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DIRECT INSOLATION MODELS

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FOREWORD

This report documents work performed by the SERI Energy Resource Assessment Branch for the Division of Solar Energy Technology of the U.S. Department of Energy. The report compares several simple direct insolation models with a rigorous solar transmission model and describes an improved, simple, direct insolation model.

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SECTION 1.0

INTRODUCTION

Solar energy (insolation) conversion systems are different from systems based on other sources of energy, because the energy source is subject to varying meteorological conditions. As a result, reliable insolation data are required at each site of interest to design a solar energy system. Historical data have been collected by the National Weather Service (NWS) on a very limited basis at 26 locations throughout the United States, and data are currently being collected at 38 locations. Because of the small number of stations in this network and the variability of insolation, it is essential to have accurate models to predict insolation at other locations. The accuracy of these models and experimental data affects the design, performance, and economics of solar systems.

Numerous simple insolation models have been produced by different investigators over the past half century. The goal of these models has been to provide an uncomplicated estimation of the available insolation. These models, by very different methods, account for the influence of each atmospheric constituent on solar radiation. This, in turn, leads to confusion and questions of validity from prospective users.

This study compares several of the more recent models of the direct component of the insolation for clear sky conditions. The comparison includes seven simple models and one rigorous model that is a basis for determining accuracy. The results of the comparisons are then used to formulate two simple models of differing complexity. The most useful formalisms of present models have been incorporated into the new models.

The criteria for evaluating and formulating models are simplicity, accuracy, and the ability to use readily available meteorological data.

In the future, a similar analysis of models for global and diffuse insolation is planned. Simple global and diffuse models will be compared with a rigorous model that uses Monte Carlo techniques. Additional comparisons are planned, with very carefully taken experimental data for both direct and diffuse insolation components. As many meteorological measurements as can reasonably be taken will be included with these data.

The goal of this work is to produce a well-documented global insolation model that includes the direct and diffuse clear sky insolation as well as cloud-and ground-reflected insolation. This report is the first step toward achieving that goal.

SECTION 2.0

DESCRIPTION OF MODELS

A rigorous atmospheric transmission model has served as a basis for comparing the accuracy of simple empirical models. The next few sections present a description of the rigorous model and the mathematical expressions that form the simplified models.

2.1 SOLTRAN MODEL

The rigorous model, called SOLTRAN, was constructed from the LOWTRAN [1-3] atmospheric transmission model produced by the Air Force Geophysics Laboratory and the extraterrestrial solar spectrum of Thekaekara [4].

The LOWTRAN model has evolved through a series of updates and continues to be improved with new data and computational capabilities. In this model, a layered atmosphere is constructed between sea level and 100-km altitude by defining atmospheric parameters at 33 levels within the atmosphere. The actual layer heights at which atmospheric parameters are defined are: sea level (0.0 km) to 25-km altitude in 1.0-km intervals, 25 to 50 km in 5-km intervals, and at 70 km and 100 km, respectively. At each of these 33 altitudes the following quantities are defined: temperature, pressure, molecular density, water vapor density, ozone density, and aerosol extinction and absorption coefficients. A complete description of the standard model atmospheres incorporated in this code is given by McClatchey et al. [5].

The absorption coefficients of water vapor, ozone, and the combined effects of the uniformly mixed gases (CO_2, N_2O, CH_4, CO, N_2, and O_2) are stored in the code at 5-cm^{-1} wavenumber intervals with a resolution of 20 cm^{-1}. The average transmittance over a 20-cm^{-1} interval as a result of molecular absorption is calculated by using a band absorption model. The band absorption model is based on recent laboratory measurements complemented by using available theoretical molecular line constants in line-by-line transmittance calculations.

The effects of earth curvature and atmospheric refraction are included in this model. The results of earth curvature become important along paths that are at angles greater than 60° from the zenith, and refractive effects then dominate at zenith angles greater than 80°.

The scattering and absorption effects of atmospheric aerosols (dust, haze, and other suspended materials) are stored in the code in extinction and absorption coefficients as a function of wavelength. These coefficients were produced by a MIE code for defined particle size distributions and complex indices of refraction. Four aerosol models are available, representing rural, urban, maritime, and tropospheric conditions.

A user can choose any one of six standard atmospheric models incorporated in the code or can construct his own atmosphere by using a combination of parameters from the standard models or by introducing radiosonde data.

Some of the outputs of the LOWTRAN code include the total transmittance; the transmittance of H_2O, O_3, and the uniformly mixed gases; and aerosol transmittance at each wavelength value specified. In the SOLTRAN model these transmittance values are multiplied by Thekaekara's corresponding extraterrestrial solar irradiance at each wavelength of interest. A sum (integration) of the results of these individual multiplications is then performed over the spectral interval of interest to produce a value of the broadband terrestrial direct beam irradiance. The current version of SOLTRAN is limited to a spectral region between 0.25 and 3.125 μm because of a limited extraterrestrial solar spectral data file.

2.2 ATWATER AND BALL MODEL

A model for the direct solar insolation was published recently by Atwater and Ball [6]. This is a modification of an earlier model published by Atwater and Brown [7], which also includes a diffuse insolation formalism and the effect of clouds, neither of which are discussed here.

The equation for the direct insolation on a horizontal surface is given by:

$$I = I_0(\cos Z)[T_M - a_w]T_A \quad , \tag{1}$$

where

I_0 = extraterrestrial solar irradiance,

Z = solar zenith angle,

T_M = transmittance for all molecular effects except water vapor absorption,

a_w = absorptance of water vapor,

T_A = transmittance of aerosols.

The mathematical expressions for the transmittance, absorptance, and air mass M, are given by:

$$T_M = 1.041 - 0.15[M(949 \times 10^{-6}\ P + 0.051)]^{0.5} \quad ,* \tag{2}$$

$$a_w = 0.077(U_w M)^{0.3} \quad , \tag{3}$$

*Atwater and Ball recently published an errata sheet in Solar Energy, Vol. 23, p. 275, changing the coefficient, 0.15, in Eq. 2 to 0.16. This change has not been incorporated in the results presented here.

$$T_A = \exp (-\alpha M') , \tag{4}$$

$$M = 35/[(1224 \cos^2 Z) + 1]^{0.5} , \tag{5}$$

$$M' = P \cdot M/1013.$$

where

U_w = amount of water vapor in a vertical path through the atmosphere (cm),

α = total broadband optical depth of the aerosol,

P = surface pressure (mb).

A brief discussion of the form of Eq. 1 is given in Paltridge and Platt [8]. The form of Eq. 2 is a slight variation of an empirical formula derived by Kastrov and discussed by Kondratyev [9]. Equation 3 is the form derived by McDonald [10], and Eq. 5 is a modification of a formula used by Rodgers for ozone and discussed by Paltridge and Platt [8].

Equation 4 is discussed in more detail by Atwater and Brown [7]. They used a MIE theory calculation to determine the value of α, which is not the approach that would be used in a simple, user-oriented model.

Results from using this model are presented in a later section with a comparisons of other models.

2.3 HOYT MODEL

A model for solar global insolation that includes a model for the direct component is described by Hoyt [11]. The following equation is for the direct solar insolation on a horizontal surface:

$$I = I_0(\cos Z)(1 - \sum_{i=1}^{5} a_i) T_{AS}T_R \tag{6}$$

where a_i represents the absorptance values for water vapor (i = 1), carbon dioxide (i = 2), ozone (i = 3), oxygen (i = 4), and aerosols (i = 5). The parameter T_{AS} is the transmittance after aerosol scattering, and T_R is the transmittance after pure air, or Rayleigh, scattering. The following formulas define these parameters:

$$a_1 = 0.110 (U'_w + 6.31 \times 10^{-4})^{0.3} - 0.0121 , \tag{7}$$

$$a_2 = 0.00235 (U'_c + 0.0129)^{0.26} - 7.5 \times 10^{-4} , \tag{8}$$

$$a_3 = 0.045\ (U_o' + 8.34 \times 10^{-4})^{0.38} - 3.1 \times 10^{-3}\ , \tag{9}$$

$$a_4 = 7.5 \times 10^{-3}\ (M')^{0.875}\ , \tag{10}$$

$$a_5 = 0.05[g(\beta)]^{M'}\ , \tag{11}$$

$$T_{AS} = [g(\beta)]^{M'}\ , \tag{12}$$

$$T_R = [f(M')]^{M'}\ , \tag{13}$$

where

U_w' = pressure-corrected* precipitable water in the path (cm),

U_c' = pressure-corrected amount of carbon dioxide in the path [cm at standard temperature and pressure (STP), U_c' = 126 cm for air mass 1.0],

U_o' = the amount of ozone in the path (cm at STP),

M' = pressure-corrected air mass,

$g(\beta)$ = a tabulated function that is related to the angstrom turbidity coefficient β,

$f(M')$ = a tabulated function of pressure-corrected air mass.

See Hoyt [11] for the tabular data.

Because the functions $g(\beta)$ and $f(M')$ are in tabular form rather than in empirical expressions, this model is not as flexible as it could be. The use of the tables often requires interpolation between points, and the range of air masses and turbidity coefficients listed in the tables is sometimes too limited. Results of this model will be presented in a later section.

*Hoyt calculates the pressure-corrected precipitable water by multiplying the total precipitable water from radiosonde data by 0.75 in a recent report. This correction has not been made in the analysis performed here.

2.4 LACIS AND HANSEN MODEL

Lacis and Hansen [12] have described a formalism for total insolation. Since they do not separate the direct and diffuse components of the insolation, their formalism cannot be considered here. However, they derived useful empirical expressions for water vapor and ozone absorption. The water vapor absorptance is expressed by

$$a_w = 2.9\ Y\ [(1 + 141.5\ Y)^{0.635} + 5.925\ Y]^{-1} , \tag{14}$$

where $Y = MU_w$, with U_w being the precipitable water vapor (cm) in a vertical path.

The expression for ozone absorptivity in the Chappuis band is given by

$$a_o^{vis} = 0.02118\ X\ (1 + 0.042\ X + 0.000323\ X^2)^{-1} , \tag{15}$$

and for the ultraviolet band by

$$a_o^{uv} = 1.082\ X\ (1 + 138.6\ X)^{-0.805} + 0.0658\ X\ [1 + (103.6\ X)^3]^{-1} , \tag{16}$$

where $X = U_oM$ with U_o being the amount (cm) of ozone in a vertical path. The total ozone absorptivity is given by the sum

$$a_o = a_o^{vis} + a_o^{uv} . \tag{17}$$

Comparisons of the results of these expressions with other models is shown in a later section.

2.5 MACHTA MODEL

A simple model of global insolation has been constructed by Machta [13] in the form of graphs and a worksheet. This model is an approximate method for calculating solar insolation at a given location without the use of mathematical expressions. A standard value of direct solar insolation is given as 887 W m^{-2}, and a standard value of diffuse insolation is given as 142.5 W m^{-2}. These standard values are then corrected by the use of graphs and the worksheet. The corrections are made for station altitude, zenith angle, precipitable water, turbidity, and earth-sun distance. This method has greatest accuracy for very clear days and small zenith angles.

The graphs for making corrections are based on the very rigorous calculations of Braslau and Dave [14]. A few examples of calculations using this model will be illustrated in a later section.

2.6 ASHRAE MODEL

The American Society of Heating, Refrigeration and Air Conditioning Engineers, ASHRAE, publishes a simple model [15,16] for estimating solar insolation at locations in the Northern Hemisphere. This method represents the solar insolation at the earth's surface, under clear sky conditions, by using

$$I_{DN} = A\ e^{-B \sec Z} \quad , \tag{18}$$

where

A = the "apparent" extraterrestrial solar radiation,

B = the "apparent" optical attenuation coefficient,

Z = the solar zenith angle.

An atmospheric clarity adjustment, CN, called the clearness number, is then used to multiply the direct normal insolation calculated using Eq. 18. This clearness number corrects for variations in transmittance at a particular location. Values of A, B, and CN are published by ASHRAE [15] as well as tables of solar insolation for the Northern Hemisphere [16] resulting from application of these parameter values.

A thorough discussion of the origin of the ASHRAE model is presented by Hulstrom [17], and this information will not be repeated here. It is sufficient to say that Eq. 18, commonly called Beer's Law, is strictly applicable only for monochromatic radiation. If one takes the natural logarithm of Eq. 18, the result is:

$$\ln I_{DN} = \ln A - B \sec Z \quad . \tag{19}$$

A plot of this expression on a $\ln I_{DN}$ versus sec Z axis system results in a straight line, with A the intercept of the logarithmic axis and B the slope of the line. The vertical intercept A occurs for the extrapolation sec Z = 0.0, which corresponds to zero air mass or the extraterrestrial insolation.

In the model comparisons given in a later section the deviations of this model from more accurate results are indicated. Hulstrom [17] points out that the clearness numbers published by ASHRAE correct only for water vapor variations. Moreover, these are only average water vapor conditions, and it is shown here in a later section that variations in aerosol attenuation are normally a much more significant factor.

2.7 WATT MODEL

A model for global insolation has been constructed by Watt [18], based partly on the work of Moon [19]. The expression for the direct normal insolation is

$$I_{DN} = I_0\ T_{wa}\ T_{as}\ T_o\ T_{ws}\ T_L\ T_u \ , \tag{20}$$

where the transmittance functions are T_{wa} for water vapor absorption, T_{as} for dry air scattering, T_o for ozone absorption, T_{ws} for water vapor scattering, T_L for lower level aerosol absorption and scattering, and T_u for upper layer aerosol absorption and scattering. These transmittance functions are defined by

$$T_{wa} = 0.93 - 0.033 \log (U_w M_2) \quad , \tag{21}$$

$$T_{as} = 10^{-0.045 [(P/P_0) M_1]^{0.7}} \quad , \tag{22}$$

$$T_o = 10^{-(0.0071 + 0.01 U_o M_4)} \quad , \tag{23}$$

$$T_{ws} = 10^{-(0.0095 U_w M_2)} \quad , \tag{24}$$

$$T_L = 10^{-\tau_L M_2^{0.7}} \quad , \tag{25}$$

$$T_u = 10^{-\tau_u M_3} \quad , \tag{26}$$

$$\tau_L = 0.6 (\tau_{0.5} - 0.01 U_w - 0.03) \quad , \tag{27}$$

$$\tau_u = -M_3^{-1} \log(I_{obs}/I_0) - \tau_L(M_2/M_3) \quad . \tag{28}$$

The parameter P_0 is the sea level pressure; P is the pressure at the surface being considered; U_o and U_w are the amount of ozone and water vapor in cm in a vertical path; $\tau_{0.5}$ is the atomospheric turbidity at 0.5-μm wavelength; I_{obs} is undefined in Watt's report; and I_0 is the broadband extraterrestrial insolation. The parameters τ_u and τ_L are the upper and lower layer broadband turbidity or optical depth. τ_u can be taken from plots in Watt's report for past years. The M_i are called path length modifiers by Watt, and they serve the same purpose as air mass in the previous models. These path length modifiers are equal for solar zenith angles $\leqslant 70°$ and are equal to the secant of the solar zenith angle (sec Z). For solar zenith angles $\geqslant 70°$, the path length modifier is defined differently for each atmospheric constituent according to the altitudes in the atmosphere between which the constituent is concentrated. A parameter F_{zi} is calculated using the following expression:

$$F_{zi} = \{[(r/h_i)\cos Z]^2 + 2 r/h_i + 1\}^{0.5} - (r/h_i)\cos Z \quad , \tag{29}$$

where r is the earth's radius (6.4×10^6 m) and the h_i are the atmospheric altitudes (heights) between which the constituent is located. If a constituent is concentrated between two altitudes, h_1 and h_2, an F_{z1} and F_{z2} are calculated corresponding to h_1 and h_2, respectively. The values are then used in the following expression to obtain the total path length modifier:

$$M_i = \frac{h_2 F_{z2} - h_1 F_{z1}}{h_2 - h_1} \quad . \tag{30}$$

The values of h used for the various constituents are:

ozone:	$h_1 = 20$ km, $h_2 = 40$ km
dry air:	$h_1 = 0$ km, $h_2 = 30$ km
upper dust:	$h_1 = 15$ km, $h_2 = 25$ km
lower dust and water vapor:	$h_1 = 0$ km, $h_2 = 3$ km .

When the value of h is equal to zero, the corresponding F_z can be set equal to 1.0, and $M_i = F_{z2}$.

2.8 MAJUMDAR MODEL

A model for direct normal insolation has been constructed by Majumdar et al. [20]. This model is for clear sky conditions and minimal aerosol content, so that the effect of variable turbidity is not considered. A total of 161 sets of observations at three locations in India was used to arrive at the following regression equation:

$$I_{DN} = 1331.0\ (0.8644)^{(MP/1000)} (0.8507)^{(U_w M)^{0.25}} \quad , \tag{31}$$

where M is the air mass, P is the surface pressure, and U_w is the amount of water vapor in a vertical path.

Results generated from this model will be presented in a later section.

2.9 BIRD MODELS

As a result of comparing the simple models discussed in this section with the rigorous model (presented in a later section), the authors formulated two additional models. Where possible, these models used formalisms from the models previously presented. The expressions used were tuned to give the best least-squares fit to the SOLT AN data. The first model used the following expression for direct normal insolation:

$$I_{DN} = I_0 \ (0.9662) \ (T_R \ T_o \ T_u - a_w) \ T_A \tag{32}$$

where T_u is the transmittance of the uniformly mixed gases (CO_2 and O_2), and the other parameters are the same as defined earlier. The 0.9662 factor was added because the spectral interval considered with SOLT AN was from 0.3 to 3.0 µm. The total irradiance in the extraterrestrial solar spectrum in this interval is 1307 W/m^2, whereas the Thekaekara solar constant of 1353 W/m^2 is used in most of the other models. The factor of 0.9662 allows one to use I_0 = 1353 W/m^2 with the Bird Models. If a higher value of this solar constant is desired (i.e., 1377 W/m^2), it can be used without changing Eq. 32. The transmittance and absorptance equations are

$$T_R = \exp \left[- 0.0903 \ (M')^{0.84} \ (1.0 + M' - (M')^{1.01})\right] \ , \tag{33}$$

$$T_o = 1.0 - 0.1611 \ X_o \ (1.0 + 139.48 \ X_o)^{-0.3035}$$

$$-0.002715 \ X_o \ (1.0 + 0.044 \ X_o + 0.0003 \ X_o^{\ 2})^{-1} \ , \tag{34}$$

$$T_u = \exp -0.0127 \ (M')^{0.26} \ , \tag{35}$$

$$a_w = 2.4959 \ X_w \ [(1.0 + 79.034 \ X_w)^{0.6828} + 6.385 \ X_w]^{-1} \ , \tag{36}$$

$$T_A = \exp \ [-\tau_A^{\ 0.873} \ (1.0 + \tau_A - \tau_A^{\ 0.7088}) \ M^{0.9108}] \ , \tag{37}$$

$$\tau_A = 0.2758 \ \tau_A(0.38) + 0.35 \ \tau_A(0.5) \ , \tag{38}$$

$$M = [\cos Z + 0.15 \ (93.885 - Z)^{-1.25}]^{-1} \ , \tag{39}$$

where $M' = MP/P_0$, $X_o = U_oM$, $X_w = U_wM$, T_u is the transmittance of the uniformly mixed gases, τ_A is the broadband atmospheric turbidity, and $\tau_A(0.38)$ and $\tau_A(0.5)$ are the atmospheric turbidity values that are measured on a regular basis by NWS at 0.38- and 0.5-µm wavelengths, respectively. If one of the turbidity values is not available, its value can be entered as a zero in Eq. 38. The values of $\tau(0.38)$ and $\tau(0.5)$ are obtained in practice with a turbidity meter that measures the total optical depth at each wavelength. The optical depth due to molecular scattering is then subtracted from the total optical depth to obtain the turbidity (or aerosol optical depth) at each wavelength. Equation 39 is a form derived by Kasten [21]. The forms of Eqs. 34 and 36 are patterned after Lacis and Hansen [12], as shown in Eqs. 15 and 16. Some of the terms in the expression for ozone absorption used by Lacis and Hansen have been dropped in Eq. 34. This expression is still much too complicated when the relative importance of ozone is considered. The second line of Eq. 34 could be dropped without serious effects. The form of Eq. 33 can be simplified by removing the $(1.0 + M' - (M')^{1.01})$ term. This simplification provides very accurate results for $Z \leq 70°$.

The second and simplest model is given by

$$I_{DN} = I_0 \; (0.9662) \; [T_M - a_w] \; T_A \tag{40}$$

$$T_M = 1.041 - 0.15 \; [M(9.368 \times 10^{-4} \; P + 0.051)]^{0.5} \quad . \tag{41}$$

The expressions for a_w and T_A are the same as Eqs. 36 and 37, respectively. Equation 40 was used by Atwater and Ball [6], and Eq. 41 is a slight variation of Kastrov as presented by Kondratyev [9]. The variable P is the surface pressure at the location being considered. This model will be shown to provide results that are nearly as accurate as the more complex model with much less effort.

2.10 ADDITIONAL MODELS AND OTHER CONSIDERATIONS

This study is not a comprehensive comparison of simple direct insolation models. It is a comparison of the more recent models. An excellent comparison of other models is presented by Davies and Hay [22].

For the comparison of different models it is useful to know the origin of the data used to formulate the models. An attempt will be made to trace the origins of the H_2O, O_3, and uniformly mixed gas data used in the models described here. In addition, a discussion of air mass and the various forms of the transport equation for direct insolation will be presented.

2.10.1 Water Vapor

The LOWTRAN model is based on a band absorption model. The parameters in the band absorption model are based on comparisons with transmittance data taken by Burch et al. [23-33] and line-by-line transmittance calculations degraded in resolution to 20 cm^{-1}. The contributors to the line data are too extensive to reference here, but are found in a report by McClatchey et al. [34].

Atwater and Ball used an empirical expression from McDonald [10] based on old data taken by Fowle [35]. Fowle's data did not account for the weak absorption bands near 0.7- and 0.8-μm wavelengths. Because of the poor documentation of Fowle's data, McDonald could not claim an absolute accuracy greater than 30%.

The ASHRAE model is based on work by Threlkeld. Hulstrom explicates "Threlkeld determined the variable amount of water vapor on a monthly basis by a semiempirical technique. He used measurements of the broadband direct beam insolation [at Blue Hull, Mass.; Lincoln, Neb.; and Madison, Wis.] in conjunction with the Moon calculation routine, to derive indirectly the corresponding amount of precipitable water vapor" [17].

Hoyt and also Lacis and Hansen used water vapor from Yamamoto [36]. Lacis and Hansen explain, "Absorption by major water vapor bands has been measured at low spectral resolution by Howard et al. (1956). Yamamoto (1962) weighted these absorptivities with the solar flux and summed them, including estimates for the weak absorption bands near 0.7 and 0.8 μm which were not measured by Howard et al., to obtain the total absorption as a function of water vapor amount" [12]. The reference to Howard et al. is referenced here as [37].

Watt used an expression for water vapor that he derived empirically from data in Chapter 16 of Valley [38]. He then compared this expression with measured data from several locations and adjusted the coefficients to obtain the best agreement.

Machta based his model on calculations performed by Braslau and Dave [14] with a rigorous radiative transfer code. Braslau and Dave based their calculations on the database used by LOWTRAN. However, they used a mathematical formalism different from LOWTRAN for band absorption.

2.10.2 Ozone

The LOWTRAN and Machta models used the same original data sources for all the molecular absorbers. The references given in the previous section for water vapor are the same for ozone.

Atwater and Ball did not consider ozone separately but used a general formula that included all molecular effects except water vapor absorption.

The ASHRAE and Watt models are based on the ozone data used by Moon [19]. Moon, in turn, used data measured by Wulf [39] in the Chappuis band (0.5 to 0.7 μm) and data by Lauchli [40] in the Hartley-Huggins band below 0.35 μm wavelength.

Watt integrated the spectral data given by Moon to obtain broadband ozone absorption. He then modified an expression that agreed with these results to give the best agreement with broadband total transmittance data from other sources.

Hoyt used ozone data from Manabe and Strickler [41] to derive an empirical formula. Manabe and Strickler based their results on experimental data from Vigroux [42] and Inn and Tanaka [43]. Lacis and Hansen apparently based their empirical formula for ozone on the same original data sources that Hoyt used. They point out that the data for wavelengths greater than 0.34 μm were given for 18°C. They used the data at −44°C for shorter wavelengths and reduced the longer wavelength data by 25% to compensate for the difference in temperature. They produced separate expressions appropriate for the ultraviolet and visible absorption data, respectively.

2.10.3 Uniformly Mixed Gases

The uniformly mixed gases are CO_2 and O_2. LOWTRAN and Machta are based on the same original data sources given in the section about water vapor.

The ASHRAE and Watt models are based on Moon's model. Moon did not consider CO_2 and O_3 in insolation but might have included their effect with H_2O absorption.

Atwater and Ball based their model on an empirical formula that included all molecular effects except water vapor absorption according to Kondratyev [9]. This formula was based originally on Fowle's data for the constant gases.

Hoyt used Yamamoto's oxygen absorption data, which in turn were taken from Howard et al. [44]. The carbon dioxide data were taken from Burch et al. [45].

A summary of the data sources used by various modelers is condensed in Table 2-1.

Table 2-1. SOURCES OF DATA FOR CONSTRUCTION OF MODELS

Model	H_2O	O_3	$CO_2 + O_2$
SOLTRAN	Burch et al. (many) Line-by-line data	Burch et al. (many) Line-by-line data	Burch et al. (many) Line-by-line data
Atwater and Ball	Fowle (McDonald)	Kastrov	Fowle (Kastrov)
Hoyt	Howard et al. (1955) (Yamamoto)	Vigroux Inn and Tanaka (Manabe & Strickler)	Burch et al. (1960) Howard et al. (1955)
Watt	Valley & Modifications	Wulf Lauchli (Moon)	Moon
Lacis and Hansen	Howard et al. (1955) (Yamamoto)	Vigroux Inn and Tanaka (Howard et al. 1961 Handbook)	
ASHRAE	Threlkeld (Best fit 3 locations)	Wulf Lauchli (Moon)	Moon
Machta	Burch et al. (many) Line-by-line data (Dave)	Burch et al. (many) Line-by-line data (Dave)	Burch et al. (many) Line-by-line data (Dave)

2.10.4 Air Mass

The air mass is a coefficient that accounts for the increased path length through which light rays must pass in the atmosphere when the sun is not directly overhead. When the sun is directly overhead, the air mass is 1.0. The formal definition of air mass is given by Kondratyev [9] as

$$M = \int_0^\infty \rho ds / \int_0^\infty \rho dz \quad , \tag{42}$$

where dz is an increment in the vertical direction; ds is an increment along a slanted path; and ρ the density of air, or whatever component of the air that is being considered. This definition implies that differences in altitude between different surface locations must be accounted for by some means other than air mass. In calculating atmospheric attenuation over a slant path, for example, the optical depth for a vertical path is multiplied by the air mass to obtain the total optical depth. The vertical optical depth includes the effect of the altitude at which one is working. Some authors include the beginning altitude in the air mass and use the optical depth from sea level, or 1013 mb pressure. This is called the absolute, or pressure-corrected, air mass, given by

$$M' = \frac{P}{P_0} M \quad , \tag{43}$$

where P_0 = 1013 mb.

Kondratyev [9] summarizes the methods of calculation for different ranges of zenith angle. For zenith angles < 60°, sufficient accuracy can be obtained using

$$M = \sec Z \quad , \tag{44}$$

where Z is the zenith angle. For $60° \leq Z \leq 80°$, the effect of earth curvature becomes important. Geometric considerations give

$$M = \{(r/H)^2 \cos^2 Z + 2(r/H) + 1\}^{1/2} - (r/H) \cos Z \quad , \tag{45}$$

where r is the earth's radius and H the scale height defined by

$$H = \int_0^\infty \frac{\rho}{\rho_0} dz \quad . \tag{46}$$

The constant ρ_0 is the surface level density. For air or the uniformly mixed gases, $H = P_0/(\rho_0 g)$, where g is the acceleration due to gravity and P_0 is the surface level pressure.

For $Z > 80°$, the effects of refractive index become important. The correct value of air mass in this region can be found in tables (Kondratyev, for example) or can be calculated with approximate expressions. An expression that this author has found to be correct to within 1% for $Z < 89°$ is defined by Kasten [21] to be

$$M = \{\cos Z + 0.15\ (93.885 - Z)^{-1.253}\}^{-1} \quad . \tag{47}$$

This expression was used in the results given in this report (unless otherwise noted), and is called the relative air mass by Kasten.

2.10.5 Simple Transport Equation

Several forms of the transport equation have been used in the models described here. Some possible forms of the equation are:

$$I_1 = I_0\ T_R\ T_o\ T_u\ T_w\ T_A \quad , \tag{48}$$

$$I_2 = I_0\ [T_R\ T_o\ T_u - a_w]\ T_A \quad , \tag{49}$$

$$I_3 = I_0\ [T_R\ T_o - a_w - a_u]\ T_A \quad , \tag{50}$$

$$I_4 = I_0\ [T_M - a_w]\ T_A \quad , \tag{51}$$

where T_R is the transmittance due to Rayleigh scattering, T_o is the transmittance of ozone, T_u is the transmittance of the uniformly mixed gases CO_2 and O_2, T_w and a_w are the transmittance and absorptance of water vapor, T_A is the transmittance of the aerosol, and T_M is the transmittance of all molecular effects except water vapor absorption.

Tables 2-2 and 2-3 were constructed using all forms of the transport equation (Eqs. 48-51) with Bird Models and the results from SOLTRAN. Two standard atmospheres that are built into SOLTRAN were used: the midlatitude summer (MLS) and the subarctic winter (SAW) models with sea level visibilities of 23 and 5 km.

Based on the results in Tables 2-2 and 2-3, it appears that Eq. 48 provides the closest agreement with SOLTRAN. The very simple form of Eq. 50 provides results that are comparable to Eq. 48. A theoretical basis for selecting any one of these forms of the transport equation as the best has not been established by the authors. However, one assumption implicit in Eq. 48 is that the attenuation by each constituent is independent of every other constituent. In other words, the transmittance measured in pure materials can be combined in the form of Eq. 48 to produce the transmittance through a mixture of

Table 2-2. COMPARISONS OF DIRECT NORMAL IRRADIANCE FOR DIFFERENT FORMS OF THE TRANSPORT EQUATION USING BIRD MODELS AND SOLTRAN

Zenith Angle (deg)	Model Atmosphere	I_1 (W/m^2)	I_2 (W/m^2)	I_3 (W/m^2)	I_4 (W/m^2)	SOLTRAN (W/m^2)
0.0	MLS	827.1	812.5	811.2	816.6	833.5
20.0	V = 23 km	811.0	795.7	794.2	800.1	- -
30.0		789.0	772.8	771.3	777.8	- -
40.0		754.5	736.9	735.2	742.8	756.6
50.0		702.1	682.3	680.4	690.0	- -
60.0		621.3	598.5	596.2	609.1	617.7
70.0		490.2	463.3	460.6	478.4	- -
75.0		392.3	363.5	360.5	380.5	386.3
80.0		261.7	233.0	229.9	248.7	258.9
85.0		101.5	81.8	79.5	84.3	102.8
0.0	MLS	545.8	536.2	535.3	538.9	530.6
20.0	V = 5 km	522.4	512.6	511.7	515.4	- -
30.0		491.4	481.3	480.3	484.4	- -
40.0		444.4	434.0	433.0	437.5	- -
50.0		377.4	366.8	365.8	370.9	- -
60.0		285.1	274.6	273.5	279.5	270.3
70.0		163.8	154.8	153.8	159.8	- -
75.0		96.2	89.2	88.4	93.4	97.2
80.0		35.8	31.9	31.4	34.0	42.4
85.0		3.1	2.5	2.4	2.6	7.0

Table 2-3. COMPARISONS OF DIRECT NORMAL IRRADIANCE FOR DIFFERENT FORMS OF THE TRANSPORT EQUATION USING BIRD MODELS AND SOLTRAN

Zenith Angle (deg)	Model Atmosphere	I_1 (W/m^2)	I_2 (W/m^2)	I_3 (W/m^2)	I_4 (W/m^2)	SOLTRAN (W/m^2)
0.0	SAW	866.0	856.5	855.1	865.5	881.9
20.0	V = 23 km	849.4	839.5	838.0	848.9	- -
30.0		826.8	816.3	814.7	826.4	- -
40.0		791.2	779.7	778.0	791.1	804.3
50.0		737.2	724.0	722.0	737.5	- -
60.0		653.0	637.9	635.6	654.7	662.5
70.0		515.9	498.0	495.1	519.6	- -
75.0		413.0	393.7	390.5	417.2	423.3
80.0		275.3	255.9	252.6	277.3	289.0
85.0		106.2	92.6	90.2	98.8	120.0
0.0	SAW	571.5	565.2	564.3	571.2	568.5
20.0	V = 5 km	547.2	540.8	539.8	546.9	- -
30.0		514.9	508.3	507.4	514.7	- -
40.0		466.0	459.2	458.2	465.9	461.1
50.0		396.2	389.2	388.1	396.4	- -
60.0		299.6	292.7	291.6	300.4	297.8
70.0		172.3	166.3	165.4	173.6	- -
75.0		101.3	96.6	95.8	102.3	112.0
80.0		37.6	35.0	34.5	37.9	50.5
85.0		3.3	2.8	2.8	3.0	9.0

materials. One obvious situation that violates this assumption is when near-complete absorption in a single constituent occurs within the spectral band being considered. If one of the other constituents absorbs in the same spectral location, over attenuation will occur in the final results. The form of Eqs. 49 and 50 make this situation even worse.

SECTION 3.0

MODEL COMPARISONS

Where possible, each of the models was programmed on a computer to produce data for comparison. Parts of the Hoyt model were generated with a programmable hand calculator, and data from the Machta model were generated by using the worksheet format presented with the model.

General transmittance data for the midlatitude summer (MLS) and the subarctic winter (SAW) atmospheric models have been generated with the SOLTRAN code. These atmospheric models are two of the standard atmospheres defined in SOLTRAN. They were chosen primarily because the amounts of ozone and water vapor defined in them represent extremes that could be encountered in the United States. The Rayleigh scattering due to molecules and the absorption of the uniformly mixed gases (CO_2 and O_2) are relatively constant in these models. The aerosol conditions can be defined independently of the atmospheric model. As was mentioned previously, the results from the SOLTRAN code are for a spectral interval between 0.3 to 3.0 µm. If the calculations would have been made from 0.25 to 10.0 µm, the results from SOLTRAN for individual atmospheric constituents could change. However, the total transmittance of all constituents should not change appreciably (< 1%).

The amounts of ozone and water vapor in the SAW model are 0.45 cm of ozone and 0.42 cm of water vapor. The amounts in the MLS model are 0.31 cm of ozone and 2.93 cm of water vapor. Figure 3-1 presents a plot of the broadband (0.3 to 3.0 µm) transmittance versus sec Z for all of the atmospheric components in the MLS model. Figure 3-2 presents the same type of results for the SAW model atmosphere. Both figures contain the results for a 23-km visibility aerosol at sea level. The aerosol used in this paper is the one defined in the LOWTRAN 3 version, and is representative of a continental or rural aerosol.

Figures 3-1 and 3-2 show the relative importance of each atmospheric component as an attenuater of broadband radiation (0.3-3.0 µm). CO_2 and O_2 are the least important elements, and they are omitted from some models. The next element exhibiting increased attenuation is O_3, followed by H_2O. The flattening of the curve for H_2O in Fig. 3-1 with increasing zenith angle suggests that the H_2O absorption bands are approaching saturation. Molecular scattering (Rayleigh scattering) dominates total molecular absorption at large zenith angles and has a greater effect than most individual molecular species at all zenith angles. The one exception to this statement appears to be H_2O absorption for high concentrations of H_2O and for air masses < 2. The most significant attenuator at nearly all zenith angles is the aerosol.

An aerosol that produces a 23-km meteorological range at sea level is considered to produce a relatively clear atmosphere. At higher surface altitudes and remote locations, it is not uncommon during winter months to observe meteorological ranges greater than 60 km, which are extremely clear conditions. The data presented in Figs. 3-1 and 3-2 suggest that aerosol attenuation could be the most important attenuator at most locations throughout the United States. Unfortunately, it is also the component that is the most

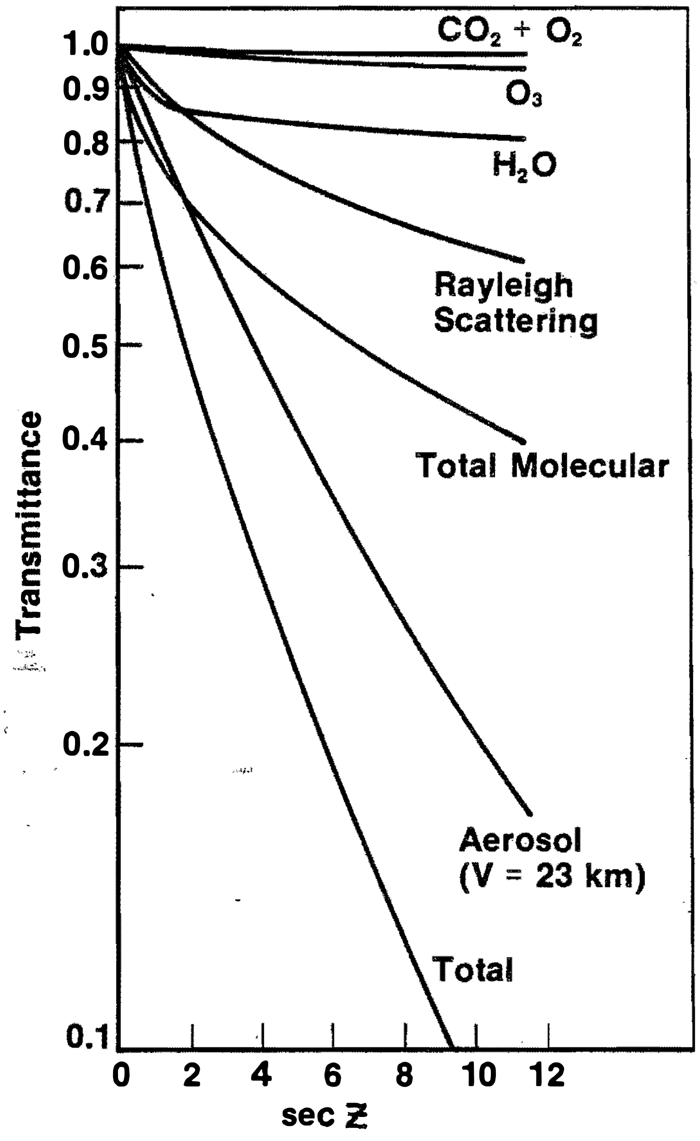

Figure 3-1. Transmittance versus Secant of Solar Zenith Angle for Midlatitude Summer Model

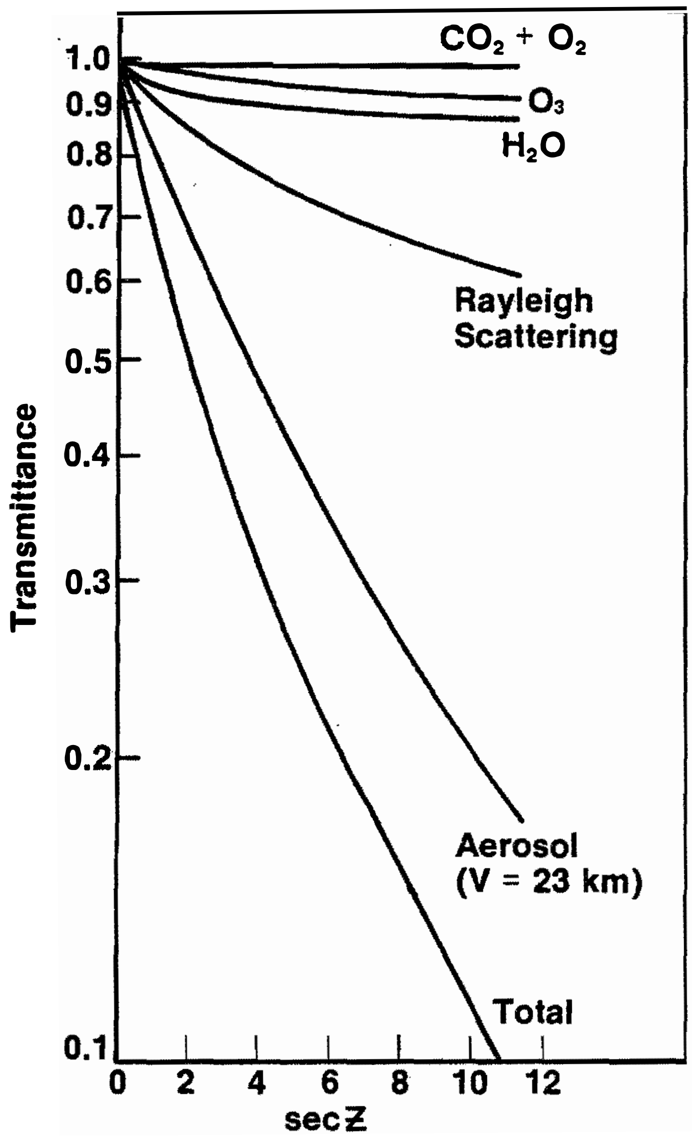

Figure 3-2. Transmittance versus Secant of Solar Zenith Angle for Subarctic Winter Model

difficult to measure and hence the least defined. It should be emphasized that these conclusions are for broadband (thermal) direct insolation, and that the situation will change significantly as the bandwidth is further restricted or global insolation is considered.

The previous section noted that the ASHRAE model assumes a plot of the total transmittance shown in Figs. 3-1 and 3-2 will scribe a straight line. The slope of this line provides the optical depth. An examination of Figs. 3-1 and 3-2 demonstrates that this assumption is reasonable over a limited range of zenith angles. If the plot were of irradiance versus sec Z, the vertical intercept at sec Z = 0 would provide the extraterrestrial irradiance, which is usually too low.

Figures 3-3 and 3-4 present O_3 absorption data for five of the models described earlier. Figure 3-3 is for 0.31 cm of O_3 (MLS), and Fig. 3-4 is for 0.45 cm of O_3 (SAW). The models produce significantly different results when compared in this manner. However, the differences are minor when the effectiveness of O_3 is accounted for. The triangular data points are a result of performing a least squares fit to the SOLT AN data with the equations of Lacis and Hansen (Bird model). The minor deviations of the triangles from the SOLT AN data are a result of attempting to fit a simple expression to various amounts of O_3.

Figures 3-5 and 3-6 present model comparisons of H_2O absorption for the two standard atmospheres being considered. Since H_2O absorption plays a significant role in transmission calculations, the differences between the models should be noticeable in the total transmission.

Figures 3-7 and 3-8 present plots of transmittance versus solar zenith angle for all molecular effects except H_2O absorption for the SAW and MLS atmospheric models, respectively. Some of the models did not readily lend themselves to this particular calculation and are not included. The surprise about these data is the accuracy of the simple expression in the Atwater model.

Figures 3-9 and 3-10 illustrate a comparison of aerosol transmittance for the MLS and SAW atmospheric models with sea level visibilities of 5 and 23 km, respectively. In most cases, aerosol attenuation is independent of the atmospheric model; but the Watt model for aerosols is dependent on the amount of H_2O.

Hoyt's model provides strong agreement with SOLT AN, but its tabular form is not as easily used as empirical formulas. The table covers an insufficient range of turbidity coefficients to include a 5-km visibility aerosol. Hoyt's data are for aerosol scattering only, and there is an additional factor for aerosol absorption in the Hoyt model.

The value of the upper layer turbidity T_u used in Watt's model was taken from historical plots that he produced. The value used, $T_u = 0.02$, was an approximate average of the historical data. The rest of the parameter values for this model were taken directly from SOLT AN.

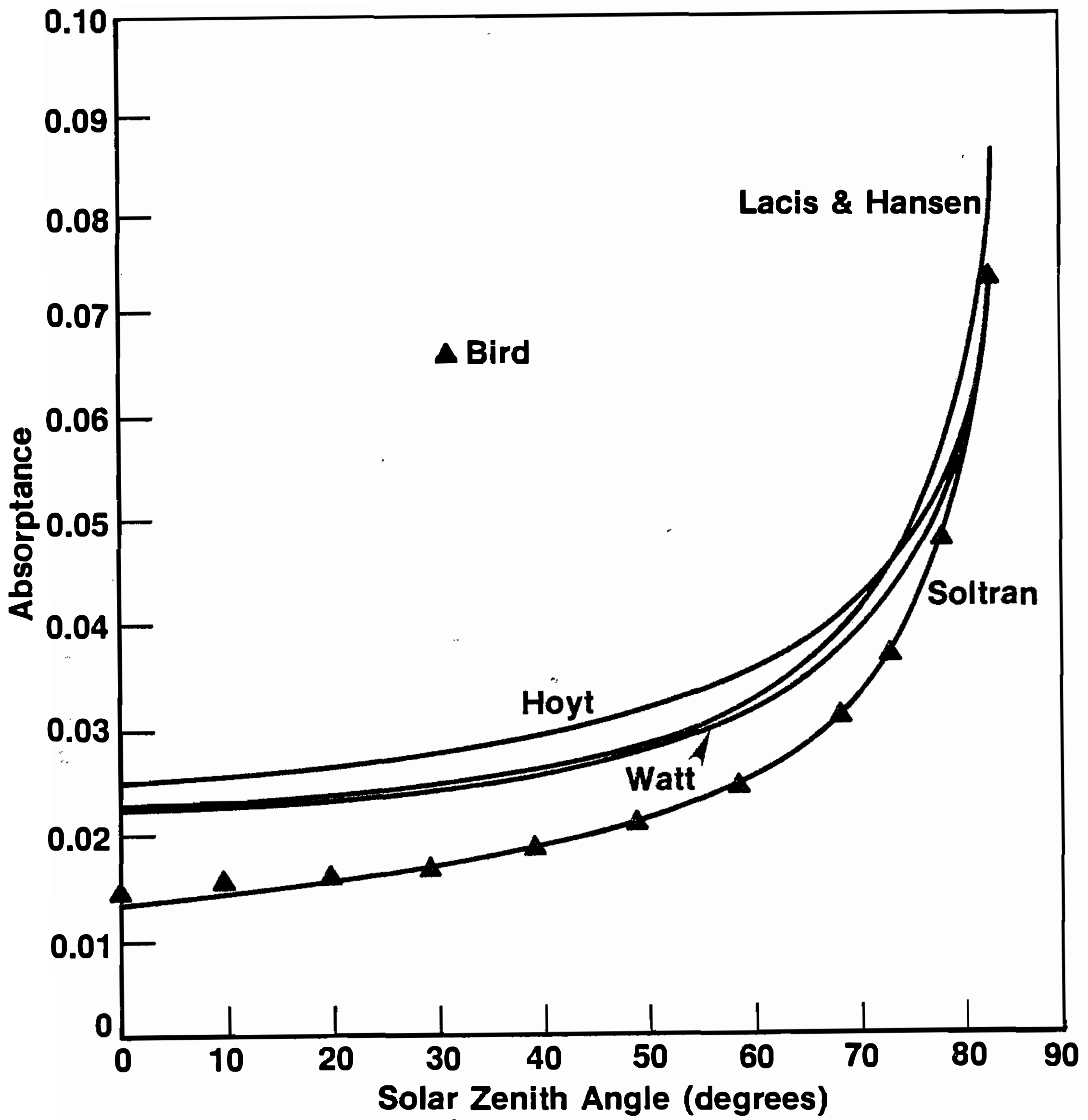

Figure 3-3. Ozone Absorptance versus Solar Zenith Angle for 0.31 cm of Ozone (MLS)

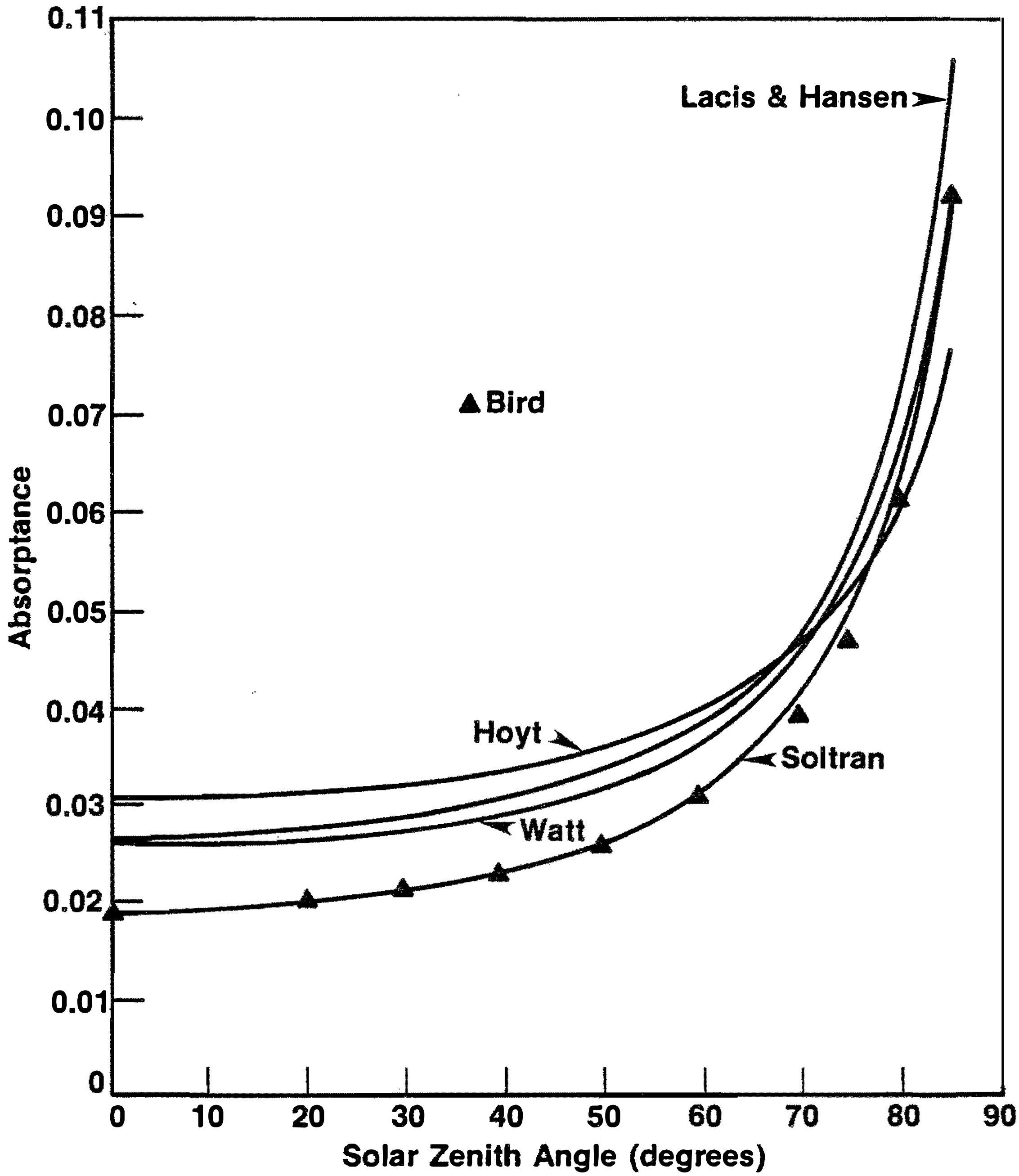

Figure 3-4. Ozone Absorptance versus Solar Zenith Angle for 0.45 cm of Ozone (SAW)

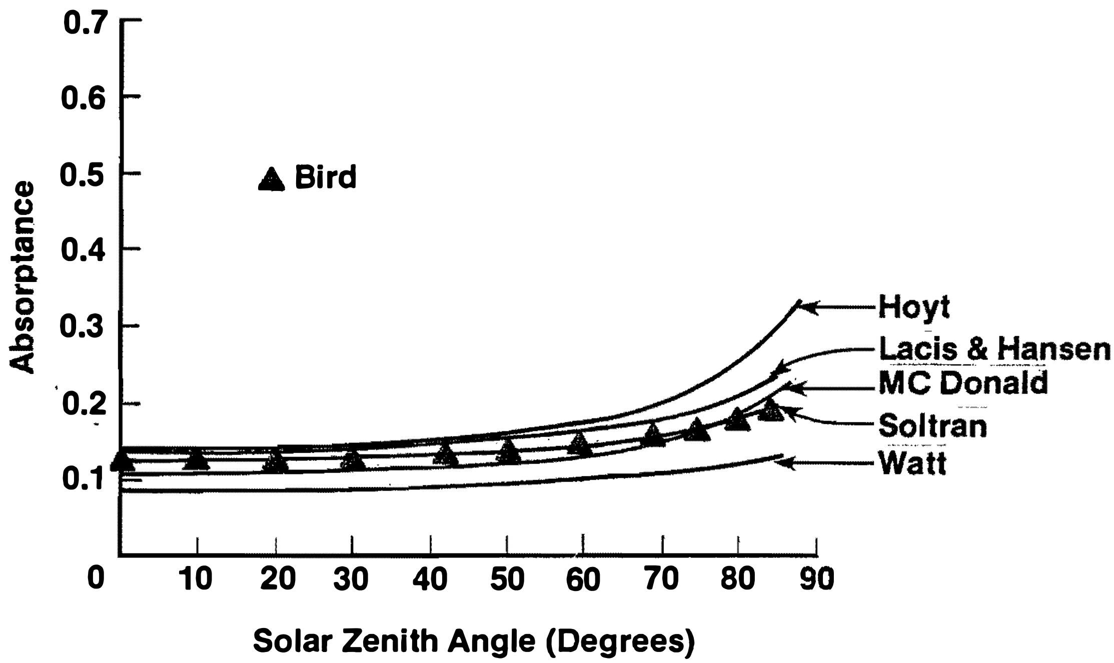

Figure 3-5. Absorptance versus Solar Zenith Angle for 2.93 cm of Water Vapor (MLS)

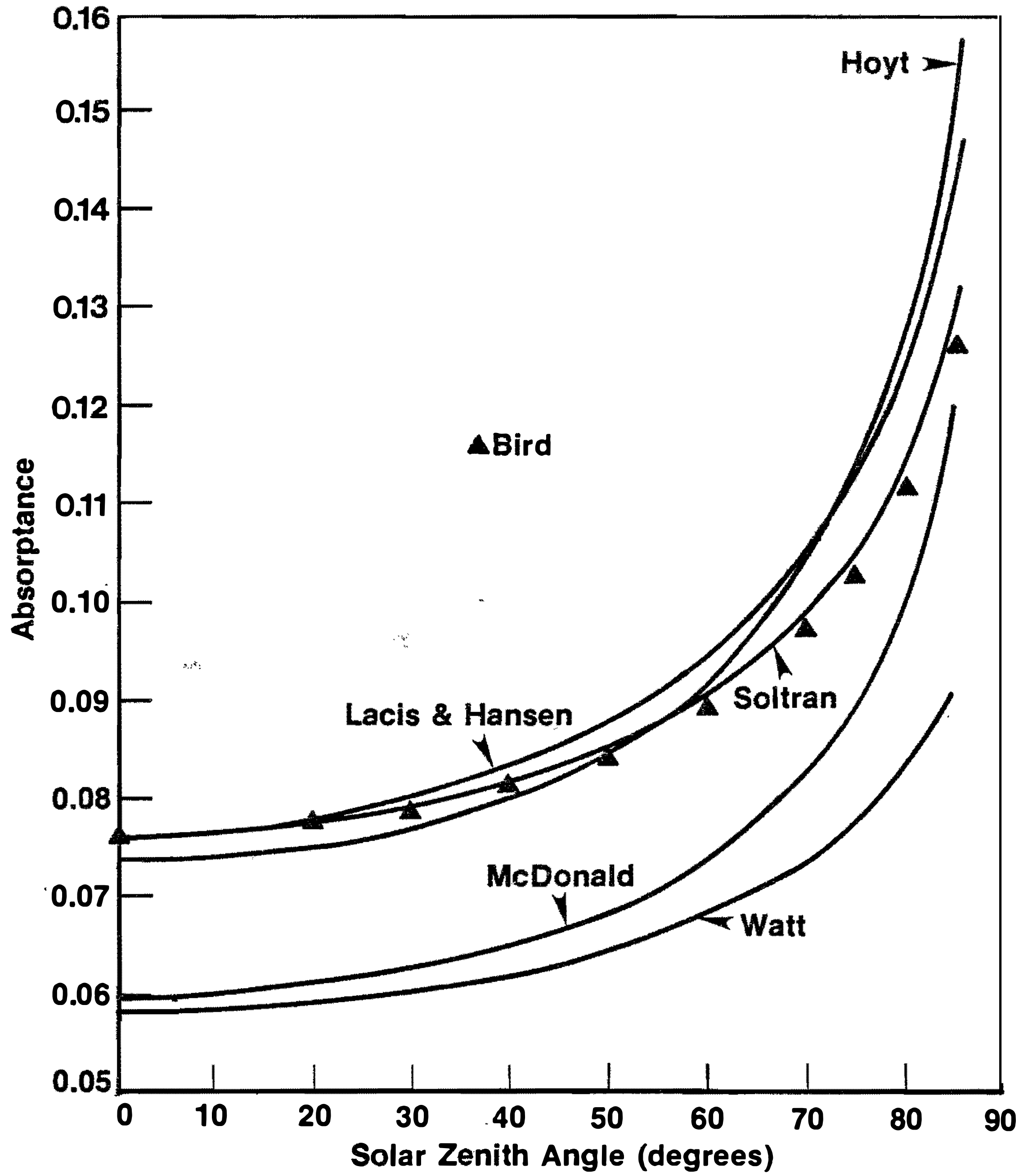

Figure 3-6. Absorptance versus Solar Zenith Angle for 0.42 cm of Water Vapor (SAW)

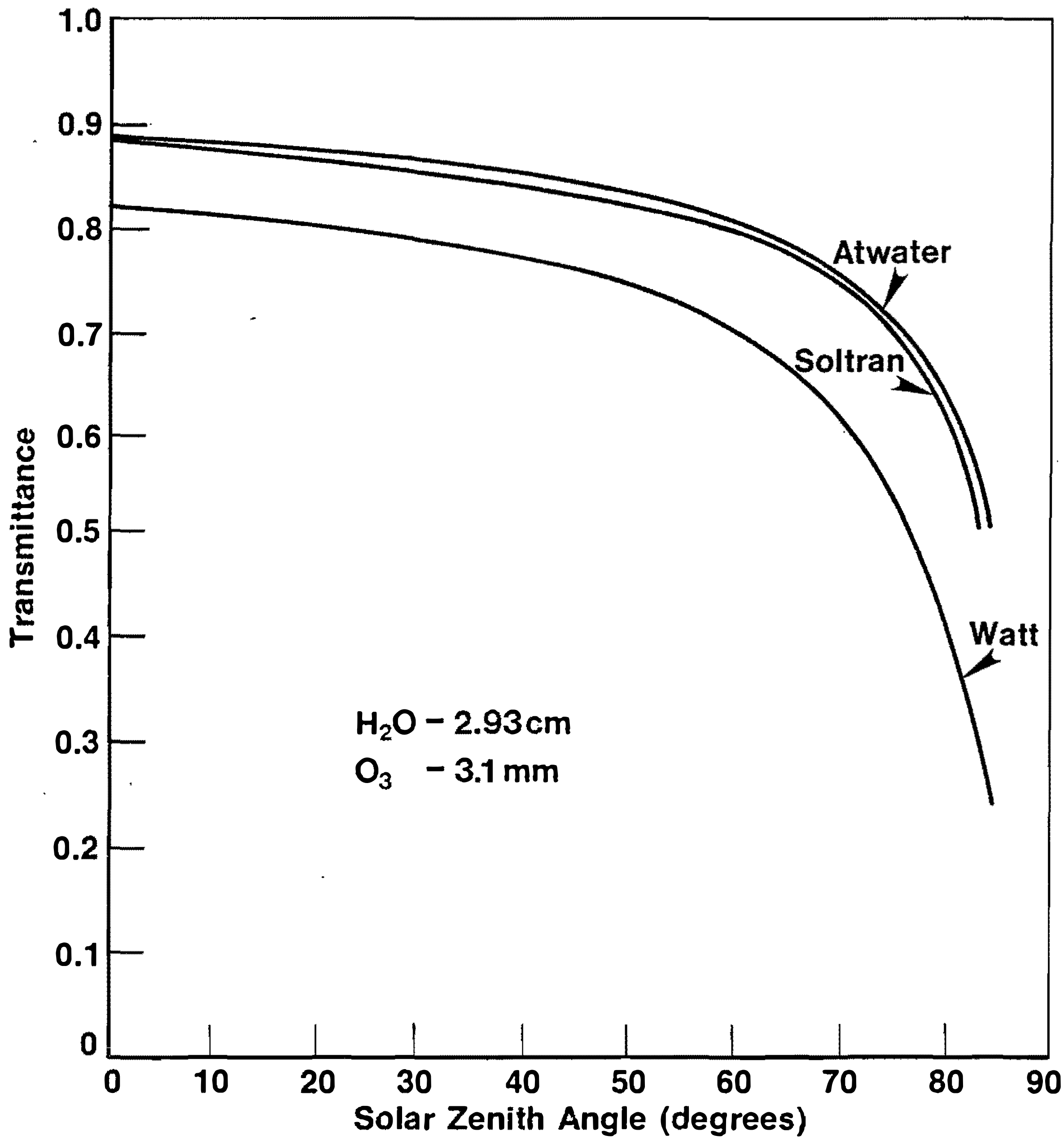

Figure 3-7. Transmittance versus Solar Zenith Angle for All Molecular Effects Except for H_2O Absorption (MLS)

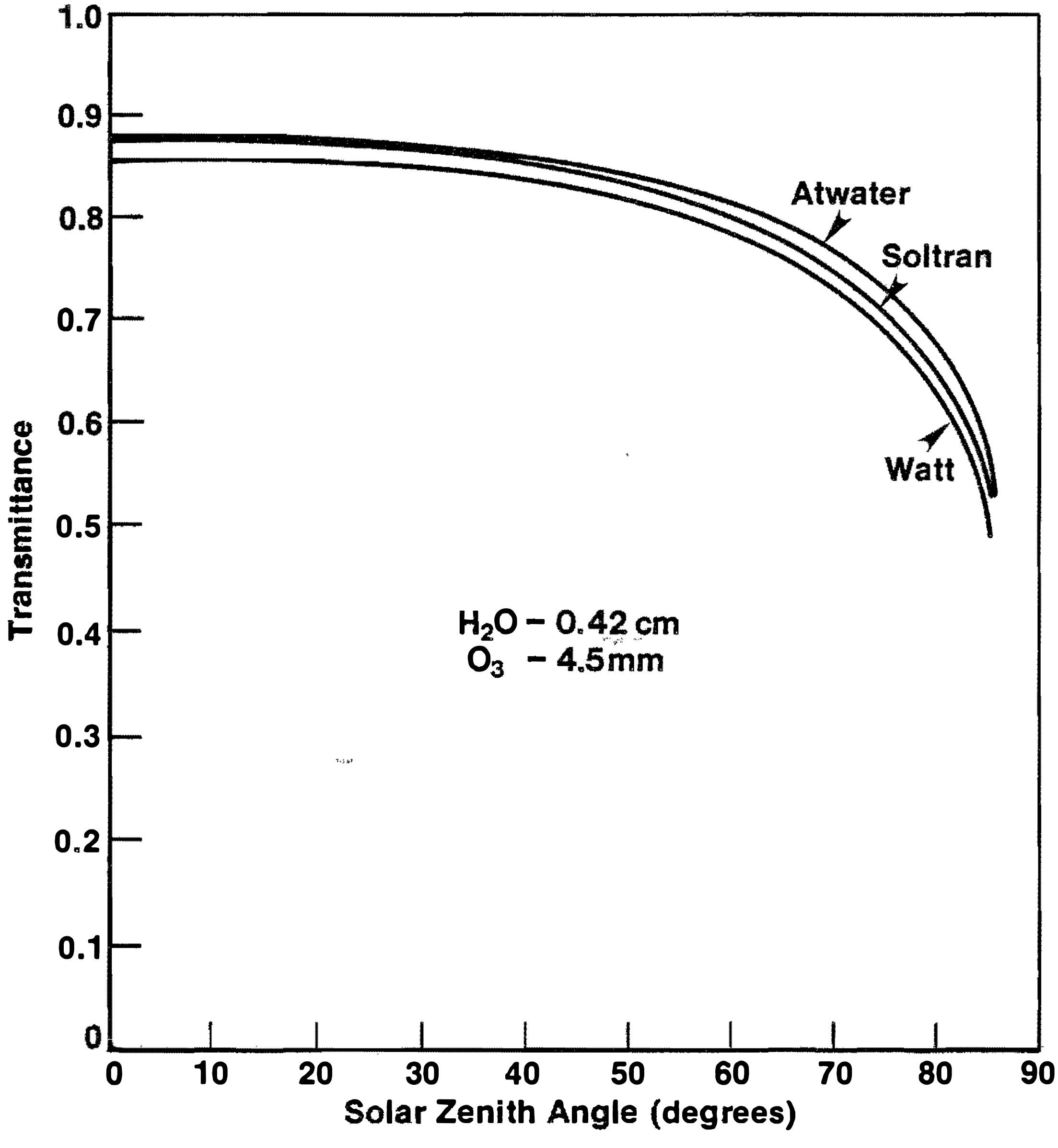

Figure 3-8. Transmittance versus Zenith Angle for All Molecular Effects Except H_2O Absorption (SAW)

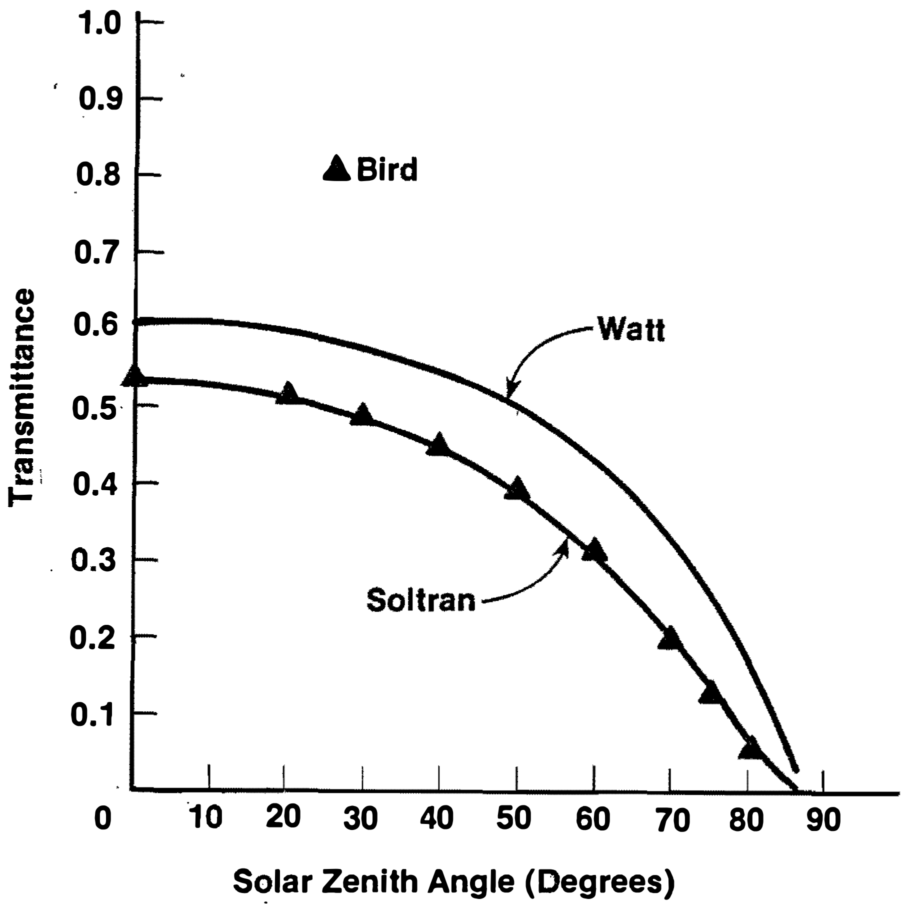

Figure 3-9. Aerosol Transmittance versus Solar Zenith Angle for 5-km Visibility Aerosol

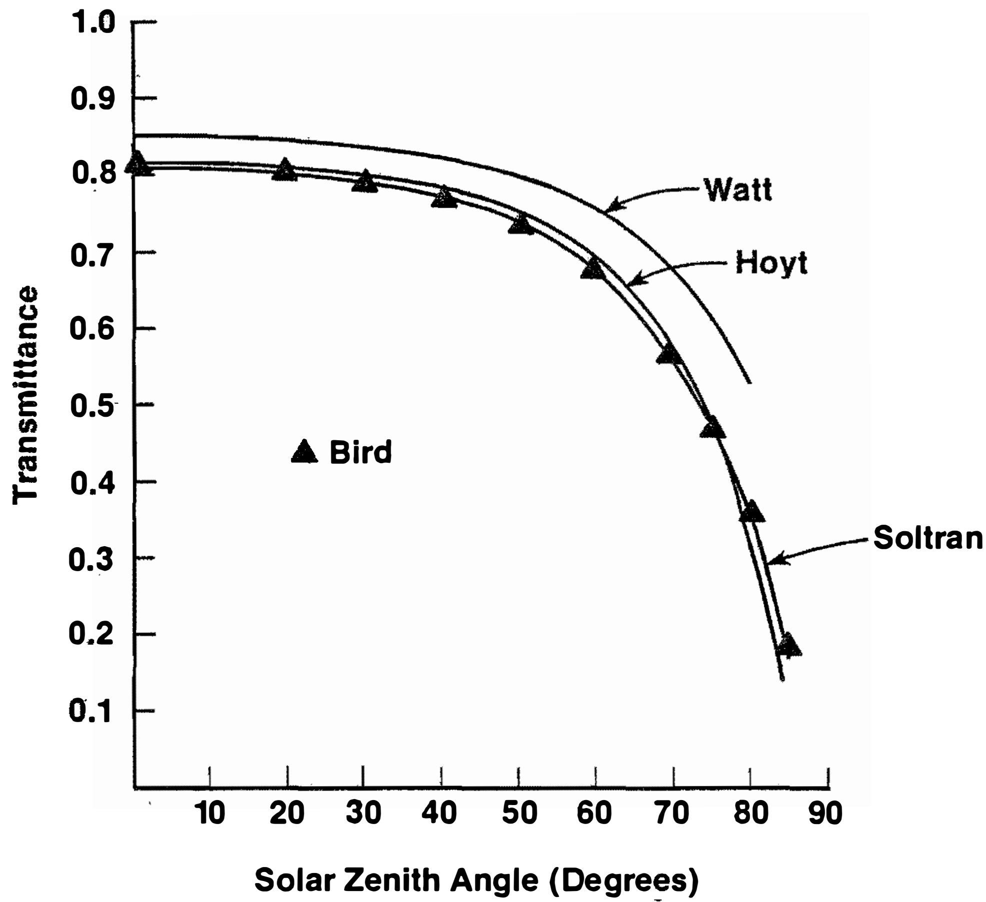

Figure 3-10. Aerosol Transmittance versus Solar Zenith Angle for 23-km Visibility Aerosol

Figures 3-11 through 3-13 illustrate the total terrestrial solar irradiance as a function of solar zenith angle for several models under different atmospheric conditions. The differences between some of the models are significant. However, the differences illustrated here are dominated by the aerosol attenuation, and the differences due to molecular effects are not obvious. If a much clearer atmosphere were modeled or a more restricted bandwidth were used, the difference in molecular effects would be more evident.

In the results given for the Atwater model, the broadband optical depth for the aerosol was taken from the Bird model. This causes close agreement with the SOLTRAN results, but Figs. 3-7 and 3-8 show that the bulk of the molecular attenuation in this model agrees very well with SOLTRAN. Atwater's H_2O absorption deviates somewhat from SOLTRAN results.

The results for Bird shown in Figs. 3-11, 3-12, and 3-13 used Eq. 49 as the transport equation.

Because of the difficulty of considering aerosol attenuation and Rayleigh scattering with Hoyt's model, it is included only in Fig. 3-12 and gives values that are lower than the SOLTRAN results over the applicable region.

Machta's model agrees with SOLTRAN within ±5% to 60° zenith angle. It is primarily limited to clear air conditions and zenith angles less than 60°. The values shown at 70° zenith angle are beginning to deviate somewhat.

The Majumdar model results have been given for the MLS atmospheric model with V = 23 km (see Fig. 3-11). The Majumdar model is for low turbidity conditions and has no provision for varying the turbidity. It is evident from Fig. 3-11 that the turbidity resulting from a sea level visibility of 23 km is too large for this model. The model is very simple, and it could be quite accurate if provisions were made to vary the aerosol attenuation.

Appendix A presents tabular data for each attenuation element for most of the models. Direct normal irradiance for the Bird model is given in Tables 2-2 and 2-3 for the same atmospheric conditions modeled in Appendix A.

This comparison and evaluation of existing simplified models for calculating the direct solar beam energy considered six models - Hoyt, Watt, Lacis and Hansen, Atwater and Ball, Machta, and Majumdar. Ideally, such models should be compared according to the attenuation of each atmospheric constituent. By doing this, differences in calculating the total broadband direct solar energy can be specifically associated with differences in how they calculate attenuation arising from each constituent. However, this was impossible because of the variety of techniques used by the models. For example, some models considered all molecular attenuation processes in a single expression, making it impossible to distinguish attenuation from specific molecular constituents. The specific comparisons performed considered the following:

- absorptance due to O_3 (Lacis and Hansen; Hoyt; Watt),
- absorptance due to water vapor (Lacis and Hansen; Hoyt; Watt; McDonald),

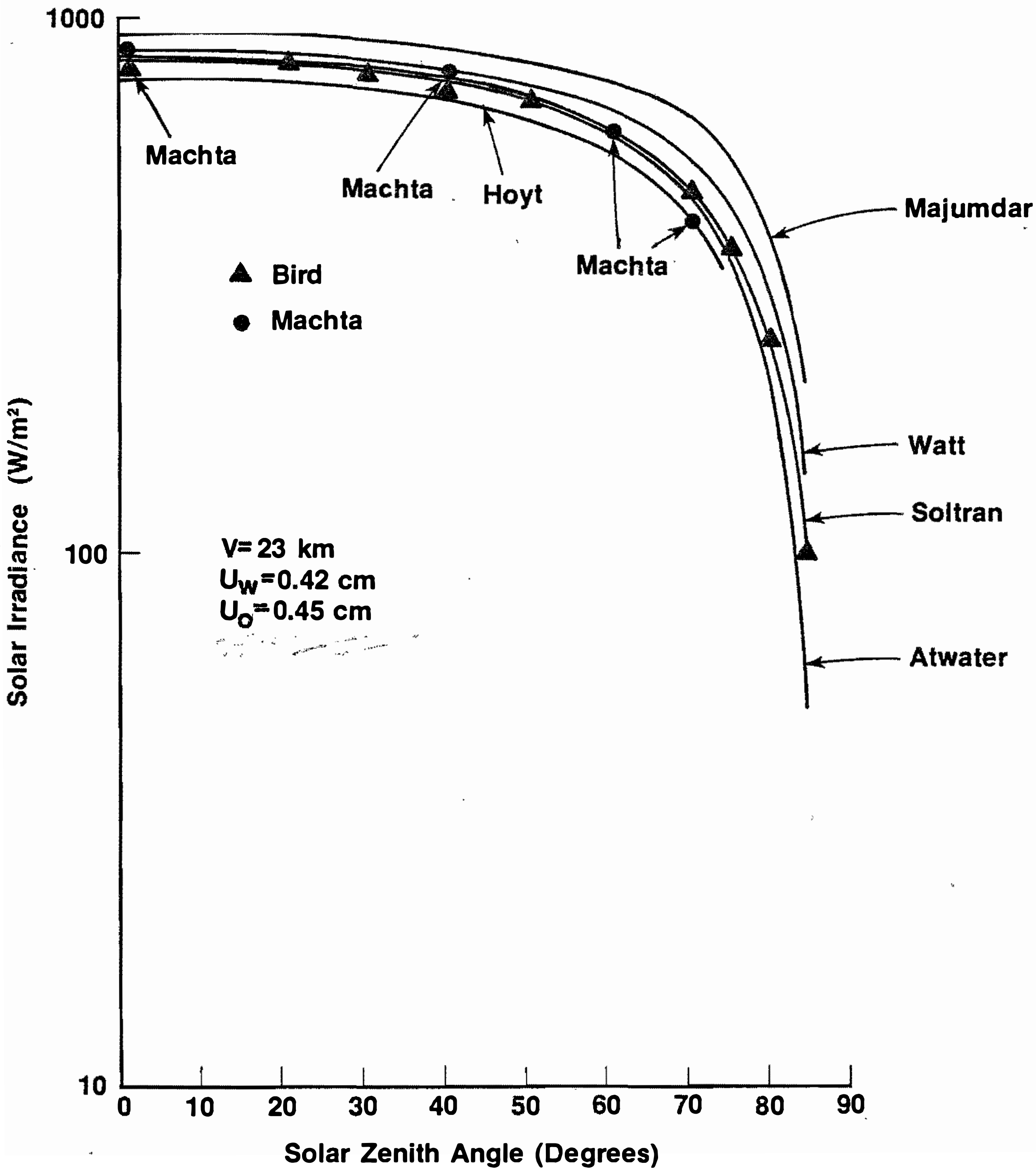

Figure 3-11. Solar Irradiance versus Solar Zenith Angle, Visibility = 23 km (MLS)

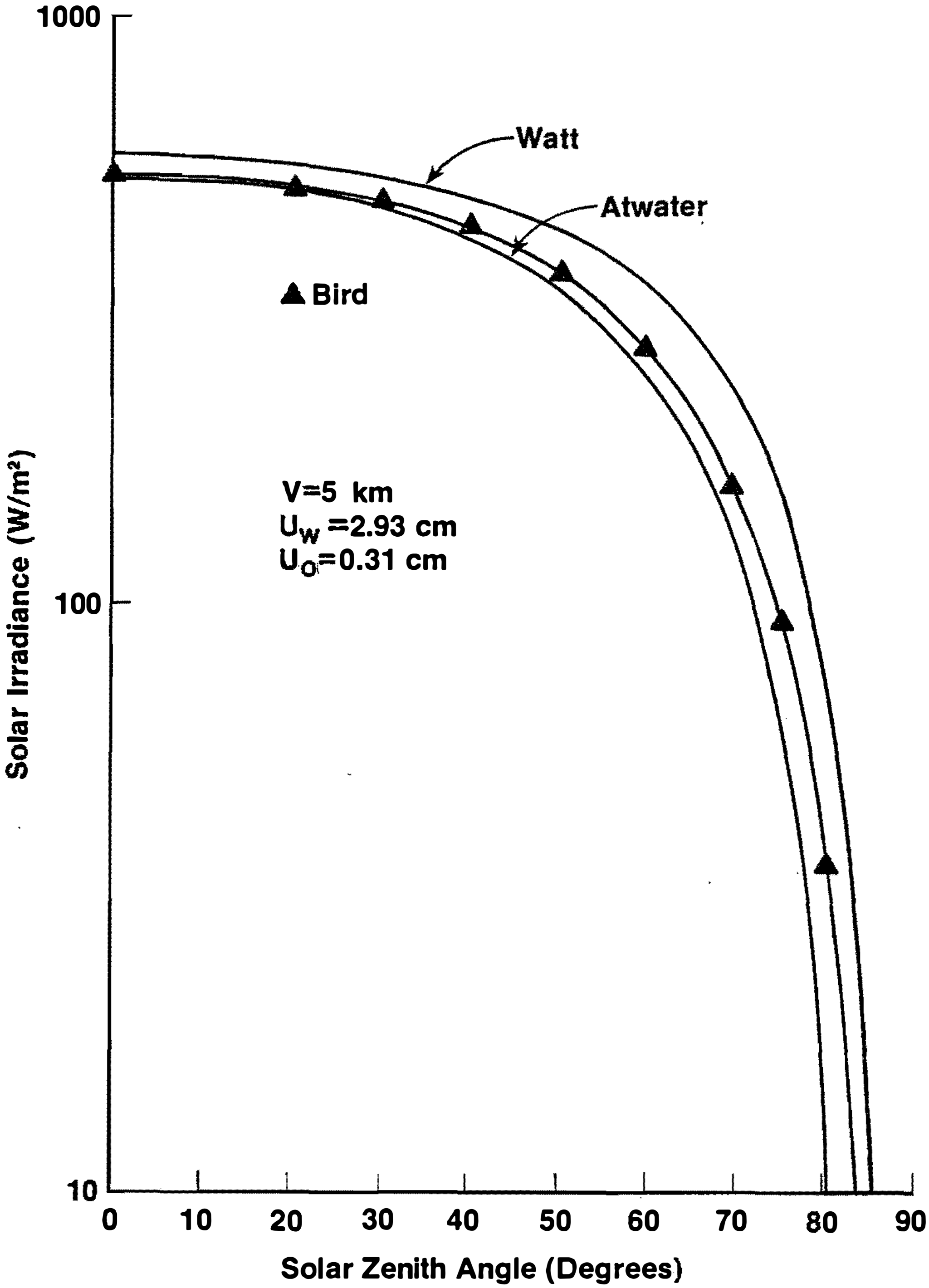

Figure 3-12. Solar Irradiance versus Solar Zenith Angle, Visibility = 5 km (MLS)

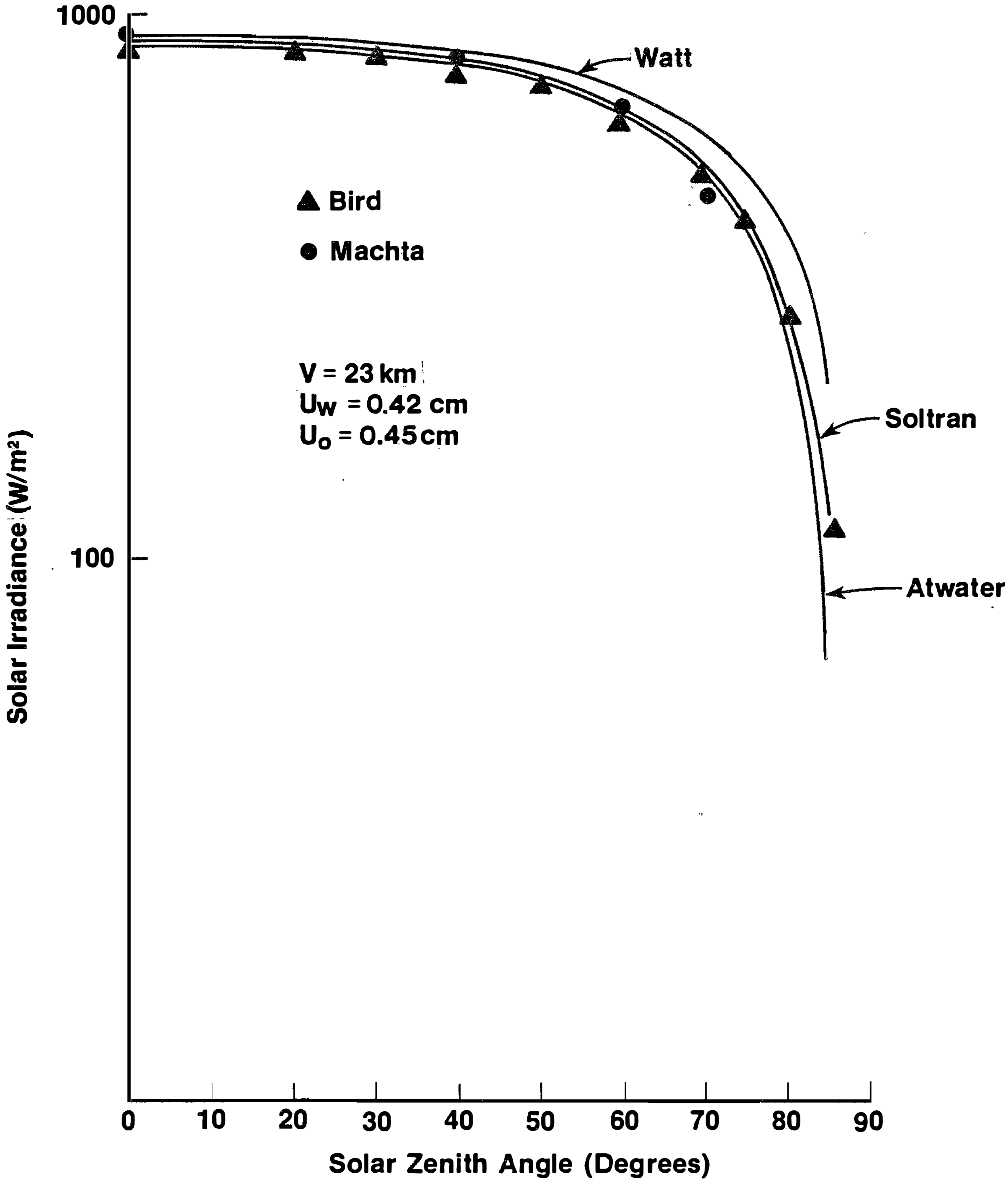

Figure 3-13. Solar Irradiance versus Solar Zenith Angle, Visibility = 23 km (SAW)

- the atmospheric transmittance due to all molecular processes except water vapor absorption (Atwater; Watt),
- the atmospheric transmittance due to aerosols (Hoyt; Watt),
- the direct solar beam irradiance versus solar zenith angle (Machta; Hoyt; Majumdar; Watt; Atwater).

In general, two sets of atmospheric conditions were considered: midlatitude summer (MLS) and subarctic winter (SAW). The MLS conditions are characterized by a precipitation water vapor of 2.93 cm (high) and an ozone amount of 0.31 cm (low). The SAW conditions are distinguished by a water vapor of only 0.42 cm (low), and an ozone amount of 0.45 cm (high). Within these conditions, two sets of atmospheric aerosol conditions were studied: clear (visual range = 23 km at sea level) and turbid (visual range = 5 km at sea level). By using these models and conditions, a reasonable range of atmospheric states was considered.

SECTION 4.0

SUMMARY AND CONCLUSIONS

The recently developed, rigorous, spectral solar radiation transport model (SOLTRAN) was modified to have the capability of calculating the broadband (thermal solar energy) direct solar beam irradiance. Such energy is utilized by solar thermal concentrator devices. The modifications to SOLTRAN allow the prediction of the broadband solar irradiance for various atmospheric conditions and for various slant paths (relative air mass) through the atmosphere. The atmospheric constituents considered are carbon dioxide (CO_2), oxygen (O_2), ozone (O_3), water vapor (H_2O), aerosols, and the molecular scattering (Rayleigh). This modified version of SOLTRAN can be utilized to generate the intensity of the direct solar beam versus time of day for various locations and atmospheric conditions. Such information is crucial to the design and performance analyses of solar concentrator systems and central receiver systems.

After having developed the broadband-thermal version of SOLTRAN, it was then used to perform the following investigations and analyses:

- definition of the relative significance of the various atmospheric constituents to the attenuation-transmittance of the direct solar beam energy;
- comparison and evaluation of simplified models/algorithms;
- development of an improved, simplified model for solar energy.

The broadband SOLTRAN calculation delineated the relative significance of the various atmospheric constituents in the transmittance of direct solar beam energy. Aerosols appear to dominate the attenuation for a reasonable range of atmospheric conditions. Molecular scattering (Rayleigh) is next in importance, followed by water vapor absorption. These three attenuation processess-aerosol scattering, molecular scattering, and water vapor absorption-nearly completely determine the transmittance of the atmosphere to direct solar energy on a clear day. Attenuation caused by CO_2, O_2, and O_3 is minor. Because aerosols and water vapor are so important in determining the available direct solar beam energy, one needs high-quality measurements of their geographic and temporal characteristics. In the absence of actual measurements of the direct beam, such measurements could be used (with a model like SOLTRAN) to assess the availability and character of the direct solar beam energy. The SERI Energy Resource Assessment Branch will determine the availability of the aerosol (turbidity) and the water vapor measurements database, their quality, their applicability to assessing direct solar beam energy, and whether improved instrumentation and techniques are required to meet the needs of solar energy applications.

The comparisons of the ozone absorptance revealed significant differences between the simplified models and SOLTRAN. The magnitude of the differences is a function of solar zenith angle and amount of ozone. In general, SOLTRAN predicts a lower absorptance due to ozone than the Hoyt, Watt, and Lacis and Hansen models. The total range of the differences is determined by the Hoyt (high) and SOLTRAN (low) models, being approximately 30% to 50% in absorptance. The Watt and the Lacis and Hansen models appear to give quite similar results, which fall between the Hoyt and SOLTRAN results. Although the 30% to 50% differences are certainly significant, they are not considered to be a significant source of differences in calculating the total broadband direct irradiance because the contribution of ozone to the total broadband attenuation is minor.

For low amounts of water vapor (0.42 cm), the comparisons of the simplified models with SOLTRAN revealed that the Lacis and Hansen and Hoyt models gave results similar to SOLTRAN, while the McDonald and Watt models gave significantly lower values for water vapor absorptance. These differences depend on solar zenith angle, but they range from 25% to 75%. For high amounts of water vapor (2.92 cm), the Hoyt, McDonald, Lacis and Hansen, and SOLTRAN models yield similar results from an approximate solar zenith angle of 0° to 60°. At greater angles the models diverge somewhat. The Watt model results in significantly lower values, by about 50%, than all other models. Again, the significance of these differences to the calculation of the broadband direct irradiance is determined by the relative significance of water vapor to the total attenuation.

The comparisons of the transmittance due to all molecular effects except water vapor revealed close agreement between the Atwater and SOLTRAN results. The Watt model gave results that were lower in transmittance, depending on solar zenith angle.

The comparison of aerosol transmittance versus solar zenith angle for the MLS conditions with turbid aerosol conditions revealed that the Watt model gave significantly higher values than the SOLTRAN model. For the SAW with clear (visual range of 23 km) conditions, the Hoyt and SOLTRAN models gave similar results. The Watt model gave significantly higher transmittance values.

The comparisons of calculated direct beam solar irradiance versus solar zenith angle were performed for the MLS conditions, with a clear atmosphere (visual range = 23 km at sea level) and a turbid atmosphere (visual range = 5 km at sea level). The comparisons for the clear atmosphere revealed that the Machta, Atwater, and SOLTRAN models agree fairly closely; the Hoyt model results in lower values of direct irradiance, but they are within approximately 10% of the SOLTRAN/Atwater/Machta values. However, at large solar zenith angles (greater than 70°) the models begin to diverge significantly. The Watt model agrees favorably with the SOLTRAN/Atwater/Machta values up to a solar zenith angle of about 70°; at greater angles the Watt model predicts significantly higher values. The Majumdar model gives much higher values of direct irradiance versus solar zenith angle than all other models, by as much as 20%. The comparisons for a turbid atmosphere could only be performed for the Watt, Atwater, and SOLTRAN models due to limitations in the other models to clear conditions. It was shown that the Atwater and SOLTRAN model agree favorably to a zenith angle of 70°. The Watt model predicts significantly higher values, especially past zenith angles of 50°. Below zenith angles of 50°, the Watt values are within about 10% of the SOLTRAN/Atwater results. Comparisons were also performed for the SAW atmosphere with clear conditions. This again revealed agreement between the SOLTRAN and Atwater models, and characteristically, that the Watt model tends to predict high values.

However, for these SAW and clear conditions, the Watt model is in fairly good agreement to zenith angles of about 70°.

Finally, the rigorous SOLTRAN results were used to develop an improved, simplified model for predicting the direct solar beam energy as a function of atmospheric conditions and solar zenith angle. The improvements consist of higher accuracy (as compared to the SOLTRAN results) and the ability to handle readily available, specific inputs to characterize the atmospheric water vapor and aerosols. Mathematical formulations were derived by comparison with SOLTRAN results for the atmospheric transmittance components of molecular (Rayleigh) scattering, ozone absorption, uniformly mixed gas (CO_2 and O_2) absorption, water vapor absorption, and aerosol scattering and absorption, as functions of relative air mass (solar zenith angle). The inputs to the model (Bird) are surface pressure, precipitable ozone, precipitable water vapor, and aerosol turbidity at 0.38 μm and at 0.500 μm. Thus the Bird model allows the calculation of the direct solar beam irradiance as a function of available atmospheric parameters, which properly consider the significant water vapor and aerosol constituents.

The absolute accuracy of the Bird, SOLTRAN, and other models can be determined only by comparisons with actual measurements of the direct solar beam irradiance and measurements of the atmospheric inputs. Unfortunately, such comparisons and measurements have been lacking in the past in the visible region [46-50]; when done, they will probably result in improvements in the SOLTRAN and simplified models. The SERI Energy Resource Assessment Branch and the Solar Energy Meteorological Research and Training sites (university research programs sponsored by DOE to collect insolation and meteorological research data at eight locations within the United States) will be collecting such data and performing research that will greatly advance the state of knowledge concerning the atmospheric influences on the direct solar beam irradiance. Consequently, this will lead to improved prediction models for the direct solar beam irradiance and improved design and predictions of solar energy conversion devices.

SERI

SECTION 5.0

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APPENDIX

TABULATED MODEL DATA

A compilation of computer outputs for the Atwater and Ball, Watt, Bird, Lacis and Hansen, Majumdar, and the Hoyt models are presented. The atmospheric models used were the Midlatitude Summer (MLS) and the Subarctic Winter (SAW) models with 23 km and 5 km sea level visibilities for each model. The direct normal irradiance (IDN) is not included for the Bird models since it was given previously in Tables 2-2 and 2-3. The SOLTAN output is also listed in Tables 2-2 and 2-3. The IDN is not given in the Hoyt model, because parts of the calculation that required look-up tables were done on a hand calculator.

For the MLS model, 2.93 cm of H_2O and 0.31 cm of O_3 was used. The SAW used 0.42 cm of H_2O and 0.45 cm of O_3. The turbidity at 0.5 and 0.38 μm wavelength was 0.2733 and 0.3469, respectively, for V = 23 km; and 0.9243 and 1.1727, respectively, for V = 5 km. In all cases, the incident extraterrestrial irradiance was 1353 W/m^2.

Table A-1. Tabulated Data for the Midlatitude Summer Atmosphere (V = 23 km) for Several Models

IO	=	1353.0000
UW	=	2.9300
UO	=	.3100
PR	=	1013.0000
TAU5	=	.2733
TAU38	=	.3469
TAUB	=	.1913

ATWATER DIRECT NORMAL

ZENITH	AIRMASS	TA	AW	TM	IDN
0.0000	1.0000	.8259	.1063	.8901	875.7792
20.0000	1.0641	.8158	.1083	.8853	857.6348
30.0000	1.1545	.8018	.1110	.8788	832.9851
40.0000	1.3050	.7790	.1151	.8686	794.1641
50.0000	1.5548	.7427	.1214	.8528	735.0055
60.0000	1.9976	.6824	.1308	.8277	643.3732
70.0000	2.9148	.5725	.1465	.7833	493.2825
75.0000	3.8419	.4795	.1592	.7452	380.1443
80.0000	5.6846	.3370	.1790	.6812	228.9542
85.0000	10.9068	.1241	.2177	.5426	54.5405

WATT DIRECT NORMAL

ZEN	TA	TH2OA	TH2OS	TO3	TAIR	IDN
0.0	.8798	.9146	.9379	.9768	.9016	899.1887
20.0	.8740	.9137	.9341	.9763	.8974	884.2390
30.0	.8659	.9125	.9287	.9757	.8917	863.8708
40.0	.8530	.9108	.9197	.9747	.8826	831.6456
50.0	.8324	.9083	.9051	.9729	.8683	782.1515
60.0	.7992	.9047	.8797	.9698	.8451	704.3894
70.0	.7345	.8992	.8291	.9635	.8029	573.1249
75.0	.6828	.8953	.7813	.9586	.7702	477.0226
80.0	.5944	.8896	.6933	.9489	.7142	336.1558
85.0	.4331	.8800	.4896	.9309	.6123	143.9323

HOYT DIRECT NORMAL

ZENITH	AW	ACO2	AO3	AO2
0.0000	.1397	.0075	.0258	.0075
20.0000	.1426	.0076	.0264	.0079
30.0000	.1464	.0078	.0274	.0085
40.0000	.1523	.0081	.0288	.0095
50.0000	.1612	.0085	.0310	.0110
60.0000	.1747	.0091	.0344	.0137
70.0000	.1969	.0101	.0401	.0190
75.0000	.2147	.0109	.0448	.0242
80.0000	.2422	.0122	.0523	.0338
85.0000	.2938	.0144	.0669	.0578

LACIS H2O AND O3

ZENITH	AIRMASS	AW	TO3
0.0000	.9995	.1341	.9776
20.0000	1.0634	.1363	.9769
30.0000	1.1536	.1392	.9761
40.0000	1.3037	.1437	.9747
50.0000	1.5525	.1503	.9725
60.0000	1.9927	.1600	.9688
70.0000	2.8997	.1751	.9618
75.0000	3.8076	.1865	.9552
80.0000	5.5790	.2028	.9432
85.0000	10.3163	.2299	.9149

MAJUMDAR DIRECT NORMAL

ZENITH	IO X TT	TH2O	IDN
0.0000	1150.6024	.8093	931.2398
20.0000	1139.9371	.8067	919.5655
30.0000	1125.0519	.8031	903.5577
40.0000	1100.7170	.7977	878.0171
50.0000	1061.5163	.7897	838.2455
60.0000	995.5666	.7778	774.3037
70.0000	872.3054	.7588	661.8765
75.0000	764.2053	.7441	568.6819
80.0000	590.3528	.7224	426.4915
85.0000	296.0123	.6845	202.6061

BIRD DIRECT NORMAL

ZEN	TA	TO3	TCO2	TR	TM	AW
0.0	.8122	.9834	.9874	.9137	.8910	.1219
20.0	.8024	.9826	.9872	.9094	.8863	.1235
30.0	.7890	.9816	.9869	.9033	.8799	.1257
40.0	.7672	.9799	.9865	.8937	.8697	.1291
50.0	.7330	.9772	.9859	.8783	.8541	.1340
60.0	.6771	.9727	.9849	.8531	.8293	.1411
70.0	.5777	.9643	.9834	.8074	.7856	.1520
75.0	.4949	.9566	.9822	.7684	.7483	.1601
80.0	.3694	.9430	.9803	.7078	.6867	.1717
85.0	.1749	.9116	.9770	.6157	.5592	.1907

Table A- 2. Tabulated Data for the Midlatitude Summer Atmosphere (V = 5 km) for Several Models.

IO	=	1353.0000
UW	=	2.9300
UO	=	.3100
PR	=	1013.0000
TAU5	=	.9243
TAU38	=	1.1727
TAUB	=	.6469

ATWATER DIRECT NORMAL

ZENITH	AIRMASS	TA	AW	TM	IDN
0.0000	1.0000	.5236	.1063	.8901	555.2999
20.0000	1.0641	.5024	.1083	.8853	528.1389
30.0000	1.1545	.4738	.1110	.8798	492.2562
40.0000	1.3050	.4299	.1151	.8686	438.2152
50.0000	1.5548	.3657	.1214	.8528	361.3449
60.0000	1.9976	.2746	.1308	.8277	258.9480
70.0000	2.9148	.1517	.1465	.7933	130.7211
75.0000	3.8419	.0833	.1592	.7452	66.0326
80.0000	5.6846	.0253	.1790	.6812	17.1770
85.0000	10.9068	.0009	.2177	.5426	.3790

WATT DIRECT NORMAL

ZEN	TA	TH2OA	TH2OS	TO3	TAIR	IDN
0.0	.5953	.9146	.9379	.9768	.9016	608.4583
20.0	.5812	.9137	.9341	.9763	.8974	588.0320
30.0	.5622	.912[illegible]	.9287	.9757	.8917	560.8678
40.0	.5328	.9108	.9197	.9747	.8826	519.4331
50.0	.4889	.9083	.9051	.9729	.8683	459.3831
60.0	.4232	.9047	.8797	.9698	.8451	373.4774
70.0	.3210	.8992	.8291	.9635	.8029	250.4940
75.0	.2502	.8953	.7813	.9586	.7702	174.8369
80.0	.1583	.8896	.6933	.9489	.7142	89.5032
85.0	.0524	.8800	.4896	.9309	.6123	17.4247

HOYT DIRECT NORMAL

ZENITH	AW	ACO2	AO3	AO2
0.0000	.1397	.0075	.0258	.0075
20.0000	.1426	.0076	.0264	.0079
30.0000	.1464	.0078	.0274	.0085
40.0000	.1523	.0081	.0288	.0095
50.0000	.1612	.0085	.0310	.0110
60.0000	.1747	.0091	.0344	.0137
70.0000	.1969	.0101	.0401	.0190
75.0000	.2147	.0109	.0448	.0242
80.0000	.2422	.0122	.0523	.0338
85.0000	.2938	.0144	.0669	.0578

LACIS H2O AND O3

ZENITH	AIRMASS	AW	TO3
0.0000	.9995	.1341	.9776
20.0000	1.0634	.1363	.9769
30.0000	1.1536	.1392	.9761
40.0000	1.3037	.1437	.9747
50.0000	1.5525	.1503	.9725
60.0000	1.9927	.1600	.9688
70.0000	2.8997	.1751	.9618
75.0000	3.8076	.1865	.9552
80.0000	5.5790	.2028	.9432
85.0000	10.3163	.2299	.9149

MAJUMDAR DIRECT NORMAL

ZENITH	IO X TT	TH2O	IDN
0.0000	1150.6024	.8093	931.2298
20.0000	1139.9371	.8067	919.5655
30.0000	1125.0519	.8031	903.5577
40.0000	1100.7170	.7977	878.0171
50.0000	1061.5163	.7897	838.2455
60.0000	995.5666	.7778	774.3037
70.0000	872.3054	.7588	661.8765
75.0000	764.2053	.7441	568.6819
80.0000	590.3528	.7224	426.4915
85.0000	296.0123	.6845	202.6061

BIRD DIRECT NORMAL

ZEN	TA	TO3	TCO2	TR	TM	AW
0.0	.5360	.9834	.9874	.9137	.8910	.1219
20.0	.5169	.9826	.9872	.9094	.8863	.1235
30.0	.4913	.9816	.9869	.9033	.8799	.1257
40.0	.4519	.9799	.9865	.8937	.8697	.1291
50.0	.3940	.9772	.9859	.8783	.8541	.1340
60.0	.3106	.9727	.9849	.8531	.8293	.1411
70.0	.1930	.9643	.9834	.8074	.7856	.1520
75.0	.1214	.9566	.9822	.7684	.7483	.1601
80.0	.0505	.9430	.9803	.7078	.6867	.1717
85.0	.0054	.9116	.9770	.6157	.5592	.1907

Table A-3. Tabulated Data for the Subarctic Winter Atmosphere (V = 23 km) for Several Models

IO = 1353.0000
UW = .4200
UO = .4500
PR = 1013.0000
TAU5 = .2733
TAU38= .3469
TAUB= .1913

ATWATER DIRECT NORMAL

ZENITH	AIRMASS	TA	AW	TM	IDN
0.0000	1.0000	.8259	.0594	.8901	928.2386
20.0000	1.0641	.8158	.0605	.8853	910.4298
30.0000	1.1545	.8018	.0620	.8788	886.1598
40.0000	1.3050	.7790	.0643	.8686	847.7640
50.0000	1.5548	.7427	.0678	.8528	788.8605
60.0000	1.9976	.6824	.0730	.8277	696.7169
70.0000	2.9148	.5725	.0818	.7833	543.4124
75.0000	3.8419	.4795	.0889	.7452	425.7525
80.0000	5.6846	.3370	.1000	.6812	265.0097
85.0000	10.9068	.1241	.1216	.5426	70.6818

WATT DIRECT NORMAL

ZEN	TA	TH2OA	TH2OS	TO3	TAIR	IDN
0.0	.8498	.9424	.9909	.9736	.9016	942.4497
20.0	.8429	.9415	.9903	.9730	.8974	928.4526
30.0	.8334	.9404	.9894	.9721	.8917	909.4148
40.0	.8181	.9386	.9881	.9706	.8826	879.3576
50.0	.7940	.9361	.9858	.9681	.8683	833.2990
60.0	.7545	.9325	.9818	.9636	.8451	761.0286
70.0	.6825	.9271	.9735	.9544	.8029	638.5592
75.0	.6246	.9231	.9652	.9474	.7702	549.3846
80.0	.5285	.9174	.9488	.9336	.7142	415.0665
85.0	.3591	.9079	.9027	.9080	.6123	221.3732

HOYT DIRECT NORMAL

ZENITH	AW	ACO2	AO3	AO2
0.0000	.0727	.0075	.0301	.0075
20.0000	.0743	.0076	.0309	.0079
30.0000	.0764	.0078	.0320	.0085
40.0000	.0797	.0081	.0337	.0095
50.0000	.0847	.0085	.0362	.0110
60.0000	.0922	.0091	.0401	.0137
70.0000	.1046	.0101	.0467	.0190
75.0000	.1146	.0109	.0521	.0242
80.0000	.1299	.0122	.0608	.0338
85.0000	.1587	.0144	.0775	.0578

LACIS H2O AND O3

ZENITH	AIRMASS	AW	TO3
0.0000	.9995	.0761	.9734
20.0000	1.0634	.0776	.9726
30.0000	1.1536	.0796	.9715
40.0000	1.3037	.0827	.9696
50.0000	1.5525	.0872	.9667
60.0000	1.9927	.0941	.9613
70.0000	2.8997	.1050	.9524
75.0000	3.8076	.1136	.9436
80.0000	5.5790	.1263	.9276
85.0000	10.3163	.1485	.8907

MAJUMDAR DIRECT NORMAL

ZENITH	IO X TT	TH2O	IDN
0.0000	1150.6024	.8780	1010.1838
20.0000	1139.9371	.8762	998.7881
30.0000	1125.0519	.8738	983.0703
40.0000	1100.7170	.8701	957.7868
50.0000	1061.5163	.8648	917.9585
60.0000	995.5666	.8567	852.9105
70.0000	872.3054	.8438	736.0339
75.0000	764.2053	.8337	637.1483
80.0000	590.3528	.8187	483.3134
85.0000	296.0123	.7919	234.4198

BIRD DIRECT NORMAL

ZEN	TA	TO3	TCO2	TR	TM	AW
0.0	.8122	.9783	.9874	.9137	.8910	.0758
20.0	.8024	.9773	.9872	.9094	.8863	.0770
30.0	.7890	.9759	.9869	.9033	.8799	.0787
40.0	.7672	.9737	.9865	.8937	.8697	.0813
50.0	.7330	.9702	.9859	.8783	.8541	.0851
60.0	.6771	.9644	.9849	.8531	.8293	.0907
70.0	.5777	.9534	.9834	.8074	.7856	.0995
75.0	.4949	.9434	.9822	.7684	.7483	.1062
80.0	.3694	.9256	.9803	.7078	.6867	.1160
85.0	.1749	.8848	.9770	.6157	.5592	.1326

Table A-4. Tabulated Data for the Subarctic Winter Atmosphere [V= 5 km] for Several Models

```
IO     =   1353.0000
UW     =      .4200
UO     =      .4500
PR     =   1013.0000
TAU5   =      .3243
TAU38  =     1.1727
TAUB   =      .6469
```

ATWATER DIRECT NORMAL

ZENITH	AIRMASS	TA	AW	TM	IDN
0.0000	1.0000	.5236	.0594	.8901	588.5626
20.0000	1.0641	.5024	.0605	.8853	560.6505
30.0000	1.1545	.4738	.0620	.8788	523.6800
40.0000	1.3050	.4299	.0643	.3686	467.7913
50.0000	1.5548	.3657	.0678	.8529	388.4651
60.0000	1.9976	.2746	.0730	.8277	280.4181
70.0000	2.9148	.1517	.0818	.7833	144.0056
75.0000	3.8419	.0833	.0889	.7452	73.9549
80.0000	5.6846	.0253	.1000	.6812	19.3821
85.0000	10.9068	.0009	.1216	.5426	.4911

WATT DIRECT NORMAL

ZEN	TA	TH2OA	TH2OS	TO3	TAIR	IDN
0.0	.5750	.9424	.9909	.9736	.9016	637.7320
20.0	.5605	.9415	.9903	.9730	.8974	617.4347
30.0	.5411	.9404	.9894	.9721	.8917	590.4373
40.0	.5110	.9386	.9881	.9706	.8826	549.2333
50.0	.4663	.9361	.9858	.9681	.8683	489.4237
60.0	.4000	.9325	.9818	.9636	.8451	403.5083
70.0	.2983	.9271	.9735	.9544	.8029	279.0931
75.0	.2289	.9231	.9652	.9474	.7702	201.3589
80.0	.1407	.9174	.9488	.9336	.7142	110.5136
85.0	.0435	.9079	.9027	.9080	.6123	26.7999

HOYT DIRECT NORMAL

ZENITH	AW	ACO2	AO3	AO2
0.0000	.0727	.0075	.0301	.0075
20.0000	.0743	.0076	.0309	.0079
30.0000	.0764	.0078	.0320	.0085
40.0000	.0797	.0081	.0337	.0095
50.0000	.0847	.0085	.0362	.0110
60.0000	.0922	.0091	.0401	.0137
70.0000	.1046	.0101	.0467	.0190
75.0000	.1146	.0109	.0521	.0242
80.0000	.1299	.0122	.0608	.0338
85.0000	.1587	.0144	.0775	.0578

LACIS H2O AND O3

ZENITH	AIRMASS	AW	TO3
0.0000	.9995	.0761	.9734
20.0000	1.0634	.0776	.9726
30.0000	1.1536	.0796	.9715
40.0000	1.3037	.0827	.9696
50.0000	1.5525	.0872	.9667
60.0000	1.9927	.0941	.9618
70.0000	2.8997	.1050	.9524
75.0000	3.8076	.1136	.9436
80.0000	5.5790	.1263	.9276
85.0000	10.3163	.1485	.8907

MAJUMDAR DIRECT NORMAL

ZENITH	IO X TT	TH2O	IDN
0.0000	1150.6024	.8780	1010.1838
20.0000	1139.9371	.8762	998.7381
30.0000	1125.0519	.8738	983.0703
40.0000	1100.7170	.8701	957.7868
50.0000	1061.5163	.8648	917.9585
60.0000	995.5666	.8567	852.9105
70.0000	872.3054	.8438	736.0339
75.0000	764.2053	.8337	637.1483
80.0000	590.3528	.8187	483.3134
85.0000	296.0123	.7919	234.4198

BIRD DIRECT NORMAL

ZEN	TA	TO3	TCO2	TR	TM	AW
0.0	.5360	.9783	.9874	.9137	.8910	.0758
20.0	.5169	.9773	.9872	.9094	.8863	.0770
30.0	.4913	.9759	.9869	.9033	.8799	.0787
40.0	.4519	.9737	.9865	.8937	.8697	.0813
50.0	.3940	.9702	.9859	.8783	.8541	.0851
60.0	.3106	.9644	.9849	.8531	.8293	.0907
70.0	.1930	.9534	.9834	.8074	.7856	.0995
75.0	.1214	.9434	.9822	.7684	.7483	.1062
80.0	.0505	.9256	.9803	.7079	.6867	.1160
85.0	.0054	.8848	.9770	.6157	.5592	.1326

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16. Abstract (Limit: 200 words)

Several recently published models of the direct component of the broadband insolation are compared for clear sky conditions. The comparison includes seven simple models and one rigorous model that is used as a basis for determining accuracy. Where possible, the comparison is made between the results of each model for each atmospheric constituent (H_2O, CO_2, O_3, O_2, aerosol and molecular scattering) separately as well as for the combined effect of all of the constituents. Two optimum simple models of varying degrees of complexity are developed as a result of this comparison. The study indicates: aerosols dominate the attenuation of the direct beam for reasonable atmospheric conditions; molecular scattering is next in importance; water vapor is an important absorber; and carbon dioxide and oxygen are relatively unimportant as attenuators of the broadband solar energy.

17. Document Analysis

a. Descriptors Insolation ; Mathematical Models ; Comparative Evaluations ; Water Vapor ; Ozone ; Transport Theory ; Gases

b. Identifiers/Open-Ended Terms SOLTRAN Model ; Atwater and Ball Model ; Hoyt Model ; ASHRAE Model ; Watt Model ; Lacis and Hansen Model ; Machta Model ; Majumdar Model ; Bird Model

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