value is ignored.
=2: Asymmetry factor is assumed to be inhomogeneous, values from ASYMPUN(T) are used, ASY value is ignored.
=3: BOTH Asymmetry factor and Omega are assumed to be inhomogeneous.

Specifies bottom surface to be added, SEE discussion in section 6. if ISURF:
=0: No bottom surface.
=1: BLACK bottom surface to be added.
ISURFT: 0, 1, 2, 3

0: No top surface.
1: BLACK top surface to be added.
2: A reflecting surface with given directional spectral emissivity and peakyness parameter is to be added.
3: A reflecting surface with given bidirectional reflectivity is added.

M: --

Fourier component number.

N: 1, 2, ..., 10

Number of Quadrature points to be used.

NONISO: 0, 1

If medium is nonisothermal: NONISO=1. Also then TMPPUN (T) would be called to specify the temperature profile.

NLAYER: 1, 2, ..., 40

Number of medium layers to be added.

OMEGA: 0.0 to 1.0

Albedo (ω) for the homogeneous case.

REFIDX: 0.0 to --

Medium refractive index.

TMPRM: 0.0 to --

Medium temperature (deg. K) for isothermal media with surfaces.

TMPSUR: 0.0 to --

BOTTOM Surface temperature (deg. K).

TMPSUT: 0.0 to --

TOP Surface temperature (deg. K).

TNOLTR: --

A vector of NLAYER numbers giving the optical thicknesses of all the NLAYER layers to be added. The final optical thickness is the sum of these numbers. Note that each layer can be of any optical thickness as long as it is such that TNOLR(J)=(2**I)*DTRLR for all J and any integer I.

WAVELN: 0.0 to --

Wavelength at which all calculations are to be done in MICRONS.

SURFACE PROPERTIES

See Section 6.

----------------- X ------------------

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When the input data specifies ISURF as 2 or 3 then that implies that a \textbf{RELECTING surface} is present at the bottom of the medium. In that case \textbf{NOTE THAT THE ADDING PACKAGE MUST USE c-function integrations for intensity calculations.} This means that the user must be careful about specifying c function spacing (DTRLR) and also in writing subprogram TMFPUN. Even if the medium is specified as isothermal (NONISO = 0), in the case of adding a reflecting surface, TMFPUN would be called during the surface adding step. Therefore TMFPUN must be \textbf{DEFINED} to be equal to the medium temperature.

The second important point to note in this case is that the primary input file on DSRN 05 must contain \textbf{ADDITIONAL DATA}, after the NAMELIST CASE data cards, as follows:

\textbf{IF ISURF = 2,} the ADDING package reads a 'peakyness parameter' (CP) and the Emissivity vector. The read statement for this is in SUBROUTINE SURIN2 and it uses the List Directed Input facility of IBM FORTRAN. The input should contain \textbf{CP} value followed by emissivities at all quadrature angles. An ISOTROPIC (diffuse) reflector is given by CP=0.0 and a perfect SPECULAR reflector by CP=1.0. Values of CP between 0.0 and 1.0 specify a surface with specular+diffuse nature.

\textbf{IF ISURF = 3,} the program reads the bidirectional reflectivity (p) in SUBROUTINE SURINP. The input should contain only the \textbf{UPPER TRIANGULAR} matrix as RHO satisfies reciprocity relation. Each I-th row of the matrix input should begin on a NEW LINE and should contain values of RHO(I,I), RHO(I,I+1), ..., RHO(I,N); although one row can occupy more than one input line if necessary. The input again uses the IBM FORTRAN's list directed input facility.

\textbf{TOP SURFACE :} When the input has ISURF.GT.0, then ADDING assumes the presence of a top surface. This surface is specified exactly like the bottom surface is, with the temperature given by TMPSTUT. The comments about surface properties input apply to the top surface also.

\textbf{NOTE that if BOTH TOP AND BOTTOM SURFACES ARE PRESENT,} the input on DSRN 05 must contain \textbf{TOP surface emissivity/reflectivity FIRST,} followed by properties of the bottom surface. Of course, if ISURF is less than 2, no data is needed for the top surface.
APPENDIX F: USER'S GUIDE FOR ADDING/DOUBLING PACKAGE FOR EXTERNAL ILLUMINATION.

This appendix describes the package of three computer codes which uses the ADDING/DOUBLING method to compute multiple scattering diffuse intensities. The three codes are designated ADNGFFT, ADNGV90, and ADINTEN. They have been designed to run in sequence using temporary intermediate storage files which are not normally saved once the run is completed. The codes perform the following functions:

**ADNGFFT:** Transforms the user-supplied or Henyey-Greenstein phase functions into sets of phase matrices for each layer and each azimuth Fourier component based on a set of zenith quadrature angles.

**ADNGV90:** Computes the exterior and interior scattering matrices for an inhomogeneous multilayer atmosphere. Each matrix represents the response to a single Fourier component of the external radiative source.

**ADINTEN:** Recombines the Fourier components of the diffuse scattering intensity to produce the azimuth and zenith angle dependent intensities for each source zenith angle.

The codes use monochromatic scattering and absorption data appropriate to a particular model atmosphere. The required data would generally be provided from line-by-line molecular absorption calculations and aerosol scattering and absorption data. Specifically, the algorithm requires (1) the optical thickness of each scattering layer, (2) the layer single scattering albedo, and (3) the phase function for single scattering in each layer. The multiple scattering geometry is plane-parallel and the codes simultaneously compute intensities at up to 10 upward and 10 downward observer zenith angles for up to 10 different solar zenith angles. The number of azimuthal orientations or angles can be set by the user, but must be 65 or less. The number of Fourier components generated by the COSINE FFT (Fast Fourier Transform) will be the same as the number of azimuth angles between 0 and 180 degrees.
which are used. The accuracy of the computed intensity at any angle will
tend to be uncertain if fewer than about ten Fourier components (angles)
are used.

F.1 PROGRAM 1, ADNGFFT

The ADNGFFT code augments the main Adding/Doubling calculation by
preparing layer-by-layer phase function data for use by ADNGV30. The
program allows a different phase function to be used with each atmospheric
layer, if desired. Each phase function is first prepared as a numerical
function of the included scattering angle $\gamma$. This function can be directly
read from File 5 or calculated from the Henyey-Greenstein form with any
chosen asymmetry parameter $g$, that is

$$P(g, \gamma) = \frac{1 - g^2}{[1 + g^2 - 2g \cos \gamma]^{3/2}}.$$  \hspace{1cm} (F.1)

The phase function is next evaluated in terms of the incident and scattered
zenith angles $\theta_j$ and $\theta_i$, and azimuth angle $\phi$ separating the two vertical
planes (reference and sun planes) by the relation

$$\cos \gamma = \mu_i \mu_j + \sqrt{1 - \mu_i^2} \sqrt{1 - \mu_j^2} \cos \phi,$$  \hspace{1cm} (F.2)

where $\mu_i = \cos \theta_i$ and $\mu_j = \cos \theta_j$. This gives $P_{ij}(g, \phi)$ (or more precisely
$P_{ij}^{++} = P_{ij}^{--}$ and $P_{ij}^{+-} = P_{ij}^{-+}$, for forward and backward scattering, re-
respectively) for a set of quadrature zenith angles defined on the hemisphere.

For each pair of quadrature points $(i, j)$, $P_{ij}^{++}$ and $P_{ij}^{+-}$ are functions of
the azimuth angle $\phi$, and Fast Fourier Transforms (FFT's) can be carried out
successively so that the $\phi$ dependence is replaced by the Fourier component

*For seven quadrature angles, the phase function is a 14 X 14 array. Since
scattering depends only on the included angle, the four corner submatrices
like $P^{++}$, etc) are related. The superscripts stand for probe-response directions.

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index n. The actual FFT is performed by the subroutine TFC which is described below.

Subroutine TFC

Purpose

Given a finite Fourier cosine series

\[ X_j = \frac{1}{2} c_0 + \sum_{k=1}^{2n-1} c_k \cos \frac{\pi}{2n} jk + \frac{(-1)^j}{2} c_{2n} \]

\( (j = 0, 1, \ldots, 2n) \)

the subroutine performs the following computations:

\( \text{IOPT} < 0 \) : Fourier analysis (computation of the coefficients \( c_k \) for given values \( X_j \)).

\( \text{IOPT} > 0 \) : Fourier synthesis (evaluation of the series for given \( c_k \)).

Usage

CALL (D)TFC(X,N,IOPT,IER,AUX,NMAX)

\( X \) . GIVEN vector of dimension \( 2N + 1 \) containing the values \( X_j \) if \( \text{IOPT}<0 \), or coefficients \( c_k \) if \( \text{IOPT}>0 \).

RESULTANT vector containing the coefficients \( c_k \) if \( \text{IOPT}<0 \), or values \( X_j \) of the series if \( \text{IOPT}>0 \).

\( \text{IOPT} \). GIVEN option parameter. The sign of \( \text{IOPT} \) specifies the selected operation (refer to the section Purpose), the magnitude of \( \text{IOPT} \) (normally 1) specifies the indexing increment for given and resultant data within vector X.

\( \text{IER} \). RESULTANT error indicator.
AUX . AUXILIARY vector of dimension NMAS used as working storage in subroutine (D) TFG which is called in TFC.

NMAS . GIVEN number of elements within vector AUX which may be used as working storage.

RESULTANT auxiliary storage size which is actually needed by subroutine (D) TFG.

Error Table

<table>
<thead>
<tr>
<th>Code</th>
<th>Explanation</th>
<th>Program action</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No error was detected.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>( N &lt; 2 )</td>
<td>Operation is bypassed</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>( 10PT = 0 )</td>
<td>Operation is bypassed</td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td>NMAX is too small.</td>
<td>Actual storage requirement of (D) TFG is returned in NMAX, vector X is destroyed, further operation is bypassed.</td>
<td></td>
</tr>
</tbody>
</table>

Remarks

If (D) TFC is used to approximate an even function with period \( T \), the given function values \( X_j \) (refer to the section Purpose) must correspond to the (equidistant) argument values

\[
\frac{T}{4n} j \quad (j = 0, 1, \ldots, 2n).
\]

Method

The algorithm is based on the Fast Fourier Transform algorithm. The Fourier cosine series of order \( 2n \) is evaluated by relating it to a real Fourier series of order \( n \).
The Fourier cosine series

\[ X_j = \frac{1}{2} c_0 + \sum_{k=1}^{2n-1} c_k \cos \frac{\pi}{2n} jk + \frac{(-1)^j}{2} c_{2n} \quad (j = 0, 1, \ldots, 2n) \]

can be evaluated by means of the real Fourier series

\[ Y_j = \frac{1}{2} a_0 + \sum_{m=1}^{n-1} (a_m \cos \frac{\pi}{n} jm + b_m \sin \frac{\pi}{n} jm) + \frac{(-1)^j}{2} a_n \]

\((j=0, 1, \ldots, 2n-1)\) with \(a_m = c_{2m} \quad (m=0, 1, \ldots, n)\)

and \(b_m = c_{2m+1} - c_{2m-1} \quad (m=1, 2, \ldots, n-1)\).

The values \(Y_j\) can be computed using subroutines (D)TFT and (D)TFG and the values \(X_j\) are then obtained from

\[ X_0 = Y_0 + \sum_{k=0}^{n-1} c_{2k+1} \]

\[ 2X_j = (Y_j + Y_{2n-j}) - (Y_j - Y_{2n-j})/(2 \sin \frac{\pi}{2n} j) \quad (j = 1, 2, \ldots, 2n-1) \]

\[ X_{2n} = Y_0 - \sum_{k=0}^{n-1} c_{2k+1} \]

For the Fourier analysis, i.e., the computation of the coefficients \(c_k\) for given \(X_j\), the relation

\[ c_k = \frac{1}{n} \left( \frac{1}{2} X_0 + \sum_{j=1}^{2n-1} X_j \cos \frac{\pi}{2n} kj + \frac{(-1)^k}{2} X_{2n} \right) \]

\((k=0, 1, \ldots, 2n)\) allows the same algorithm to be used.
ADNGFFT: MAIN PROGRAM LISTING

PROGRAM ADNGFFT: Fourier Decomposition of The Phase Function.

COMMON /INTCOM/ XMU(10), DWT(10), N
COMMON /INTERC/ NT, DTHETA, P(101)
DATA PI/3.1415926/, NMAX/32/
DIMENSION P(65), PN(65), PNP(65,10,10), PNM(65,10,10), AUX(513),
PHI(65), POUT(10,10), POUTH(10,10)
DIMENSION LABEL(20)

Read in the GIVEN Phase Function and other control variables.

Phase function given must be for equispaced values of Theta,
for Ni values of theta, where Ni is an odd integer, so that
the Phase function values are given for THETA=2(pi*(i-1)), for
i=1,2,...,Ni, where Ni=2*pi/(Ni-1).
Ni is the number of Phase Function values (< or = 10) per layer,
NL is the number of layers, N the number of quadrature (Mu)
angles to be used in the ADDING program, and Nt the number of
Fourier terms to be used in the Fourier Series decomposition.

READ(5,8) NI, NL, N, NF, IPHRPT, IFLUX, IHENGR, INOFT
WRITE(8,905) NI, NL, N, NF, IPHRPT, IFLUX, IHENGR, INOFT

905 FORMAT('PARAMETERS USED FOR THE PHASE FUNCTION CALCULATION',
1 ' //30X,' 'NI = ',13,
2 ' //30X,' 'NL = ',13,
3 ' //30X,' 'N  = ',13,
4 ' //30X,' 'NF = ',13,
5 ' //30X,' 'IPHRPT = ',13,
6 ' //30X,' 'IFLUX = ',13,
7 ' //30X,' 'IHENGR = ',13,
8 ' //30X,' 'INOFT = ',13,///)
IF (NF .LE. NFMAX) GO TO 910
WRITE(6,901)
901 FORMAT(''' /'' NUMBER OF FOURIER COMPONENTS REQUESTED IS LARGER''/
; ' THAN ALLOWED BY ARRAY SIZES, EXECUTION TERMINATED.'/
STOP
910 NF2=2*NF+1
WRITE(7) NI, NL, N, NF2
CALL QUADT
NIM=2*NI
NI1=NI-1
DT=PI/N11
N2F=2*NF
DO 1 I=1,NF2
1 PHI(I)=COS(PHI*(I-1))
C Loop for Layers:
C DO 900 I=1,NL
C SKIP THE PHASE FUNCTION TRANSFORM IF THE SAME ONE IS USED
C IN EACH LAYER:
C IF (IPERF.EQ.0) GO TO 50
IF (L.EQ.1.) GO TO 50
GO TO 250
C
C CONSTRUCT THE HENNEY-GREENSTEIN FUNCTION IF THENCR=1
C
50 IF (THENCR.EQ.0) GO TO 70
READ(5,2) GPAR
GPAR2=GPAR**2
DO 60 I=1,NI
60 DOT=COS((DTHETA*(I-1))
DOT=(1.0+GPAR2-2.0*GPAR*DOT)**1.5
P(I)=I1-GPAR2)/DOT
CONTINUE
C WRITE(6,920) GPAR
920 FORMAT('' '' HENNEY-GREENSTEIN USED WITH 
G ='' ,F6.3, '''' )
C GO TO 75
C
70 READ 5,2) (PI1, I=1,NI)
75 DO 80 I=1,NI
80 P(NC+I)=P1;

173
CC For each MU(I) and MU(J), calculate the Fourier Coefficients:

DO 300 I=1,N
   A=SQRT(1.0-XMU(I)**2)*XMU(I)
   DO 200 J=1,N
      B=SQRT(1.0-XMU(J)**2)*XMU(J)
      C=XMU(I)**2*XMU(J)
      DO 100 K=1,NF2
         D=PHI(K)
         PP(K)=FINTER(ACOS(D+C))
      100 CONTINUE
      PM(K)=FINTER(ACOS(D-C))
   200 CONTINUE
300 CONTINUE

C BYPASS FOURIER TRANSFORM IF INOPT=1

C IF(INOPT.EQ.1) GO TO 125
C
   INOPT=-1
   IER=0
   CALL TFC (PP, NF, INOPT, IER, AUX, 513)
   INOPT=-1
   IER=0
   CALL TFC (PM, NF, INOPT, IER, AUX, 513)
   PP(I)=PP(I)/2.0
   PM(I)=PM(I)/2.0
   PP(NF2)=PP(NF2)/2.0
   PM(NF2)=PM(NF2)/2.0

C 125 CONTINUE

C DO 150 K=1,NF2
C     PN(K,1)=PHI(K)
150     PNM(K,1)=PHI(K)
C CONTINUE

C CONTINUE

C NF2KRT=NF2
C WRITE(7) (PNM(K,1),I=1,K),J=1,N)
C WRITE(7) (PNM(K,1),I=1,K),J=1,N)
C CONTINUE

C TRANSPOSE THE PHASE FUNCTION DATASET TO WRITE LAYERS FIRST:

C WRITE (8) NT, NK, N, NF2KRT
DO 30 K0=1,NF2WRT
REWIND 7
READ (7) NI, NL, N, NF2
DO 30 L=1,NL
DO 10 K=1,NF2WRT
READ(7) ((NP(K,L,J),L=1,N),J=1,N)
10 READ(7) ((PNM(K,L,J),L=1,N),J=1,N)
C
C
DO 20 J=1,N
DO 20 I=1,N
   POUTP(I,J)=PNP(K0,I,J)
   POUTM(I,J)=PNM(K0,I,J)
20 WRITE(8) ((POUTP(I,J),I=1,N),J=1,N)
   WRITE(8) ((POUTM(I,J),I=1,N),J=1,N)
30 CONTINUE
STOP
END
The results of the FFT's are written to File 7 and the entire process is repeated (if \( P(\gamma) \) is different) for each successive layer. Since the A/D code performs calculations based on all layer data for a single Fourier component at a time, the phase function data must be reordered by Fourier component and then by layer rather than vice versa. The data is therefore read from File 7, reordered, and then written to File 8, which is then passed to ADNGV90.

F.2 PROGRAM 2, ADNGV90

Some key features of the adding/doubling algorithm and its application to solar scattering are outlined below. The reader is also referred to Appendix E where a description of the original A/D code can be found. The code was first developed specifically to model radiative transfer in plane-parallel media with internal infrared emission sources. The solar scattering problem requires a change in perspective, but the same equations apply. Specific changes which supercede the code description of Appendix E are given here.

The user will note that some of the options related to thermal emission which are described in Appendix E have been "turned off" in this solar scattering code. The original A/D code was also controlled interactively from a terminal and some modifications have been made to allow batch processing. Phase function data is passed from ADNGFPT through File 12 rather than from the user directly via File 5. The albedo data is specified at the end of File 5 as an array indexed by layer and not in functional form as suggested by Appendix E. Most other features which remain active are unchanged.

The A/D scattering functions \( S_F \) and \( T_F \) are the computed quantities which directly apply to the solar scattering problem. They represent the
the radiative response of the medium at the top or bottom surfaces to an internal unidirectional source of illumination. The solar problem having an external source which drives radiative intensities within the medium (including both surfaces) calls for interchanging the source and observer orientations, or equivalently, having the photons move backward. This switch is done after the A/D calculations for each Fourier component are completed and prior to computing the actual intensities in ADINTEN. The scattering functions themselves are denoted by

$$S_F^\pm (i, j, n, t_r, t_o)$$ and $$T_F^\pm (i, j, n, t_r, t_o)$$

with the following nomenclature:

- **S** indicates diffuse scattering, that is, upward intensity exiting the medium at the top surface due to illumination directed downward, or downward intensity at bottom surface due to upward illumination.
- **T** indicates diffuse transmittance; upward intensity if the illumination is upward, or downward intensity if the illumination is downward.
- **+** indicates source illumination is directed upward.
- **-** indicates source illumination is directed downward.
- **F** refers to internal illumination. Response to be found at top or bottom exterior surfaces.
- **i** index for the zenith angle of response intensity.
- **j** index for the zenith angle of the source.
- **n** azimuthal Fourier component index. The n'th component of the intensity field responds only to the n'th component of the driver.
- **r** optical depth of the driver (source) location as measured from the top. "r" serves as a source location index.
- **o** total medium optical thickness.
Implicit Functional Arguments of the Scattering Functions:

\( a(i) \) albedo function of optical depth (altitude).

\( p_{ij}^{\pm}(i) \) Forward (++, --) and backward (+-, ->) phase matrices by Fourier component and optical depth (altitude).

The code actually computes weighted forms of these functions which appear as

\[
SFIP(i, j, r) = \frac{1 + \delta_{i,n}}{4 \mu_j} s_P^+ d_j
\]

\[
SFIM(i, j, r) = \frac{1 + \delta_{i,n}}{4 \mu_i} s_P^- d_j
\]

\[
TFIP(i, j, r) = \frac{1 + \delta_{i,n}}{4 \mu_i} t_P^+ d_j
\]

\[
TFIM(i, j, r) = \frac{1 + \delta_{i,n}}{4 \mu_i} t_P^- d_j,
\]

where \( d_j \) is the quadrature weighting factor appropriate to the j\'th source zenith angle. The quantities SFIM, SFIP, TFIM, and TFIP are computed together with other scattering functions in ADNCV90. The roles of internal source and external response are then reversed through reciprocity, and two new scattering matrices SWARP and SWARM representing upward and downward internal response caused by an external source are introduced. They are given by

\[
SWARP = \frac{1 - \delta_{i,n}}{4 \mu_j} \frac{\mu_j}{\mu_i} TFIP(j, i) d_i^{-1}
\]
\[ SV_{\text{ARM}} = \left( \frac{1}{1 + \delta_{o,n}} \right)^\frac{1}{\mu_i} \mu_i S_{\text{F1M}}(j, i) d_i^{-1}, \quad (F.5) \]

for each Fourier component \( n \) and observer level \( r \).

ADNGV90 FILE STRUCTURE:

FILE 1: This file contains a run label of 80 characters.

FILE 5: Primary input file for control of Adding/Doubling calculations.

RECORD 1: NAMELIST CASE PARAMETERS:

- \text{NLAYER} : NUMBER OF HOMOGENEOUS LAYERS (=NL)
- \text{DTRLR} : OPTICAL DEPTH SPACING USED FOR COMPUTING BOTH INTERNAL SCATTERING FUNCTIONS AND FOR FINAL MULTIPLE SCATTERING INTENSITIES. CONSTRAINED TO BE \( \text{DTRLR} = 20/(2^I) \) WHERE \( T_0 \) IS THE TOTAL OPTICAL DEPTH AND \( I \) IS ANY NON-NEGATIVE INTEGER.
- \text{TNOTLR} : A SET OF NLAYER REAL NUMBERS GIVING THE OPTICAL THICKNESS OF EACH LAYER STARTING FROM THE TOP. CONSTRAINED TO BE OF THE FORM \( \text{TNOTLR}(J) = (2^I)^\text{DTRLR} \) FOR ALL LAYERS \( J \) AND ANY NON-NEGATIVE INTEGER \( I \).
- \text{INHOMO} : 
  - =0 OPTION NOT ACTIVE
  - =1 INHOMOGENEOUS ATMOSPHERE; SET \text{NLAYER}=1 IF HOMOGENEOUS ATMOSPHERE IS NEEDED.
- \text{IOCTL1} : CONTROLS AMOUNT OF OUTPUT ON FILE 6.
  - =1 ALL SCATTERING FUNCTIONS PRINTED AFTER EACH LAYER ADDITION.
  - =2 OPTION NOT ACTIVE.
  - =3 ALL FUNCTIONS PRINTED ONLY AFTER FINAL SCATTERING FUNCTIONS COMPUTED.
  - =4 OPTION NOT ACTIVE.
  - =5 NO OUTPUT ON FILE 6 EXCEPT HEADER.

RECORD 2: OMGFUN : SET OF NLAYER REAL NUMBERS WHICH ARE LAYER-BY-LAYER SINGLE SCATTERING ALBEDOES ARRANGED FROM THE TOP LAYER DOWN.
FILE 12: Must be the same file as ADNGFFT File 8. Contains the phase function data by Fourier component.

FILE 13: A new intermediate file which is passed to ADINTEN. Contains external to internal scattering matrices by Fourier component.

F.3 PROGRAM 3 ADINTEN

The code ADINTEN carries out the last step in the calculation of internal intensities based on an external driving source. File 7 contains the external-to-internal scattering functions ordered by Fourier component and observer level. These functions are read from File 7 and transposed so as to appear as functions of the Fourier index \( n \) at each level. They are inverse Fourier transformed by the same subroutine TFC (see section F.1) as was used for the FFT of the phase function data. The intensities are given by

\[
I^+(r, 0, \phi) = \text{IFT} \ (\text{SVARP}) ,
\]

and

\[
I^-(r, 0, \phi) = \text{IFT} \ (\text{SVARM}) ,
\]

for a unidirectional external source of unit strength where IFT means inverse Fourier transform. These upward and downward intensities are written to the standard output file (File 6). In addition, the zeroth Fourier components of the scattering functions are used by themselves to calculate the upward and downward radiative fluxes as

\[
\Omega^+_j(r) = \sum_i \mu_i d_i [\text{SVARP} (i, j)]_r, \ n=0 ,
\]

(F.8)
and

\[ Q^-(r) = \sum_i \mu_i d_i [SVARM (i, j)]_r, n=0, \quad \text{(F.9)} \]

at each observer level \( r \) and each solar zenith \( j \). The flux calculation can be carried out without performing more than one Fourier component A/D calculation in ADNGV90. (See directions specifying FLUX=1 in section F.1). For these special flux calculations, the inverse FFT is suppressed and the intensities which are printed represent the zeroth component only. These intensities are correct in the case of isotropic scattering (GPAR = 0.0). Fluxes are written directly to a separate output file [File 10].
ADINTEN : MAIN PROGRAM LISTING

C
C THIS PROGRAM READS THE FOURIER COMPONENTS OF THE SCATTERING
C FUNCTIONS WRITTEN BY THE ADDING PROGRAM AND INVERSE FOURIER
C TRANSFORMS THEM TO CALCULATE THE INTERIOR INTENSITIES DUE TO
C SOLAR INTENSITIES AT THE TOP OF THE MEDIUM.
C
C
C REAL*8 XM, DWT, XMUDWT, DWTINV
C
C DIMENSION SS(10,10,41), TSM(10,10,41), XI(65,10,10),
: XM(10,10,10), AUX(513)
C DIMENSION XM(10,10), DWT(10), XMUDWT(10), DWTINV(10)
C DIMENSION FLUX(10), FLUXM(10), FLUXQ(10)
C
C
C READ(7) N1, NL, N, NF2
C
C READ THE QUADRATURE WTS. AND COSINES FROM FILE 7
C
C READ(7) (XM(1), I=1,N)
C READ(7) (DWT(I), I=1,N)
C
C CAN ADD XM INV(1) NEXT TIME BOTH PROGRAMS
C ARE COMPILED
C
C
C READ(7) (XMUDWT(I), I=1,N)
C READ(7) (DWTINV(I), I=1,N)
C
C N1=(NF2-1)/2
C READ(7) NRS
C
C WRITE(10,100)
C
C 100  EL=1, NRS
C READ 7
C READ(7) N1, NL, N, NF2
C READ(7) (XM(1), I=1,N)
C READ(7) (DWT(I), I=1,N)
C READ(7) (XMUDWT(I), I=1,N)
C READ(7) (DWTINV(I), I=1,N)
C N2 = N1
C WRITE(7)

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permit fully legible reproduction
DO 10 K=1,NRS
READ(7) ((SSM(I, J, K), I=1, N), J=1, N)
10 READ(7) ((TSM(I, J, K), I=1, N), J=1, N)
DO 11 J=1,N
DO 11 I=1,N
XI(I, J, K)=SSM(I, J, K)
11 XI(I, J, K)=TSM(I, J, K)
CONTINUE
C
C
DO 40 J=1,N
C
FLUXP(J)=0.0
FLUXM(J)=0.0
C
DO 40 I=1,N
C
FLUXP(J)=FLUXP(J)+XI(I, J, K)*XMR(I)*DWT(I)
FLUXM(J)=FLUXM(J)+XM(I)*XMR(I)*DWT(I)
C
IF(NF2.EQ.1) GO TO 40
C
IOPT=1
IER=0
XI(NF2, J)=2.0*XI(NF2, I, J)
XIM(NF2, J)=2.0*XIM(NF2, I, J)
CALL TFC(XI(NF2, I, J), NF, IOPT, IER, AUX, 513)
IF(IOPT=1)
IER=0
XIM(NF2, J)=2.0*XIM(NF2, I, J)
XIM(I, J)=2.0*XIM(I, I, J)
CALL TFC(XI(NF2, I, J), NF, IOPT, IER, AUX, 513)
CONTINUE
WRITE(0,41) KL
41 FORMAT(/' K-LEVEL NUMBER = ', I2, 
', ---------------',/)
C
WRITE OUT UP AND DOWN FLEXES AT THIS LEVEL
C
TWOPT=0.28318511
C
DO 45 J=1,N
C
FLUXP(J)=FLUXP(J)+TWOPT*
FLUXM(J)=FLUXM(J)+TWOPT*
FLUXD(J)=FLUXD(J)+TWOPT*
45 CONTINUE
C
WRITE FLEXES TO ENERY STORAG... FLEX NUMBER = 10
WRITE(10,197) KL, (FLUXP(J), J=1,N)
WRITE(10,198) KL, (FLUXM(J), J=1,N)
WRITE(10,199)
196 FORMAT('///, ' ADDING/DOUBLING FLUXES', ////)
197 FORMAT(' R-LEV',14,' FLUXP ',7E15.6,/,20X,7E15.6)
198 FORMAT(' R-LEV',14,' FLUXM ',7E15.6,/,20X,7E15.6)
199 FORMAT(' ')
C
DO 50 L=1,NP2
   WRITE(6,46) KL, L
46 FORMAT('///, ' R-LEVEL : ',12,' ; PH1 INDEX : ',12/'
  ; ' INTENSITY-PLUS (1,J)/
  ; ' ------------------------'///,1',5X,'VALUES ->'/)
   DO 47 J=1,N
47 WRITE(6,48) L, (XLP(L,1,J), J=1,N)
48 FORMAT('///, ' XLP',12.14(T=,10D12.4))
   WRITE(6,49)
49 FORMAT('///, ' INTENSITY-MINUS (1,J)/
  ; ' ------------------------'///,1',5X,'VALUES ->'/)
   DO 50 J=1,N
50 WRITE(6,48) L, (XLM(L,1,J), J=1,N)
100 CONTINUE
C
ADD A MARKER AT THE END OF DATA ON FILE 10
C
   WRITE(10,299)
299 FORMAT(' *** *** *** ',105X)
C
STOP
END
F.4  ADDING/DOUBLING SAMPLE IBM JOB CONTROL CARDS AND DATA FILES
APPENDIX G: A PLANE-PARALLEL SINGLE SCATTERING CODE (PPSS1)

INPUT/OUTPUT FILES REQUIRED:

FILE IS USED FOR PARAMETER INPUT USING
THE NAMELIST CASE. FILE MUST FOLLOW NAMELIST INPUT FORMAT.
WRITE (6,...)/PRINT - OUTPUT FILE.
WRITE (10) - FLUX OUTPUT IS
WRITTEN DIRECTLY TO DISK FILE 10.
READ (12) - PHASE FUNCTION FOURIER COMPONENT INPUT. FOURIER COMPONENTS SHOULD NOT BE USED
EXCEPT FOR N=1 FLUX CALCULATIONS.

The GLOBAL variables are passed to all routines through the
following COMMON blocks. Any variable NOT appearing in a COMMON
is local to the routine and is used for temporary storage and
intermediate calculations.

COMMON /SCALAR: TFNLAL,TLLAYER,DTMAX,DTINIT,CONN,OMEGA,T1,T2,T,
: TMLSPR,TMLSPUT,TMLRLR,ASY2,ASYSQ,
: CONN,TOOL,TOPI,ASY,DTR,TMPK,NLAYER,NAC,NCIN,
: NM,MP1,NX,NM1,MSMALL,NDUBL,1LAYER,NONISO,ISURF,
: NA,NDUB,NRS,NAC1,NAC2,1NHOMO,1OCTL1,1OCTL2,
: 1OCTL3,1OCTL4,1OCTL5,1SURFT
COMMON /VECTOR: XNK(10),NMGNV(10),DWT(10),DWTINV(10),
: TMLRLR(40),NMULWT(10),
: ORG(1,41)
COMMON /MATRIX: PHASLB(10,10),PHASEF(10,10)
DIMENSION AMNTP(7,7,41),AMNMT(7,7,41)

CALL INPUT

WRITE(10,990) NLLAYER,(TMLRLR(11),11=1,NLLAYER)
WRITE(10,990) NLLAYER,(TMLRLR(11),11=1,NLLAYER)
990 FORMAT ///,' SINGLE SCATTERING CASE RUN'.
: //, ' NUMBER OF LAYERS =',NLAYER,
: //, ' WITH OPTICAL DEPTHS --- ',5(F12.0, ',',29X),///

END
LOOP OVER AZIMUTHAL ANGLES PHI

DO 1000 NPHI=1,N

DO 50 NR=1,NLEVEL
DO 50 J=1,N
DO 50 I=1,N

AMNTP(I,J,NR)=0.0
AMNMC(I,J,NR)=0.0

CONTINUE

LOOP OVER SOURCE LAYERS

DO 500 ILayer=1,NLayer

READ IN THE PHASE FUNCTION FOR THIS LAYER
AND THIS VALUE OF PHI.

READ(12) (PHASE(I,J),I=1,N),J=1,N
KLAB=12
READ(12) (PHASE(I,J),I=1,N),J=1,N
WRITE(6,919) (PHASE(I,J),I=1,N),J=1,N
WRITE(6,919) (PHASE(I,J),I=1,N),J=1,N
FORMAT(//, ' PHASE FUNCTION', '/', 7(F15.6,/,))

LOOP OVER BOTH QUADRATURE ANGLES

DO 400 I=1,N
DO 400 J=1,N

SSSP=PHASE(I,J)*OMGFUN(ILAYER)*XINV(I)/F0KP1
SSSM=PHASE(I,J)*OMGFUN(ILAYER)*XINV(J)/F0KP1
EXP1=EXP(-TNOTLR(ILAYER)*XINV(I))
EXP2=EXP(-TNOTLR(ILAYER)*XINV(J))
SSSP=SSSP*(I,J)*EXP1*EXP2*(XINV(I)+XINV(J))
DPRAT=EXP(-TNOTLR(ILAYER))
IF(1.EQ.J) GO TO 100
DIFRAT=(EXPMU1-EXPMUJ)/(XMUNV(J)-XMUNV(1))
100 CONTINUE
SSSM=SSSM-DIFRAT
C
C MULTIPLY SCAINT. SOURCES BY DIRECT SOLAR TRANS
C
DSTKAN=1.0
C
IF(LAYER.EQ.1) GO TO 120

MAX=LAYER+1
DO 110 NEXLAY=1,MAX

DSTKAN=DSTKAN*EXP(-TNOLT(NEXLAY)*XMUNV(J))

110 CONTINUE
120 SSSP=SSSP*DSTKAN
SSSM=SSSM*DSTKAN
C
C ADD CONTRIBUTION TO TOP OF SCATTERING LAYER
C
Nt=LAYER
ANTP(I, J, Nt)=ANGTP(I, 1, Nt)+SSSP
C
C ADD PART TO BOTTOM OF SCAT. LAYER
C
Nt=LAYER+
ANTM(I, J, Nt)=ANTM(I, 1, Nt)+SSSM
C
IF(LAYER.EQ.1) GO TO 250

1 FILL IN ABOVE TOP OF SCAT. LAYER

NMAX=LAYER+1
DO 200 NSTEP=1,NMAX
Nt=LAYER-NSTEP
SSSP=SSSP*EXP(-TNOLT(Nt)*XMUNV(J))
ANTM(I, J, Nt)=ANTM(I, 1, Nt)+SSSP

200 CONTINUE
C
C FILL IN BELOW BOTTOM OF LAYER
C
250 IF(LAYER.EQ.NLAYER) GO TO 350

NMAX=LAYER+1
DO 300 N=NMAX,NLEVEL
Nt=NSTEP=1
SSSM=SSSM*EXP(-TNOLT(Nt)*XMUNV(J))
ANTM(I, J, Nt)=ANTM(I, 1, Nt)+SSSM
300 CONTINUE
300 CONTINUE
350 CONTINUE
400 CONTINUE
500 CONTINUE

C WRITE OUT ACTUAL INTENSITIES

C DO 550 NR=1,NLEVEL
WRITE(6,992) NR,NPHI
992 FORMAT(' I',//,/, ' SINGLE SCATTERING INTENSITIES AT',
  ' R-LEVEL : ', 12., ' PHI INDEX : ', 12., //)
WRITE(6,992) ((AMNTP(1,J,NR),J=1,N),1=1,N)
993 FORMAT(' I',//,/, ' INTENSITY UP',
  ' SOLAR ZENITH --- ',
  ' /', ' ------------------- ',//,7(5X,7E12.4,/,//)
WRITE(6,994) ((AMNTM(1,J,NR),J=1,N),1=1,N)
994 FORMAT(' I',//,/, ' INTENSITY DOWN',
  ' SOLAR ZENITH --- ',
  ' /', ' ------------------- ',//,7(5X,7E12.4,/,//)
550 CONTINUE

C IF(M.NE.1) GO TO 1000

C WRITE(10,995)
995 FORMAT(' I',//,/, ' INTEGRATED SINGLE SCATTERING FLUXES FOLLOW',//)
C AT THIS POINT, ARRAYS AMNTP AND AMNTM CONTAIN
C THE ANGLE DEPENDENT ZEROTH FOURIER INTENSITIES.

C SUM OVER OBSERVER ANGLE 1 TO GET ACTUAL UP AND DOWN FLUXES

C DO 600 J=1,N
DO 600 NR=1,NLEVEL
AMNTP(1,J,NR)=AMNTP(1,J,NR)*XR(1)*TOOP1*DWT(1)
AMNTM(1,J,NR)=AMNTM(1,J,NR)*XR(1)*TOOP1*DWT(1)
600 CONTINUE

C DO 700 J=1,N
DO 700 NR=1,NLEVEL
DO 650 K=2,N
AMNTP(1,J,NK)=AMNTP(1,J,NK)+AMNTP(1,J,NK)*XR(K)*TOOP1*DWT(K)
AMNTM(1,J,NK)=AMNTM(1,J,NK)+AMNTM(1,J,NK)*XR(K)*TOOP1*DWT(K)
650 CONTINUE
700 CONTINUE

C WRITE OUT FLUXES LEVEL BY LEVEL

C DO 800 NR=1,NLEVEL

C WRITE FLUXES TO EXTRA STORAGE FILE NUMBER 10
C WRITE(6,998)
This subroutine determines the input and starting parameters.

SUBROUTINE INPUT

DIMENSION (G110)
COMMON (SCALAR/ TITLAL, TAKER, BTMAX, BTNTT, CONN, OMEGA, T1, T2, T,
  TPSUR, TPSUT, TDKR, ASY2, ASYSQ,
  CONNS, T0P1, FORP1, ASY, TDR, TPRM, TLAKE, NAK, NC1IN,
  X, Y, NP1, NN, NM1, NSMALL, NDUBL, THAK, NCONSO, TSURF,
  NA, NDUP, NRS, NAK1, NAC2, INBO10, I0C1L1, I0C1L2,
  I0C1L3, I0C1L4, I0C1L5, I0C1L6)
COMMON (ARRAY/ XM1(10), XM1NV(10), BW110), BW1NV(10),
  T1ALT(10), T1ALT(10),
  CMF1N(41)

COMMON (ARRAY/ PHASE1(10), PHASE2(10), PHASE3(10,10), PHASE4(10,10))

COMMON (ARRAY/ BCI, BE2, DMEGA, DMY, ETA10, INBO1K
  T1ALT1, T1ALT2, T1ALT3, T1ALT4, T1ALT5, T1ALT6,
  T1ALT7, T1ALT8, T1ALT9, T1ALT10)

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The following NAMELIST is used to input run parameters:

```
NAMELIST /CASE/ N, M, OMEGA, XM, C, NONISO, ISURF, ASY, DTMAX,
            TPSUR, NPSUR, TPSUR, WAVEIN, RELAX, ICTLI1, ICTLI2,
            ICTL13, ICTL14, ICTL15, TPSUR
```

```
DATA NMAX/40/, NHMAX/10/
```

```
DATA statements for raw data tables used to generate quadrature weights for points. The resulting weights are used for a Gaussian quadrature scheme.

```
DATA XM02 / 0.5773502692 /
1   XM03 / 0.7745968692 ,
1       0.0        ,
1   C3  / 0.5555555555 ,
1       0.8888888889 ,
1   XM04 / 0.8611363116 ,
1       0.3399810436 ,
1   C4  / 0.3478548451 ,
1       0.6521451549 ,
1   XM05 / 0.9061798459 ,
1       0.5384695101 ,
1       0.0 .
1   C5  / 0.2369268851 ,
1       0.4786288705 ,
1       0.5688888889 /

DATA XM06 / 0.9324973142 ,
1       0.6612093867 ,
1       0.236919861 ,
1   C6  / 0.1713024426 ,
1       0.36761531826 ,
1       0.4679139566 ,
1   XM07 / 0.9491079123 ,
1       0.7415311826 ,
1       0.4058451514 ,
1       0.0 /

DATA XM08 / 0.1294849662 ,
1       0.2797053915 ,
1       0.3818306505 ,
1       0.4179391837 ,
1   XM09 / 0.9602898584 ,
1       0.7800000000 ,
1       0.5255525255 ,
1       0.815446425 /
```
<table>
<thead>
<tr>
<th>DATA C8 /</th>
<th>DATA C9 /</th>
<th>DATA C10 /</th>
<th>DATA XML 15 /</th>
<th>DATA XML 15 /</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1012285363, 0.2229810345, 0.3137066459, 0.3628637834 /, 0.9681602395, 0.8360311073, 0.6133714327, 0.3242534234, 0.1 0.22238-10345, 0.3137066459, 0.3628637834 /, 0.9681602395, 0.8360311073, 0.6133714327, 0.3242534234, 0.1</td>
<td>0.0812743884, 0.1606481607, 0.2606106964, 0.3123470770, 0.3302395550 /, 0.9739065285, 0.8650833657, 0.6794095663, 0.4333953941, 0.1488743390 /</td>
<td>0.0666713443, 0.1494513492, 0.2190863625, 0.2692667193, 0.2935242247 /, 0.9879925180, 0.9372733924, 0.8482065834, 0.7244177144, 0.5709721726, 0.3941513471, 0.2012946940, 0.1 0.0</td>
<td>0.07497552420, 0.0760604475, 0.1041592205, 0.1395704779, 0.1662992058, 0.1581610001, 0.1984314853, 0.2025828419 /</td>
<td>0.07497552420, 0.0760604475, 0.1041592205, 0.1395704779, 0.1662992058, 0.1581610001, 0.1984314853, 0.2025828419 /</td>
</tr>
</tbody>
</table>

All run parameters are INITIALIZED to their DEFAULT values:

`...`

`OMEGA = 0...`

`N = 0...`

`NDNLS = 0...`
INHOMO = 0
INHOMK = 0
NLAYER = 1
TNOT = 0.0
TFINAL = 1.
ASY = 0.0
DTMAX = 3.05D-05
TNNOT(1) = 1.0
DTLR = 1.0
F0RP1 = 12.56637062
F0RP2 = 6.28318531
ISURF = 0
TNOTS = 5.0
CGMSKX = 0.95
ASYSUR = -0.8
ISURFT = 0
TNPSUR = 325.0
TNPSUT = 325.0
TNPRM = 325.0
WAVLEN = 5.0
REIDX = 1.0
J0CTL1 = 1
J0CTL2 = 0
J0CTL3 = 0
J0CTL4 = 0
J0CTL5 = 0

Parameter input overriding the defaults is done using IBM FORTRAN
NAMELIST input technique. The data is read using NAMELIST /CASE/.

READ(6,CASE)
READ(12, NBR3, NLAY2, N, M)

Check for possibilities of Storage overflow :

IF (N .LE. NMAX) GO TO 8
WRITE(6,7) N, NMAX
WRITE(1,7) N, NMAX
7 FORMAT(//' *** ERROR **** IN ADING PACKAGE :
       ' TOO MANY QUADRATURE POINT SPECIFIED.'//
       ' N = ',N, '. MAXIMUM ALLOWED = ',NMAX,//
       ' *** EVALUATION TERMINATED ****'/)
CALL EXIT
8 IF (NLAYER .LE. NLMAX) GO TO 9
WRITE(6,8) NLAYER, NLMAX
WRITE(1,8) NLAYER, NLMAX
8 FORMAT('NOD DATA 'NLAYER'層')
CALL EXIT

FORMAT(/// '***** ERROR ***** IN ADDING PACKAGE :\///
\; ' LAYER THICKNESS STORAGE WILL BE EXCEEDED, EXECUTION STOPPED.'
\; // ' N LAYER = ',13,'; MAXIMUM ALLOWED = ',13//'\;
\; ' INCREASE TNOL NR DIMENSION IN ALL COMMONS.'//)

CONTINUE

10 IF(N.NE.1) GO TO 11
   XMU(1) = XMU2
   XMU(2) = -XMU2
   C(1) = 1.
   C(2) = i.
11 IF(N.NE.3) GO TO 12
   XMU(1) = XMU3(1)
   XMU(2) = XMU3(2)
   XMU(3) = -XMU3(1)
   C(1) = C(1)
   C(2) = C(3)
12 IF(N.NE.4) GO TO 13
   DO 128 i = 1,2
      XMU(1) = XMU4(1)
      C(1) = C(1)
128 C(5-1) = C(1)
   DO 129 i = 3,4
129 XMU(1) = -XMU4(5-1)
13 IF(N.NE.5) GO TO 14
   DO 138 i = 1,2
      XMU(1) = XMU5(1)
      C(1) = C(1)
138 C(i+1) = C(i+1)
   XMU(1) = 0.
   C(1) = C(1)
   DO 139 i = 4,5
139 XMU(1) = -XMU5(i+1)
14 IF(N.NE.6) GO TO 15
   DO 148 i = 1,3
      XMU(1) = XMU6(1)
      C(1) = C(1)
148 C(7-1) = C(1)
   DO 149 i = 4,6
149 XMU(1) = -XMU6(7-1)
15 IF(N.NE.7) GO TO 16
   DO 158 i = 1,3
      XMU(1) = XMU7(i)
      C(1) = C(1)
158 C(i+1) = C(i+1)
   XMU(2) = 0.

C)
C(4) = C7(4)
DO 159 I = 5,7
159 XMU(I) = -XMU8(8-I)
16 IF(N.NE.8) GO TO 17
   DO 168 J = 1,4
   XMU(I) = XMU8(I)
   C(I) = C8(I)
   168 C(9-I) = C8(I)
   DO 169 I = 5,8
   169 XMU(I) = -XMU8(9-I)
17 IF(N.NE.9) GO TO 18
   DO 178 J = 1,4
   XMU(I) = XMU9(I)
   C(I) = C9(I)
178 C(10-I) = C9(I)
   XMU(5) = 0.
   C(5) = C9(5)
   DO 179 I = 9,9
179 XMU(I) = -XMU10(10-I)
18 IF(N.NE.10) GO TO 19
   DO 188 J = 1,5
   XMU(I) = XMU10(I)
   C(I) = C10(I)
188 C(11-I) = C10(I)
   DO 189 I = 9,9
189 XMU(I) = -XMU10(11-I)
19 IF(N.NE.11) GO TO 20
   DO 198 J = 1,7
   XMU(I) = XMU15(I)
   C(I) = C15(I)
198 C(18-I) = C15(I)
   XMU(8) = 0.
   C(8) = C15(8)
   DO 199 I = 9,15
199 XMU(I) = -XMU10(I)
20 CONTINUE
C
C
DO 200 J = 1,N
200 XMU(I) = .5*XMU(I) + .5
DO 21 I = 1,N
   XMUINV(I) = 1./XMU(I)
   DWT(I) = C(I)*0.5
   DWTINV(I) = 1./DWT(I)
   XMU(DWT(I)) = XMU(I)*DWT(I)
C
RETURN
END
PLANE-PARALLEL SINGLE SCATTERING PROGRAM PPSS1:
SAMPLE IBM JOB CONTROL CARDS AND DATA FILES

/*JOBPARM T=1.1=9
*/PHASEFIT EXEC PGM=MAIN
/*STEP1B DD DSN=DOT4101.ADNGFIT,LOAD,DISP=SHR
/**T05F001 DD */
   51 32 7 1 1 0 1 1
0.8
/**T06F001 DD SYSOUT=A
/**T07F001 DD DSN=STMP1,UNIT=SCRATCH,DISP=(NEW,DELETE,DELETE),
   /*SPACE=(CYL,(1,1))
/**T08F001 DD DSN=STMP2,UNIT=SCRATCH,DISP=(NEW,PASS),
   /*SPACE=(CYL,(1,1))
/**PPSS EXEC PGM=MAIN
/*STEP1B DD DSN=DOT4101.PPSS1,LOAD,DISP=SHR
/**T05F001 DD */
GCASE
NLAYER=32,
NOUTL= 0.2520882E-06, 0.4097418E-05, 0.4014033E-05, 0.7848409E-05,
   0.1596591E-04, 0.7304554E-04, 0.3850379E-03, 0.1793371E-03,
   0.2433453E-03, 0.2548368E-03, 0.2478541E-03, 0.2505557E-03,
   0.2301920E-03, 0.2297376E-03, 0.2439593E-03, 0.2655097E-03,
   0.2909857E-03, 0.3144068E-03, 0.3249425E-03, 0.3344070E-03,
   0.3309527E-03, 0.2279736E-02, 0.156998E-03, 0.8913260E-04,
   0.1802612E-03, 0.4156892E-03, 0.9852635E-03, 0.2502452E-02,
   0.6078091E-02, 0.1590397E-01, 0.4777626E-01, 0.1064715E+00,
GEND
0.2059533E+00 0.2059541E+00 0.2059497E+00 0.2094232E+00
0.2050724E+00 0.3171340E-01 0.2313057E-03 0.2261108E-03
0.2521912E-03 0.3641597E-03 0.4637628E-03 0.5429178E-03
0.6191996E-03 0.5990531E-03 0.4841997E-03 0.3604653E-03
0.3537481E-03 0.3454756E-03 0.3681581E-03 0.4311963E-03
0.5791909E-03 0.1052119E-02 0.5051012E-02 0.1527380E-01
0.1397186E-01 0.9038797E-02 0.4659929E-02 0.2893881E-02
0.2289353E-02 0.9467696E-01 0.2802829E+00 0.3485013E+00 /
/**T06F001 DD SYSOUT=A
/**T12F001 DD DSN=STMP2,DISP=(OLD,DELETE),UNIT=SCRATCH
/**T10F001 DD DSN=DOT4101.SSFLUX.DATA,
   /*DISP=OLD,KEEP,KEEP),
   /*DCB=(D80RG=PS,1,RECL=133,RECFM=F1,BLKSIZE=2000)
/**T10F002 DD DSN=DOT4101.SSFLUX.DATA,
   /*DISP=OLD,KEEP,KEEP),
   /*DCB=(D80RG=PS,1,RECL=133,RECFM=F1,BLKSIZE=2000)