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Status Report October 1, 1978
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Richard Bird and Roland Hulstrom

Solar Energy Research Institute
A Division of Midwest Research Institute

1536 Cole Boulevard
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APPLICATION OF MONTE CARLO TECHNIQUES TO INSOLATION CHARACTERIZATION AND PREDICTION

STATUS REPORT OCTOBER 1, 1978
JUNE 1, 1979

RICHARD BIRD
ROLAND HULSTROM

JULY 1979

PREPARED UNDER TASK NO. 3621.10

Solar Energy Research Institute

1536 Cole Boulevard
Golden, Colorado 80401

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FOREWORD

This is a status report performed in compliance with Contract Number EG-77-C-01-4042 for the Division of Solar Technology of the U.S. Department of Energy. The report describes preliminary research in the use of Monte Carlo techniques for studying various aspects of solar radiation transport (Task No. 3621.10) and was prepared by the staff of the Energy Resource Assessment Branch of the Solar Energy Research Institute.

Roland L. Hulstrom, Chief
Energy Resource Assessment Branch

Approved for:

SOLAR ENERGY RESEARCH INSTITUTE

K. J. Touryan
Acting Assistant Director
for Research

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SUMMARY

The objective of this study is to use the Monte Carlo method to investigate solar radiation transport through the atmosphere and its reflection from the earth's surface. The rigorous model used in this study allows a detailed understanding of the various aspects of the radiation field at the earth's surface. This knowledge can be used to compare and formulate simple models that are more appropriate for work on solar applications. Phenomena of interest include: the spectral distribution of direct, diffuse-sky, and ground-reflected insolation; the total broadband insolation; circumsolar insolation; the effect of ground albedo; the relationship between insolation on horizontal surfaces and insolation on tilted surfaces; the importance of higher orders of scattering and reflection; the effects of clouds; and the effects of various types of atmospheric aerosols. This report is preliminary in nature in that it is primarily a description of the Monte Carlo method itself and its applications rather than a detailed presentation of results used in solar radiation transport calculations.

SECTION 1.0

OBJECTIVE

In the past, very little effort has been expended on applying rigorous radiation transport models to solar energy problems. Several different computational methods of solving the radiative transfer equation have been demonstrated. Among these are the Monte Carlo method, the method of spherical harmonics, the discrete ordinates method, the matrix operator method, and the DART method. The Monte Carlo method was selected for first consideration in this study.

A major goal of the study is to use a rigorous model to investigate different aspects of solar radiation transport. With this approach, a detailed understanding of the various absorption and scattering phenomena is gained. The formulation of simple, user-oriented models then can be undertaken with greater confidence.

This report is of a preliminary nature; later reports will provide more details of results obtained from applying the Monte Carlo codes to solar radiation transport. This report provides a general description of the Monte Carlo technique, a discussion of its capabilities, a sketch of possible applications, the current status of the Monte Carlo codes, and a delineation of future efforts.

SECTION 2.0

MONTE CARLO COMPUTATIONAL METHOD

The Monte Carlo method, as the name implies, is a statistical technique of solving the equation of radiative transfer. Probability distributions that characterize photon scattering and absorption events are sampled randomly. One photon at a time is followed on its three-dimensional path through the scattering medium. The generation of a photon trajectory is begun by randomly sampling an angle from a probability distribution that describes the spatial distribution of light being emitted from a source. A random length is then drawn from a probability distribution of the distances traveled between successive collisions. Next, a random direction is selected from two angular probability distributions that describe polar and azimuthal scattering, respectively. After a new direction is established, the procedure for choosing a random length and direction is repeated until the desired number of collisions have occurred. At each scattering event, decisions must be made on the probability of absorption, the probability of interaction with a molecule or with an aerosol particle, the probability of absorption at a lower boundary, and the probability of scattering a photon upward from a lower boundary. This concept is illustrated in Fig. 2-1 for a spherically layered atmosphere.

The Monte Carlo method has been applied to nuclear and light scattering problems for nearly 20 years. As a result of this extensive effort, many efficiency techniques have been devised to greatly decrease the computational time required. For example, photon trajectories are never terminated because of absorption; instead, a statistical weight is associated with each photon and is appropriately adjusted after each collision. The initial value of the weight is unity, and the photon trajectory is terminated only when the weight becomes less than a small predetermined value. Collisions are forced so that photons never leave the atmosphere. The weighting factor associated with the photon is adjusted each time a forced collision occurs to remove any bias from the results. The codes described here use the backward Monte Carlo method (Collins et al. 1972). This means that photons are traced backwards from the receiver to the source. This technique is especially useful when a finite receiver and a broad source are modeled. The probability of a photon entering a finite receiver with a restricted field-of-view (FOV) is very small, and this method forces all photons to enter the receiver.

Two codes named BRITE and FLASH are discussed here. These codes were developed by Radiation Research Associates, Inc., of Fort Worth, Texas. The BRITE code is for an infinite, plane-parallel atmosphere, and the FLASH code is for a spherical-shell atmosphere. The plane-parallel atmosphere is simpler and more efficient in computer time. However, the plane-parallel geometry loses accuracy as the sun approaches the horizon. The direct component begins to deviate at solar zenith angles > 60° due to earth curvature, and the exact effect of earth curvature on the diffuse component is something that will have to be studied.

In BRITE and FLASH, a multilayered atmosphere is utilized within which the scattering and absorption properties can be varied with altitude. Both molecular (Rayleigh) and aerosol (MIE) scattering events can occur, and the scattering functions for each of these events are allowed to vary independently

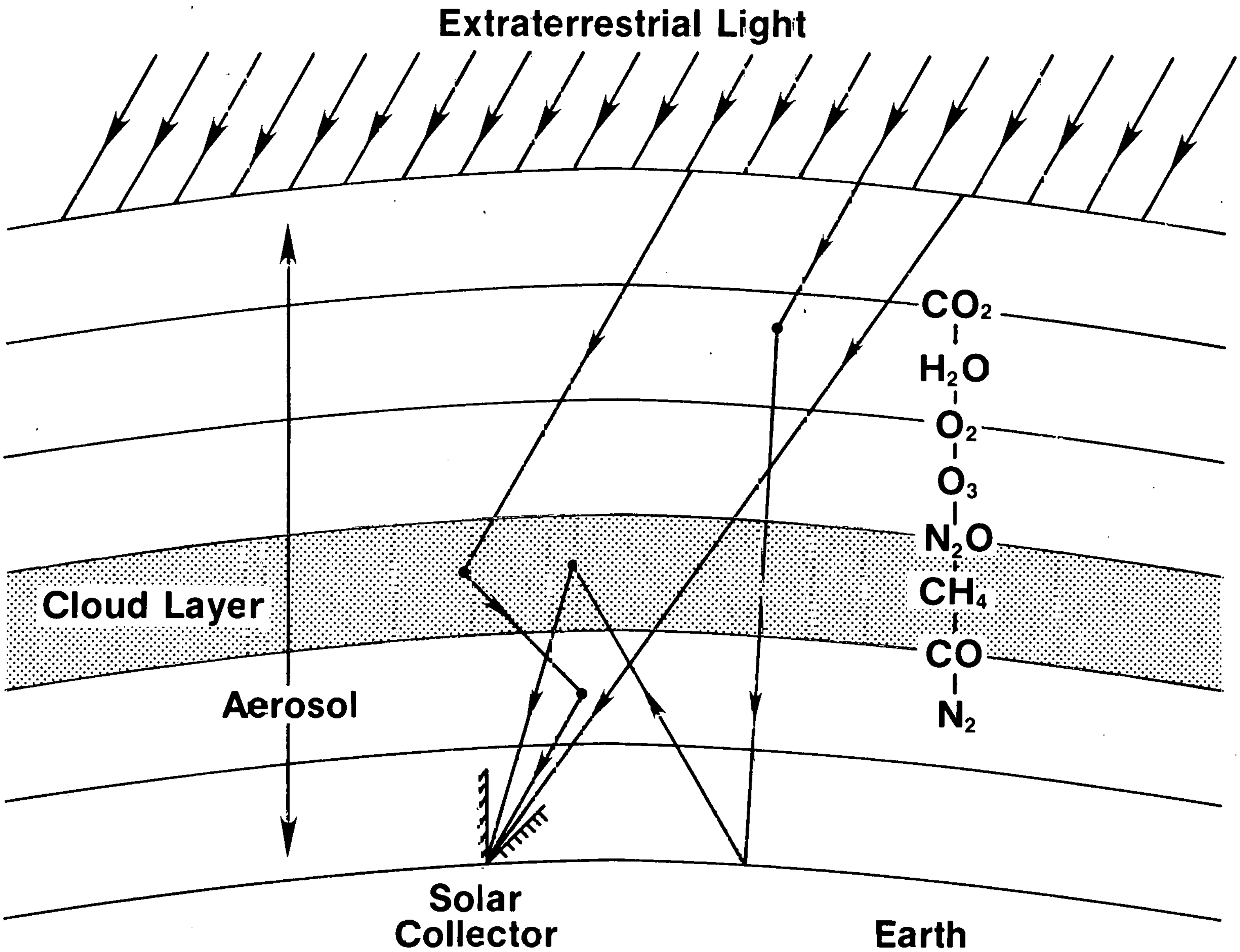

Figure 2-1. Atmospheric Structure for the Monte Carlo Insolation Model

and arbitrarily with altitude. Ground reflection for various albedos is included as an additional type of scattering event. The ground reflection can be assumed to be either lambertion, isotropic, or of some arbitrary type. These codes also treat absorption by aerosols, ozone, water vapor, carbon dioxide, oxygen, and other molecular species. An additional feature of these codes is that the state of polarization (Stokes parameters) of the scattered light is traced through all orders of scattering. Reflected light is traced through all orders of scattering. Reflected light from the ground is assumed to be unpolarized.

We built several unique features into these programs for application to solar problems. Up to 10 wavelengths can be modeled simultaneously in a single computer run. The only assumption is that the aerosol scattering and aerosol absorption properties are constant over the wavelength interval being considered. This is a very accurate assumption for relatively narrow wavelength intervals, and this capability decreases the computer time by nearly a factor of 10 when data over a broad spectrum, such as the solar spectrum, are desired. Up to nine incident angles of the solar radiation can be modeled in one computer run. In addition, two choices of receiver geometry are available. A conical beam geometry is available in which the cone about the receiver axis can be divided into a combination of up to 15 polar bins with up to 15 azimuthal bins within each polar bin. Either average spectral radiance (W m^{-2} μm^{-1} sr^{-1}) or spectal irradiance (W m^{-2} μm^{-1}) can be calculated for each angular bin along with the total integrated value for all bins. The second geometry is for the calculation of spectral radiance at point directions on a spherical surface. This geometry allows storage of the data for future use in any receiver geometry desired. A final capability incorporated for solar application is that of modeling up to six different ground albedos simultaneously.

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SECTION 3.0

ATMOSPHERIC AND TERRAIN CONSIDERATIONS

The codes described in this report can model an atmosphere with up to 75 boundaries where aerosol, molecular, and meteorological parameters can be defined as a function of altitude. The parameters are assumed to vary exponentially between each boundary. Two different aerosol phase functions can be defined for each atmospheric model, which allows two different types of aerosols to be modeled simultaneously. This number can be increased easily, if necessary, by increasing array dimensions within the codes. A brief description of the methods used to model each scattering and absorption phenomenon is presented in this section.

3.1 RAYLEIGH SCATTERING

The interaction of light with air molecules is defined with the Rayleigh scattering coefficient. The Rayleigh scattering coefficient is dependent upon the air density, which is slightly dependent upon temperature and pressure. The temperature and pressure dependence is so small that it can usually be considered to remain constant at any given location in the atmosphere. The Rayleigh scattering coefficient $\sigma_R(h)$ at altitude h is given by

$$\sigma_R(h) = 10^5 \frac{8\pi^3}{3} \frac{(M_\lambda^2 - 1)^2}{\lambda^4} \frac{N(h)}{N_0^2} \left(\frac{6 + 3\Delta}{6 - 7\Delta}\right) \text{km}^{-1}, \tag{1}$$

where

λ = wavelength (cm),

M_λ = index of refraction at ground level,

$N(h)$ = molecular number density at altitude h (cm^{-3}),

N_0 = molecular number density at sea level (cm^{-3}),

Δ = depolarization factor ($0 \leq \Delta \leq 0.5$).

The refractive index at ground level can be calculated as a function of wavelength by

$$(M_\lambda - 1)\, 10^8 = A_1 + \frac{A_2}{B_1 - \lambda^{-2}} + \frac{A_3}{B_2 - \lambda^{-2}} , \tag{2}$$

where the constants, as given by Peck and Reeder (1972), are

$$(M_\lambda - 1)\, 10^8 = 8060.51 + \frac{2480990.0}{132.274 - \lambda^{-2}} + \frac{17455.7}{39.32957 - \lambda^{-2}} . \tag{3}$$

Equation 1 accounts for the depolarization attributable to the anisotropy of the atmospheric molecules. The theory limits the depolarization factor to $\Delta \leqslant 0.50$ (Chandrasekhar 1960). One recent value of the depolarization factor is given as 0.0139 (Hoyt 1977).

The Rayleigh scattering coefficient may be calculated as a function of altitude by

$$\sigma_{R(\lambda,h)} = \sigma_{R(\lambda,0)} \frac{N(h)}{N_0} \quad . \tag{4}$$

The angular scattering properties of the molecules are described by the Rayleigh phase function given by

$$R_j(\theta) = \frac{3}{8\pi(1 + \Delta/2)} M_j \quad , \tag{5}$$

where M_j represents $M_1 = (1 - \Delta) \cos^2\theta$ and $M_2 = 1 + \Delta$.

The Rayleigh parameters are built into the computer codes and require no external calculations.

3.2 AEROSOL ATTENUATION AND SCATTERING

In many cases, aerosol scattering is the dominant atmospheric effect. Aerosol scattering and absorption are accounted for by using MIE light scattering theory. This theory provides the exact solution for a plane wave of radiation being scattered from a homogeneous sphere. Many texts discuss the formal solution derived by MIE (e.g., Kerker 1969), which is beyond the scope of this discussion, but we present here a brief description of the parameters required for computations. The aerosol extinction coefficient for a polydispersion of spherical particles is given by

$$\alpha = \frac{\lambda^3}{4\pi^2} \int_{x_1}^{x_2} \sum_{n=1}^{\infty} (2n + 1) \left[R_e\left(a_n + b_n\right)\right] n(x)\, dx \quad , \tag{6}$$

where $n(x)$ is the particle size distribution, $x = 2\pi r/\lambda$ (r = the particle radius), and a_n and b_n are the MIE amplitude functions given by

$$a_n(x,m_0) = \frac{\psi_n(x)}{\zeta_n(x)} \left[\frac{A_n(y) - m_0 A_n(x)}{A_n(y) - m_0 B_n(x)}\right] \tag{7}$$

and

$$b_n(x,m_0) = \frac{\psi_n(x)}{\zeta_n(x)} \left[\frac{A_n(x) - m_0 A_n(y)}{B_n(x) - m_0 A_n(y)}\right] \quad , \tag{8}$$

where $\psi_n(x)$ and $\zeta_n(x)$ are Riccati-Bessel functions of the first and third kind, respectively, and $A_n(x)$ and $B_n(x)$ are logarithmic derivatives of Riccati-Bessel functions of the first and third kind, respectively. The variable m_0 is the complex index of refraction of the aerosol material expressed by $m_0 = n_1 - in_2$ and $y = m_0 x$.

Riccati-Bessel functions and logarithmic derivatives of Riccati-Bessel functions can be calculated from recursion formulas of the following form:

$$f_n(x) = \frac{2n - 1}{x} f_{n-1}(x) - f_{n-2}(x) \quad (9)$$

and

$$F_n(x) = \left[n/x - F_{n-1}(x)\right]^{-1} - n/x \quad , \quad (10)$$

where $f_n(x)$ and $F_n(x)$ represent Riccati-Bessel functions and logarithmic derivatives of Riccati-Bessel functions, respectively. These upward recursion formulas contain instabilities for ψ_n and A_n, and downward recursion formulas are often used. The MIE scattering coefficient is given by

$$\sigma_{AS} = \frac{\lambda^3}{4\pi^2} \int_{x_1}^{x_2} \sum_{n=1}^{\infty} (2n + 1)\left[|a_n|^2 + |b_n|^2\right]n(x)\, dx \quad , \quad (11)$$

and the absorption coefficient of aerosols is obtained from

$$\sigma_{AA} = \alpha - \sigma_{AS} \quad . \quad (12)$$

The parameter that describes the angular scattering properties of the aerosol particles is the MIE phase function. The phase function is expressed by

$$P_j(\theta) = \frac{4\pi}{\sigma_{AS}} \left(\frac{\lambda}{2\pi}\right)^3 \int_{x_1}^{x_2} n(x)\, i_j(\theta)\, dx \quad , \quad (13)$$

where σ_{AS} is the MIE scattering coefficient and i_j represents the MIE intensity functions given by

$$i_1(\theta) = \left| \sum_{n=1}^{\infty} \frac{(2n + 1)}{n(n + 1)} \left(a_n\pi_n + b_n\tau_n\right)\right|^2 \quad (14)$$

and

$$i_2(\theta) = \left| \sum_{n=1}^{\infty} \frac{(2n + 1)}{n(n + 1)} \left(a_n\tau_n + b_n\pi_n\right)\right|^2 \quad . \quad (15)$$

π_n and τ_n are the MIE angular functions, which can be calculated from the following recursion formulas:

$$\pi_n(u) = \frac{2n - 1}{n - 1} u\pi_{n-1} - \frac{n}{n - 1} \pi_{n-2}(u) \quad (16)$$

and

$$\tau_n(u) = nu\pi_n(u) - (n + 1)\, \pi_{n-1}(u) \quad , \quad (17)$$

where $u = \cos\theta$ and θ is the angle of scatter. Calculations can be started by setting $\pi_1(\theta) = 1$ and $\pi_2(\theta) = 3\cos\theta$.

A separate program called MIE2 is used to calculate the extinction and scattering coefficients and the MIE phase matrix for use in the BRITE and FLASH programs.

3.3 SURFACE ALBEDO

As was mentioned in Section 2.0, the BRITE and FLASH codes have the capability of treating six different values of the ground albedo per computer run. The albedo of the ground surface is given by

$$ALB = A_0 + A_1 \cos \theta_0 \quad , \tag{18}$$

where A_0 and A_1 are input values and θ_0 is the angle between the direction of the photon and the normal to the reflection surface. If A_1 is zero, the albedo is independent of the incident angle. The angular distribution of the light reflected from the surface may be defined as an isotropic or cosine distribution or an arbitrary reflection distribution defined with tabular input data.

3.4 MOLECULAR ABSORPTION

Molecular absorption is a significant attenuator of light passing through the atmosphere. The absorption of light at UV and visible wavelengths is mostly due to ozone. Since ozone absorption varies slowly with wavelength, it can be treated in the form of a Beer's law attenuation function. The ozone attenuation is built into the Monte Carlo codes using cross sections given by Selby et al. (1978).

The methods we utilized for gaseous band absorption (H_2O, O_2, O_3, CO_2, CO, N_2O, and CH_4) are based upon methods given by Goody (1964) and McClatchey (1964). The transmission averaged over a finite frequency interval is used rather than the absorption cross section for a given wavelength. The average transmission over a series of absorption lines is given by

$$T_g = \exp\left\{ - \left[m \sum S(i) \right] \left[\Delta\nu \left(1 + \frac{m}{4} \left(\frac{\sum S(i)}{\sum \sqrt{S(i)\alpha(i)}} \right)^2 \right)^{1/2} \right]^{-1} \right\} \quad , \tag{19}$$

where

m = number of molecules/cm^2 along the path,

$S(i)$ = strength of line i,

$\alpha(i)$ = line width of line i,

$\Delta\nu$ = width of frequency range over which the summations are made.

Substituting $A = \sum S(i)$ and $B = \sum \sqrt{S(i)\alpha(i)}$ and taking into account the pressure dependency leads to

$$T_g = \exp\left\{ - m A \left[\Delta\nu \left(1 + \frac{m}{4} \frac{1013}{p} \left(\frac{A}{B}\right)^2 \right)^{1/2} \right]^{-1} \right\} \tag{20}$$

Equation 20 gives the transmission through a homogeneous layer. It is obvious from this equation that the total transmission along the path of a photon through an inhomogeneous layer cannot be obtained by simply multiplying the transmissions through each one of the layers traversed by the photon unless the inequality

$$\frac{m}{4} \times \frac{1013}{p} << \left(\frac{B}{A}\right)^2$$

holds, in which case Eq. 20 reduces to Beer's law:

$$T_g = \exp(-\text{ constant} \times m) \quad . \tag{21}$$

In the case of

$$\frac{m}{4} \times \frac{1013}{p} >> \left(\frac{B}{A}\right)^2 \quad ,$$

Eq. 20 transforms to

$$T_g = \exp\left(-\text{ constant} \times \sqrt{mp}\right) \quad , \tag{22}$$

and therefore

$$T_g(2m) = \exp(-\text{ constant} \times \sqrt{2mp})$$
$$\neq T_g(m)\, T_g(m) = [\exp(-\text{ constant} \times \sqrt{mp})]^2 \quad .$$

McClatchey (1964) has suggested that the transmission along an inhomogeneous path can be calculated by replacing the quantities m and p in Eq. 20 with effective absorber amounts m_e and effective pressures p_e:

$$m_e = \int \frac{A_T}{A_0}\, dm = \frac{1}{A_0} \sum \left(A_T\ \Delta m\right) \tag{23}$$

and

$$m_e p_e = \int \left(\frac{B_T}{B_0}\right)^2 p\ dm = \frac{1}{B_0^2} \sum\left(B_T^2\ p\ \Delta m\right) \quad , \tag{24}$$

where the subscripts T and 0 denote the actual temperature and an effective temperature, respectively.

Equation 20, when applied to an inhomogeneous path, then becomes

$$T_g = \exp\left\{ -\ m_e A_0 \left[\Delta\nu \left(1 + \frac{m_e}{4}\ \frac{1013}{p_e}\ \left(\frac{A_0}{B_0}\right)^2 \right)^{1/2} \right]^{-1} \right\} \tag{25}$$

or, after substitution of Eqs. 23 and 24,

$$T_g = \exp\left\{ -\sum A_T\ \Delta m \left[\Delta\nu \left(1 + \frac{1013}{4}\ \frac{\left(\sum A_T\ \Delta m\right)^2}{\sum B_T^2\ \ p\Delta m} \right)^{1/2} \right]^{-1} \right\} \quad . \tag{26}$$

When evaluating Eq. 26, FLASH and BRITE first determine the two arrays

$$AH(J,N,h) = A_T(J,N,h)\ m(J,h) \tag{27}$$

and

$$BH(J,N,h) = 4\,\frac{p(h)}{1013}\,B_T^2(J,N,h)\;m(J,h) \quad , \tag{28}$$

where m is the molecular density ($cm^{-2}\ km^{-1}$) and J, N, and h denote the species, wavelength, and altitude, respectively. The total transmission along the path of a photon is then computed by FLASH and BRITE using the equation

$$T_g(N) = \exp\left\{-\sum_j\left[\sum_i AH(J,N,i)\;S(i)\right]\left[\Delta\nu\left(1+\frac{\left(\sum_i AH(J,N,i)\;S(i)\right)^2}{\sum_i BH(J,N,i)\;S(i)}\right)^{1/2}\right]^{-1}\right\}, \tag{29}$$

where S(i) is the geometric path traversed through the i^{th} layer.

The averaged cross sections were compiled using the AFGL atmospheric absorption line parameter data (Rothman 1978) and are stored on magnetic tape for wavelengths in the range of 0.5593 to 1000.0 μm. The data have a resolution of 20 cm^{-1} at 5 cm^{-1} spacing, and they were computed for seven temperatures from 175 K to 325 K.

SECTION 4.0

APPLICATIONS OF MONTE CARLO CODES

The BRITE and FLASH computer codes have many applications for understanding in detail the scattering and absorption phenomena involved in solar energy transport. Many of these areas of interest have been identified, and undoubtedly many more applications will arise in the future.

Possible applications include studies of:

- models of realistic atmospheres with detailed atmospheric constituent height profiles, curvature effects, refractive index effects, and other meteorological effects;
- the spectral insolation distribution for direct, diffuse-sky, and ground-reflected radiation;
- the total broadband insolation under varying conditions;
- the circumsolar or aureole phenomena;
- the effect of ground albedo;
- the importance of multiple scattering and reflection;
- the relationships between insolation on horizontal and insolation on tilted surfaces;
- the effects of clouds; and
- aerosol size distribution, complex index of refraction, and height profile effects.

These codes are especially useful for computing the broadband and spectral global insolation, which includes the direct, diffuse-sky, and ground-reflected insolation on surfaces with arbitrary orientations. We plan to pursue a detailed study of all aspects of these areas of interest.

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SECTION 5.0

CAPABILITIES AND LIMITATIONS

Several of the capabilities of the Monte Carlo codes are discussed in Section 2.0. These capabilities and some of the limitations are summarized in this section.

The codes have a great deal of flexibility for defining the structure of the atmosphere. The aerosol and individual molecular components can be defined with any desired height profiles. The profiles can include cloud layers that are homogeneous in the horizontal direction. The temperature and pressure height profiles can be defined as desired. The atmospheric geometry can either be plane-parallel or spherical-shell. Ground surface albedo can be varied from zero to one.

Several features that improve computer efficiency include: the capability of modeling up to 10 wavelengths simultaneously, the option of modeling six simultaneous values of the ground albedo, and the choice of conical or point-direction receiver geometries.

It is extremely difficult to compare various types of rigorous light transport models. Some methods are most efficient when few atmospheric layers are used, whereas the number of layers does not significantly affect other methods. Some models are limited to one wavelength and one incident angle, while others have varied capabilities. For these and other reasons it is unwise to make simple comparisons among various methods.

One possible limitation of the Monte Carlo approach is that it is statistical rather than deterministic. This means that the final results obtained with the Monte Carlo method can deviate somewhat depending on the random number sequence used and the total number of photon histories used. However, with reasonable run times, the standard deviation can be as low as 1%. This is well within insolation measurement and atmospheric definition capabilities.

Some argue that computer cost in utilizing the Monte Carlo technique is a limitation. Modeling a broadband spectrum for complicated atmospheres is very time consuming with any computer method, but it is not clear that other techniques are more efficient than the Monte Carlo approach when its full capabilities are utilized.

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SECTION 6.0

CURRENT STATUS AND FUTURE EFFORTS

The Monte Carlo codes and other codes that are used in conjunction with them are operational on the Denver Bureau of Reclamation CDC centralized computer system. These codes have been checked for accuracy by comparison with other published data and model results as well as for internal consistency.

In the future, output from these codes will be compared with a variety of carefully taken insolation data. These data will be collected at the Insolation Research Laboratory which is currently being constructed near the SERI permanent site in Golden, Colorado. An important aspect of this data is that various meteorological parameters will be measured to help construct a realistic atmosphere. A comparison will be made with results obtained from already existing simple algorithms for computing various components of insolation. In addition, when it is deemed appropriate, new and improved simple models will be constructed as a result of this study.

An investigation, both experimental and theoretical, of the possible applications of these codes listed in Section 4.0 will be undertaken.

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SECTION 7.0

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16. Abstract (Limit: 200 words)

The objective of this study is to use the Monte Carlo method to investigate solar radiation transport through the atmosphere and its reflection from the earth's surface. The rigorous model used in this study allows a detailed understanding of the various aspects of the radiation field at the earth's surface. This knowledge can be used to compare and formulate simple models that are more appropriate for work on solar applications. Phenomena of interest include: the spectral distribution of direct, diffuse-sky, and ground-reflected insolation; the total broadband insolation; circumsolar insolation; the effect of ground albedo; the relationship between insolation on horizontal surfaces and insolation on tilted surfaces; the importance of higher orders of scattering and reflection; the effects of clouds; and the effects of various types of atmospheric aerosols. This report is preliminary in nature in that it is primarily a description of the Monte Carlo method itself and its applications rather than a detailed presentation of results used in solar radiation transport calculations.

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