Spectral Fluxes of Solar Radiation in Broken Clouds: Algorithms for Calculation

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Introduction

The most Atmospheric Radiation Measurement (ARM) clear- and cloudy- sky radiation experiments have been performed with broadband fluxes. Because the fluxes are integrated over wavelength, it is difficult to understand the causes of unavoidable differences between calculated and observed broadband fluxes in those experiments. Therefore for better understanding of the mechanisms of cloud-radiation interaction, it is necessary to measure and calculate the spectral distribution of solar radiation in the atmosphere. The comparison of spectral measurements and calculations provides an excellent foundation to analyze the ability of different models to compute the solar irradiance.

Over the last decade a suite of spectral radiative transfer (RT) models has been developed at Atmospheric and Environmental Research, Inc. (AER). The foundation of the suite of AER models is *line-by-line* Radiative Transfer Model (LBLRTM) (Cloudh et al. 1992). The numerically accurate Code for High Resolution Accelerated Radiative Transfer (CHARTS) was developed to extend the capabilities of LBLRTM to treatment of clouds and aerosols in *horizontally-homogeneous* atmosphere (Moncet and Clough 1997).

Under assumption of horizontally homogeneous atmosphere, the spectral fluxes with *lower* spectral resolution can be calculated using the SMARTS2 (Gueymard 1995), SBDART (Ricchiazzi 1998), and MODTRAN (Berk et al. 1989) RT codes. O'Hirok and Gautier (1998, 2000) have suggested an algorithm of spectral radiation calculations capable of incorporating *3D effects* of real *clouds* on the basis of *k*-distribution method.

Stochastic RT approach has been shown to be a promising approach to simulating *domain-averaged shortwave* radiation fields. Titov and Zhuravleva (1997) presented an efficient algorithm for computing the mean spectral fluxes in the near-IR spectral range (with 10 to 20 cm^{-1} resolution), based on the solution of closed system of equations for mean intensity in a statistically homogeneous Poisson model of *broken clouds*. The present work describes a modification of this algorithm which uses expansion of the transmission function into the series of exponents (method of *k*-distribution) to consider molecular absorption. Absorption coefficients are calculated based on HITRAN-2000 spectroscopic database taking into account the filter functions of Rotating Shadowband Spectroradiometer (RSS), 360 to 1100 nm, 1024 channels (see, e.g., Harrison et al. 1999). Also presented are the algorithms developed by ourselves to calculate the spectral fluxes of solar radiation under conditions of clear-sky and overcast horizontally homogeneous clouds.

k-Distribution Method

To treat the molecular absorption, in this paper we use a modification of the method of exponential series as described in (Firsov et al. 2002). The effective transmission function associated with molecular absorption in the spectral interval $\Delta\lambda=(\lambda_1,\lambda_2)$ can be represented as

$$T_{\Delta\lambda}(m)=\int\limits_{\lambda_1}^{\lambda_2} F^*(\lambda)I_0(\lambda)T(m,\lambda)d\lambda \Big/ I_{0,\Delta\lambda} \quad I_{0,\Delta\lambda}=\int\limits_{\lambda_1}^{\lambda_2} F^*(\lambda)I_0(\lambda)d\lambda \tag{1}$$

Here $F^*(\lambda)$ is the point spread function, which is largely determined by the filtering bandpass

$F(\lambda)$; $I_0(\lambda)$ is the spectral solar constant; $T(m,\lambda)=\exp\left(-m\int\limits_0^{H_{atm}}\kappa_{mol}(\lambda,h)dh\right)$ is the

monochromatic transmission function in the vertically inhomogeneous Earth's atmosphere; $\kappa_{mol}(\lambda, h)$ is the molecular absorption coefficient at the wavelength λ and the height h; m is the optical mass in the direction of Sun; and H_{atm} is the top height of the atmosphere.

According to the ideology of *k*-distribution method, $T_{\Delta\lambda}(m)$ can be converted to the form

$$T_{\Delta\lambda}(m)=\int\limits_0^1\exp\left(-m\int\limits_0^{H_{atm}}k(g,h)dh\right)dg=\sum_{i=1}^{N}C_i\exp\left(-m\int\limits_0^{H_{atm}}k(g_i,h)dh\right) \tag{2}$$

where $k(g, h)$ is the effective absorption coefficient in the space of cumulative wavelengths g; g_i and C_i are the nodes and coefficients of the Gaussian quadrature formulas; and $\sum_{i=1}^{N}C_i=1$.

In order to avoid problems with taking into account the overlaps of different gas absorption bands within *k*-distribution technique, in this paper we used the following calculation scheme:

- for prescribed meteorological conditions (pressure, temperature, and concentration of absorbing gases) we calculated the molecular absorption coefficients by the *line-by-line* (*LBL*) method

- using these results, and taking into account the spectral dependence of solar constant $I_0(\lambda)$ and filter function of recording instrument $F(\lambda)$, we then calculated the effective absorption coefficients and coefficients of Gaussian quadratures by the *k*-distribution method.

The results obtained with the approach described above were compared with benchmark calculations of upward and downward fluxes with 500 cm^{-1} spectral resolution (Fomin and Gershanov 1996). Spectral line parameters were taken from HITRAN-92 and HITRAN-2000 data base versions (http://www.hitran.com), while the solar irradiance data are from LOWTRAN7 (Kneizys et al. 1996). The continuum absorption was calculated according to CKD24 model of Clough et al. (http://rtweb.aer.com). The vertical profiles of temperature, air pressure, and concentrations of atmospheric gases (H_2O, CO_2, O_3, CH_4 etc.) were specified according to AFGL meteorological model for midlatitude summer (MLS) (Anderson et al. 1986).

For the 10,000 to 10,500 cm^{-1} (952 to 1000 nm) band our calculations of transmitted radiation in a purely absorbing atmosphere, calculated by *LBL* and *k*-distribution method and results of Fomin and Gershanov (1996), obtained by *LBL* method using HITRAN-92, agree to within 0.1%. As the number N of quadratures grows, the accuracy of *k*-distribution method increases: the relative difference changes from ~1% at N=4 to ~0.1% at N=10. The discrepancies in downward fluxes, due to a change to HITRAN-2000, increase to ~2% at the underlying surface level.

Effect of the Filter Function

Before proceeding to radiation calculations, we consider the effect of the filter function $F(\lambda)$. In the spectral regions free of noticeable molecular absorption, different approximations of the real filter function $F(\lambda)$ are often used (as a rule, in the form of a Π-shaped profile). The presence of absorption bands of atmospheric gases can radically change the situation, and the use of such approximations in place of the actual filtering bandpass can lead to considerable errors in radiation calculations.

We use the model reference line profiles corresponding to RSS, 1024 channels, approximated by the truncated Gaussian function (ftp://oink.asrc.cestm.albany.edu/pub/RSS102):

$$F(\lambda,\lambda_0) = \exp\left(-\left((\lambda-\lambda_0)/w(\lambda_0)\right)^2\right) \text{ for } |\lambda-\lambda_0| \le \lambda_{0,\max} \tag{3}$$

We estimate the error of transmission function $T_{\Delta\lambda}(m)$, arising due to replacement of reference line profile (3) by its approximation in the form of Π-shaped profile :

$$\delta_T = 100\% \times \left(T_{\Delta\lambda}^{\Pi}(m) - T_{\Delta\lambda}^{Gaus}(m)\right) / T_{\Delta\lambda}^{Gaus}(m).$$

Results have shown that the δ_T value increases with growing atmospheric gas absorption (Figure 1). For solar zenith angle $SZA = 75^\circ$ it is ≈2% at λ=591 nm and ≈8% at λ=761 nm; in water vapor absorption band 940 nm the δ_T values reach ≈25%; and at λ=947 nm, $\delta_T \approx 330\%$.

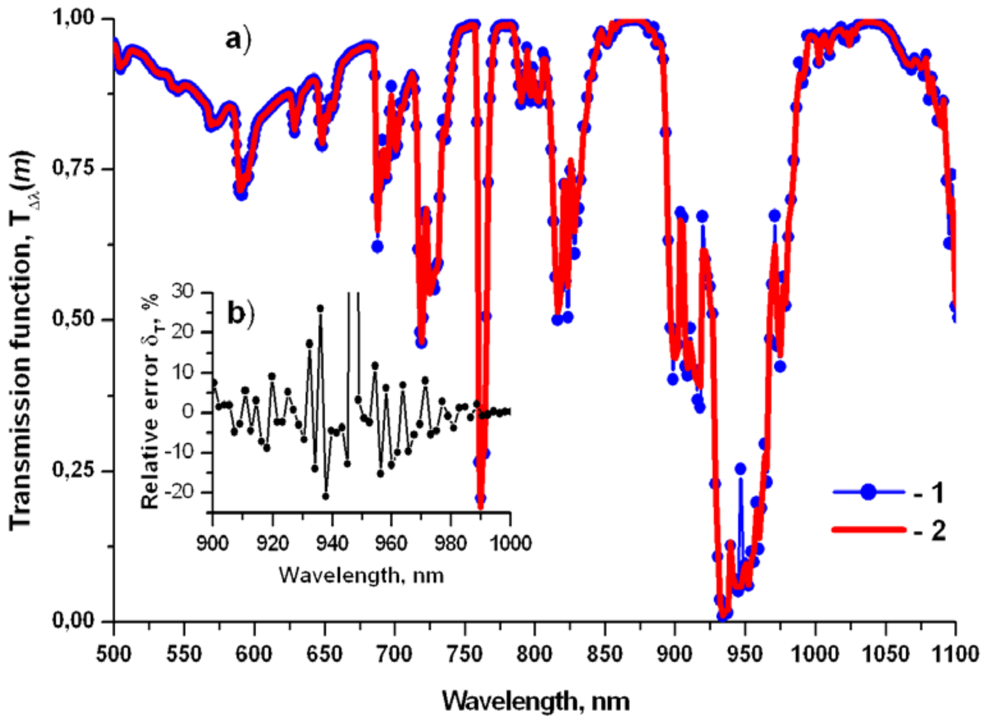

Figure 1. (a) Transmission of the purely gaseous atmosphere (*LBL* method): Gaussian filter function (3) (curve 2), rectangular-shaped filter function (spectral width of rectangular filter function equals that of Gaussian filter function at height exp(-1)) (curve 1). (b) Relative error $\delta_T(\%)$ of transmission function due to the use in the calculations of Π-shaped profile instead of Gaussian filter function. *SZA*=75^{o}. Here and in the Figure 2, the calculations are performed using HITRAN-2000; solar constant at the top of the atmosphere is as given by Kurucz et al. (1992); MLS model is used.

Simulation of Radiative Characteristics

To calculate the radiative characteristics $R_{\Delta\lambda}$ (flux, radiance), two methods can be used. The **first method** is based on representability of $R_{\Delta\lambda}$ (according to formula (2)) in terms of the sum'/

$$R_{\Delta\lambda} = \sum_{i=1}^{N} C_i R_i \,.$$

Here R_i is monochromatic radiation at a cumulative wavelength g_i, corresponding to the *i*th set of effective molecular absorption coefficients $k(g_i, h)$, $1 \le i \le N$, which can be calculated based on some or another method of solution of RT equation.

To calculate the spectral radiative fluxes R_i, $1 \le i \le N$, in *horizontally homogeneous clear-sky and cloudy atmosphere*, we used the Monte Carlo method (Marchuk et al. 1976). Photon trajectories were modeled in the medium consisting of clouds, aerosol, and air molecules using a standard method. Within the wavelength interval $\Delta\lambda$, i.e., for $1 \le i \le N$, the optical characteristics of clouds (*cl*) and aerosol (*aer*), as well as Rayleigh (*r*) scattering coefficients were assumed constant. In the *j*th atmospheric layer, the scattering coefficients $\sigma_{s,j}^{mix}$ and scattering phase function $g_j^{mix}(\mu)$ of mixture were defined by

$$\sigma_{s,j}^{mix} = \sigma_{s,j}^{cl} + \sigma_{s,j}^{aer} + \sigma_j^r,\ g_j^{mix}(\mu) = \left(\sigma_{s,j}^{cl} g_j^{cl}(\mu) + \sigma_{s,j}^{aer}(\mu) g_j^{aer}(\mu) + \sigma_j^r g^r(\mu)\right) / \sigma_{s,j}^{mix}$$

where μ is the cosine of the scattering angle.

The extinction coefficient of mixture at each *i*th step was varied according to the formula

$$\sigma_{j,i}^{mix,1} = \sigma_j^{cl} + \sigma_j^{aer} + \sigma_j^r + k_j^i,\ i=1,\dots,N.$$

It was assumed that the incident radiation is reflected Lambertianly from underlying surface with albedo A_S.

The **second method** of treatment of molecular absorption is based on idea of Van de Hulst and Irvine (1963) that the scattering and absorption occur independently. In accordance with this approach, the photon trajectory modeling in the medium is performed disregarding molecular absorption, that is the extinction coefficient is defined as $\sigma_j^{mix,2} = \sigma_j^{cl} + \sigma_j^{aer} + \sigma_j^r$. Treatment of molecular absorption at each collision point involves introduction of auxiliary statistical weight of photon, which is determined by transmission function and decreases with growing absorption optical path traversed by the photon (Marchuk et al. 1976).

Table 1 presents upward ($F_{clr}^{\uparrow}$) and downward ($F_{clr}^{\downarrow}$) fluxes of solar radiation, calculated by methods I and II in the band 10,000 to 10,500 cm^{-1} for N=4. The calculations are performed for *molecular-aerosol* atmosphere and correspond to 50 and 51 ICRCCM cases (Fouquart et al. 1991). The accuracy of our calculations is not higher than 0.05-0.1%; the upward fluxes $F_{clr}^{\uparrow}$ in vicinity of underlying surface with A_s=0.0 are calculated with accuracy 1.0-1.5%. The flux calculations, made by the methods I и II, agree to within the calculation error.

For comparison purposes, Table 1 also presents the results of benchmark calculations of Fomin and Gershanov (1996). When HITRAN-92 is used, disagreement between our $F_{clr}^{\downarrow}$ ($F_{clr}^{\uparrow}$) results and benchmark calculations is due to the representation of transmission function in the form of the sum of four exponents. Rather significant (> 0.15 W/m^2) discrepancies in $F_{clr}^{\downarrow}$ at $z \le 3$ km, given in the third and fifth (respectively, in fourth and sixth etc.) columns of Table 1 arise due to change from HITRAN-92 to HITRAN-2000.

The spectral fluxes in the *cloudy* atmosphere, calculated by both methods in the band 10,000 to 10,500 cm^{-1} taking into account filter functions (3) are presented in Table 2. The cloud-scattering phase functions were computed from Mie theory, with the gamma-size distribution function for “wide” drop size spectrum (Feigelson 1981). As in the case of the clear-sky atmosphere, the flux calculations, made by different methods, agree to within the calculation error.

Table 1. Fluxes of Upward/Downward Radiation $F_{clr}^{\uparrow}(h) \big/ F_{clr}^{\downarrow}(h)$ (W/m^2) In Molecular Aerosol Atmosphere (maritime I) in the Band 10,000 to 10,500 cm^{1}, Calculated by Ourselves Using Two Different Methods. Solar irradiance data are from LOWTRAN7 (Kneizys et al, 1996). The number of terms in series in (2) *N*=4; MLS; $SZA = 30^{\circ}$.

h, km	***A***									
	A_s=0					**A_s=0.8**				
	Fomin (1996)	**Our Calculation**				**Fomin (1996)**	**Our Calculation**			
	LBL	**Method I**	**Method II**	**Method I**	**Method II**	***LBL***	**Method I**	**Method II**	**Method I**	**Method II**
	HITRAN-92			**HITRAN-2000**		**HITRAN-92**			**HITRAN-2000**	
0	0 / 22.87	0 / 22.74	0 / 22.74	0 / 22.40	0 / 22.39	18.57 / 23.22	18.48 / 23.10	18.48 / 23.10	18.20 / 22.74	18.20 / 22.73
1	0.0592 / 24.96	0.061 / 24.68	0.0616 / 24.68	0.0599 / 24.40	0.0603 / 24.39	16.84 / 25.21	16.90 / 24.94	16.90 / 24.94	16.55 / 24.64	16.54 / 24.64
2	0.117 / 26.79	0.121 / 26.66	0.121 / 26.67	0.118 / 26.43	0.118 / 26.45	16.08 / 26.94	16.18 / 26.82	16.17 / 26.83	15.79 / 26.59	15.78 / 26.60
3	0.128 / 28.23	0.132 / 28.36	0.132 / 28.35	0.129 / 28.21	0.130 / 28.23	15.74 / 28.36	15.84 / 28.51	15.84 / 28.50	15.44 / 28.35	15.43 / 28.37
4	0.142 / 29.28	0.146 / 29.57	0.146 / 29.56	0.142 / 29.48	0.143 / 29.47	15.57 / 29.41	15.68 / 29.71	15.68 / 29.69	15.27 / 29.61	15.27 / 29.60
5	0.154 / 30.00	0.16 / 30.33	0.16 / 30.34	0.157 / 30.28	0.157 / 30.26	15.48 / 30.11	15.60 / 30.45	15.59 / 30.45	15.18 / 30.39	15.18 / 30.37
10	0.219 / 31.31	0.224 / 31.35	0.224 / 31.34	0.221 / 31.35	0.221 / 31.34	15.38 / 31.36	15.49 / 31.40	15.49 / 31.39	15.07 / 31.40	15.07 / 31.39
12	0.239 / 31.40	0.245 / 31.41	0.245 / 31.38	0.242 / 31.41	0.232 / 31.43	15.36 / 31.43	15.47 / 31.44	15.47 / 31.42	15.06 / 31.44	15.06 / 31.46
20	0.264 / 31.44	0.274 / 31.44	0.274 / 31.46	0.27 / 31.44	0.27 / 31.46	15.37 / 31.44	15.48 / 31.45	15.48 / 31.47	15.06 / 31.45	15.06 / 31.47
50	0.274 / 31.45	0.286 / 31.45	0.286 / 31.47	0.282 / 31.45	0.283 / 31.47	15.37 / 31.45	15.48 / 31.45	15.48 / 31.47	15.07 / 31.45	15.06 / 31.47
70	0.274 / 31.45	0.286 / 31.45	0.286 / 31.47	0.283 / 31.45	0.283 / 31.47	15.37 / 31.45	15.48 / 31.45	15.48 / 31.47	15.07 / 31.45	15.06 / 31.47
100	0.274 / 31.45	0.286 / 31.45	0.286 / 31.45	0.283 / 31.45	0.283 / 31.45	15.37 / 31.45	15.48 / 31.45	15.48 / 31.45	15.07 / 31.45	15.06 / 31.45

Table 2. Spectral Fluxes of Upward and Downward Solar Radiation (W/[m^2×nm]) in the Cloudy Atmosphere in the Band 952 to 1000 nm, Calculated by Two Different Methods (*N*=4) Using HITRAN-2000. Solar irradiance data are from (Kurucz et al. 1992). Wavelengths and parameters of filter functions correspond to RSS: ftp://oink.asrc.cestm.albany.edu/pub/RSS102. The cloud layer occupies the height interval 1 to 2 km; cloud extinction coefficient $\sigma^{cl}(\lambda = 550\,nm) = 10\ km^{-1}$; aerosol profile corresponds to continental aerosol as defined by *WCP*. MLS; *SZA*=60°; A_s=0.2.

λ, nm	Method I $F^{\downarrow}(z=0)$	Method II $F^{\downarrow}(z=0)$	Method I $F^{\uparrow}(z=100\ km)$	Method II $F^{\uparrow}(z=100\ km)$
952.624	0.02742	0.02743	0.05159	0.05151
954.485	0.03731	0.03729	0.06711	0.06699
956.354	0.03855	0.03842	0.06793	0.06789
958.222	0.05292	0.05277	0.08802	0.08798
960.099	0.04425	0.04424	0.07568	0.07553
961.985	0.05898	0.05882	0.09770	0.09782
963.858	0.06806	0.06785	0.1088	0.1089
965.752	0.06705	0.06693	0.1079	0.1079
967.643	0.1025	0.1026	0.1545	0.1543
969.533	0.1148	0.1150	0.1716	0.1714
971.432	0.1189	0.1190	0.1762	0.1761
973.340	0.1005	0.1006	0.1519	0.1518
975.246	0.0933	0.09352	0.1425	0.1423
977.151	0.1082	0.1084	0.1617	0.1617
979.064	0.1047	0.1049	0.1573	0.1572
980.988	0.1233	0.1238	0.1820	0.1817
982.909	0.1249	0.1253	0.1850	0.1847
984.828	0.1345	0.1348	0.1972	0.1970
986.757	0.1470	0.1473	0.2116	0.2114
988.695	0.1506	0.1511	0.2164	0.2162
990.631	0.1498	0.1501	0.2148	0.2146
992.565	0.1525	0.1527	0.2178	0.2177
994.509	0.1565	0.1566	0.2229	0.2229
996.451	0.1567	0.1569	0.2233	0.2233

To calculate the mean fluxes of solar radiation in the *broken clouds*, in this work we use the ideology of one of the methods suggested earlier by Titov and Zhuravleva (1997). (Here this method corresponds to method II). The entire spectral range is divided into K_{int} subintervals according to spectral resolution specified. In each subinterval, the mean spectral fluxes are calculated based on the solution of equations for mean intensity by the Monte-Carlo method with cloud and aerosol optical characteristics assumed constant. Previously, this algorithm was implemented by ourselves for transmission functions suggested by Golubitskii and Moskalenko (1968); here it is modified to take the opportunity of representation of transmission function in the form of finite exponential series (*k*-distribution method). Such an approach allows us to efficiently use in the studies the new achievements of atmospheric spectroscopy and, thereby, facilitates improvement of accuracy of radiation calculations.

Figure 2 presents calculations of mean spectral fluxes $< F^{\downarrow}(h=0) >$ and $< F^{\uparrow}(h=100\ km) >$ for conditions of broken clouds. Also shown in the figure are results obtained by ourselves in a traditional approximation of horizontally homogeneous atmosphere:

$$F^{(\uparrow\downarrow)}(h) = pF_{overcast}^{(\uparrow\downarrow)}(h) + (1-p)F_{clr}^{(\uparrow\downarrow)}(h) \tag{4}$$

where p is the cloud fraction.

These results qualitatively agree with our earlier conclusions about influence of cloud random geometry on solar RT.

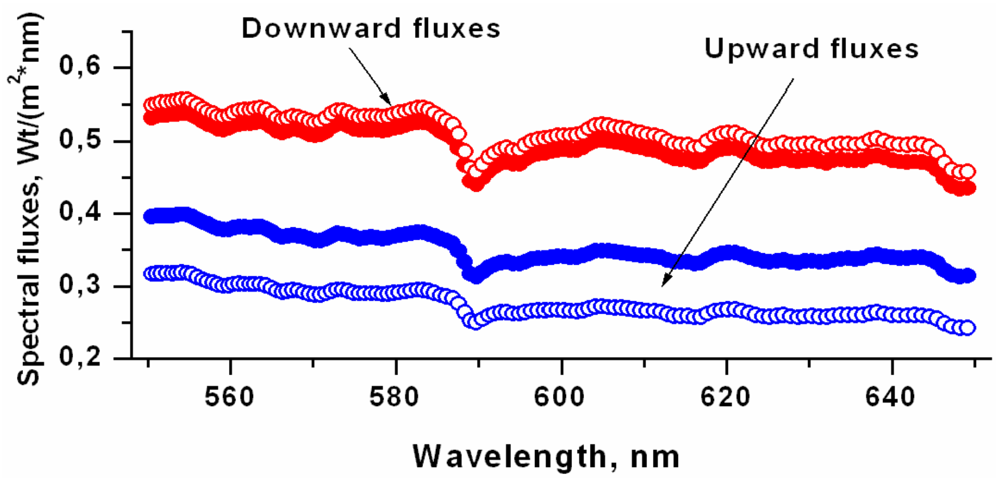

Figure 2. Computations of mean fluxes of downward $< F^{\downarrow}(h=0) >$ and upward $< F^{\uparrow}(h=100\,km) >$ radiation with cloud fraction *p*=0.5 and mean cloud diameter *D*=0.5 km (closed symbols). The cloud layer occupies the height interval 1-2 km; *SZA*=60°; A_s=0.2; $\sigma^{cl}(\lambda = 0.55\ km) = 10\ km^{-1}$. Open symbols indicate the fluxes calculated in the approximation of *horizontally homogeneous* model (4).

Our Plans

1. We are planning to use the RSS-derived radiation measurement data and information about optical and geometrical cloud properties from ground-based ARM Program observations for validation of our algorithms in the clear-sky and cloudy atmosphere.

2. The use of this algorithm in the mean spectral flux computations of high spectral resolution (say, $\Delta\nu$ corresponding to RSS spectral resolution) may require several hundreds of spectral intervals. As a result, the cost of the computation is prohibitive and hence the algorithms then have limited use. The computation effort is reduced by employing in the mean spectral flux computation the method of dependent tests. Use of this approach together with *k*-distribution method is the next step of our work.

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References

Anderson, G., S. Clough, F. Kneizys, J. Chetwynd, and E. Shettle, 1986: AFGL Atmospheric Constituent Profiles (0 - 120 km). Air Force Geophysics Laboratory, AFGL-TR-86-0110, Environmental Research Paper No. 954.

Anderson, G. P. et al., 1999: MODTRAN4: Radiative transfer modeling for remote sensing. *Proc. SPIE, Optics in Atmos. Propagation and Adaptive System III*, **3866**:2-10.

Berk A., L. S. Bernstein, and D. C. Robertson, 1989: MODTRAN: A moderate resolution model for LOWTRAN7, GL-TR-89-0122. Geophys. Dir., Phillips Lab., Hanson AFB, Mass.

Clough, S. A., M. J. Iacono, and J. L. Moncet, 1992: Line-by-line calculations of atmospheric fluxes and cooling rates: Application to water vapor. *J. Geophys. Res*., **100**:16519-16535.

Feigelson, E. M., 1981: Radiation in a cloudy atmosphere. Gidrometeoizdat, Leningrad.

Firsov, K. M., T. Yu. Chesnokova, V. V. Belov, A. B. Serebrennikov, and Yu. N. Ponomarev, 2002: Exponential series in RT calculations by the Monte Carlo method in spatially inhomogeneous aerosol-gaseous media. *Vychislitelnye Technologie*s, **7**(5):77-87.

Fomin, B. A. and Yu. V. Gershanov, 1996: Tables of the benchmark calculations of atmospheric fluxes for ICRCCM test cases. Part II: Shortwave results. Preprint IAE 5990/1, Moscow.

Fouquart, Y., B. Bonnel and V. Ramaswamy, 1991: Intercomparing shortwave radiation codes for climate studies, *J. Geophys. Res*., 96, 8955-8968.

Golubitskii, B. M. and N. I. Moskalenko, 1968: Spectral transmission functions in the H2O vapor and CO_2 bands, *Izv. Acad. Sci. USSR Atmos. Oceanic Phys*., **3**:346-359.

Gueymard, C. A., 1995: SMARTS, A Simple Model of the Atmospheric Radiative Transfer of Sunshine: Algorithms and performance assessment. Technical Report No FSEC-PF-270-095, Cocoa, FL: Florida Solar Energy Center.

Harrison, L., M. Beauharnois, J. Berndt, P. Kiedron, J. Michalsky, and Q. Min, 1999: The Rotating Shadowband Spectroradiometers (RSS) at SGP. *Geophys. Res. Lett*., **26**:1715-1718.

Kneizys. F. X., D. S. Robertson, L. W. Abreu, P. Acharya, G. P. Anderson, L. S. Rothman, J. H. Chetwynd, J.E.A. Selby, E. P. Shetle, W. O. Gallery, A. Berk, S. A. Clough, L. S. Bernstein, 1996: The MODTRAN 2/3 report and LOWTRAN 7 model. Phillips Laboratory, Geophysics Directorate. Hanscom AFB, MA 01731-3010.

Kurucz, T. L., 1992: Synthetic infrared spectra, *Infrared Solar Physics*, *IAU Symp*. *154.* D. M. Rabin and J. T. Jefferies, eds., Kluwer, Acad., Norwell Massachusetts.

Marchuk, G. I., G. A. Mikhailov, M. A. Nazaraliev, R. A. Darbinyan, B. A. Kargin, and B. S. Elepov, 1976: *Monte-Carlo Method in Atmospheric Optics*. Novosibirsk: Nauka, Russia.

Moncet, J. L. and S. A. Clough, 1997: Accelerated monochromatic radiative transfer for scattering atmospheres: Application of a new model to spectral radiance observations. *J. Geophys. Res*., **102**:21853-21866.

O'Hirok, W., and C. Gautier, 1998: A three-dimensional radiative transfer model to investigate the solar radiation within a cloudy atmosphere. Part I: Spatial effects. *J. Atmos. Sci*., **55**:2162-2179.

O'Hirok, W., and C. Gautier, 2000: High resolution heating and cooling rates in 3-D clouds. In *Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting,* U.S. Department of Energy, Washington, D.C. Available URL: http://www.arm.gov/docs/documents/technical/conf_0003/turner-dd.pdf

Ricchiazzi, P., S. Yang, C. Gautier, and Sowle, 1998: SBDART: A research and teaching software tool for plane-parallel radiative transfer in the earth's atmosphere. *Bull. Amer. Meteor. Soc*., **79**:2101-2114.

Titov, G. A., T. B. Zhuravleva, and V. E. Zuev, 1997: Mean radiation fluxes in the near-IR spectral range: Algorithms for calculation. *J. Geophys. Res*., **102**(D2):1819-1832.

Van de Hulst, M. C., and W. M. Irvine, 1963: Scattering in model planetary atmospheres. *Meteorol. Soc. R. Sci*., **5**:78-86, Liege, Belgium.