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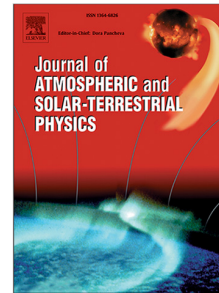
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Highlights

Calculation of Surface Spectral Irradiance using the Geant4 Monte Carlo toolkit

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- A new radiative transfer model based on the Geant4 Monte Carlo toolkit was developed.
- Calculation of spectral direct normal irradiance using Geant4 and the new reference spectrum SOLAR-ISS.
- The Geant4 simulation was validated under different atmospheric conditions.
- Geant4 quite agrees with the MYSTIC code, but it could not agree entirely with the Beer-Lambert law.
- The attenuation of solar irradiance was studied in the presence and absence of aerosols.

Calculation of Surface Spectral Irradiance using the Geant4 Monte Carlo toolkit*

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ABSTRACT

The spectral direct normal irradiance (DNI) of the surface spectral irradiance, with a spectral resolution of 1 nm in the range of 280-1600 nm, and 5 nm in the range of 1600-3000 nm, has been calculated for the first time with the Geant4 Monte Carlo simulation toolkit using the US Standard Atmosphere 1976 model and the reference extraterrestrial solar spectrum SOLAR-ISS. The atmospheric attenuation of DNI has been studied with and without aerosols. In the presence of aerosols corresponding to 10 km visibility, the total solar DNI attenuation can reach about 84% in the UV domain, 56% in the visible domain and 35.08% in the rest of the infrared domain. The Geant4 results have been compared to those calculated by the MYSTIC code of LibRadtran package and the Beer-Lambert law under the same atmospheric conditions. The average relative transmittance difference between Geant4 and MYSTIC is of the order of few percent in the entire solar spectrum. In the case of atmosphere with aerosols corresponding to 23 km visibility, the most important average of the relative difference between Geant4 and MYSTIC transmittances is about 7.5% in the UV domain and stays between 1.19% and, 3.31% in the rest of the spectrum. More importantly, in this last case of the atmosphere, the values of the spectral transmittance of Geant4 remain intermediate between those of MYSTIC and Beer-Lambert law in the entire visible range up to 800 nm.

1. Introduction

Accurate estimation of the surface solar irradiance (SSI) is of great importance in developing and operating solar energy systems and in other atmospheric science applications like weather forecasting and climatology (Sun et al., 2021; Paulescu and Paulescu, 2021; Yang, 2020; Antonanzas-Torres et al., 2019). However, SSI is very dependent on the atmosphere conditions in addition to variations due to external causes like the 11 year solar cycle, volcanic emissions and earth orbit shifts (Fligge et al., 2001). The Earth's atmosphere conditions are mainly determined by its constituents of gas molecules, water vapor, aerosols and clouds, where all of them are changing over time. The surface solar irradiance can be obtained by three different methods; ground measurements, space-borne observations from satellites and computational models (Wild et al., 2017; Huang et al., 2019; Wang et al., 2011; Paulescu et al., 2013; Zerlaut, 1983; Lu et al., 2023; Zou et al., 2016). Our present work which calculates the solar spectral irradiance at the surface of the earth by the Monte Carlo method based on a radiative transfer model falls into this last category of methods.

Computational models can be divided into two classes, the parametric and empirical models and the physical or the radiative transfer models (RTM). Parametric and empirical models use as inputs the geographical and measured meteorological parameters to model the solar irradiance data under clear-sky conditions or under clouds conditions. Among the meteorological parameters, air temperature, relative humidity, sunshine duration, cloud covers and the sun inclination are the most commonly used data in this class of models. In the presence of clouds in the atmosphere, a realistic estimate of the SSI should include their effects on solar radiation. A common approach when starting from

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a clear-sky model is to calculate the physical properties of the clouds from satellite images and integrate them in the clear sky model. In this way, many of these models attempt to extend the use of measured meteorological data at a local area to a larger area or to a region scale or even to other locations on earth using different methods like regression analysis of historical measured solar irradiance either in-situ or by satellite during an adequate period of time (Paulescu and Schlett, 2003; Almorox et al., 2021; Huang et al., 2019; Arumugham and Rajendran, 2021; Bailek et al., 2020; Antonanzas-Torres et al., 2019; Berrizbeitia et al., 2020). Parametric and empirical models are also used in general purpose applications due to their mathematical simplicity and high execution speed, in addition to the number of inputs required which is relatively small. In the production of electricity through photovoltaic or Concentrated Solar Power (CSP) systems, for example, it is also crucial to have efficient weather forecasting for short and medium time periods. That is why many existing models attempt to have this ability to predict solar irradiance according to the atmosphere conditions forecasting in order to be more efficient and reliable in solar energy applications (Razagui et al., 2021; Kumari and Toshiwal, 2021; Zambrano and Giraldo, 2020)).

The physical models or the RTM simulate radiation attenuation through different atmospheric layers. These models can take into account more details of the interaction processes of solar radiation with the atmospheric components and obtain surface spectral irradiance with high resolution. They can also easily integrate the effects of different atmospheric components, but their computational cost in computing time is much higher, and the number of inputs required can be greater than of those of parametric and empirical models. We may cite here two of the first pioneers radiative transfer models; the Leckner's spectral model which calculates direct, diffuse and global spectral solar irradiance at ground level, using the attenuating properties of the atmosphere and the extraterrestrial irradiance (Leckner, 1978), and the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS2), designed to evaluate the surface solar irradiance components in the shortwave spectrum (spectral range 280 to 4000 nm) under clear-sky conditions (Gueymard et al., 1995). Among the next generation of radiative transfer models, we may mention here the libRadtran model (Mayer and Kylling, 2005) and some other models which are based on this later model ((Mayer, 2009), (Mueller et al., 2009), (Lefevre et al., 2013)).

Currently, there are dozens of codes of models and codes based on the theory of radiative transfer which calculate the solar surface irradiance under clear-sky or clouds conditions but those which use rigorous line-by-line calculation over the whole solar radiation spectrum are very consuming of computing time and therefore inefficient in general purpose applications of solar radiation. Many radiative transfer models are now using approximations to speed up the calculations while remaining validly accurate. These approximations should in principal allow performing complex calculations over a wide spectral range efficiently and accurately. In these approximations, it is required to replace the huge number of radiation absorption and scattering coefficients of each atmosphere component by a reasonably smaller number representing globally their physical properties and also, to group the wide solar spectrum range into appropriate wavelength intervals or bands in order to reduce the number of calculations required while remaining within the context of monochromatic radiative transfer theory (Natraj, 2013; Kopparla et al., 2016; Qu et al., 2017; Lacin and Oinas, 1991; Goody et al., 1989)). This leads us to mention separately the radiative transfer codes which can do both line-by-line calculation and band calculation like (BTRAM (Chapman et al., 2009), LibRadTran (Mayer and Kylling, 2005; Bernhard et al., 2016), MODTRAN (Berk et al., 1998), LIDORT/VLIDORT, (Spurr, 2008)) from the codes that can do band calculation only like (6SV1 (Kotchenova et al., 2006), DART (Gastellu-Etchegorry et al., 1996), MSCART (Wang et al., 2017), FARMS (Xie et al., 2016), MOSART (Cornette, 2006)). We can also mention the recent broadband analytical model proposed by Rosa and Silva (2021) for estimating radiative transfer in cloudy atmospheres.

In this article, we have essentially calculated the atmospheric spectral transmission of solar radiation and its spectral irradiance at the earth surface with a spectral resolution of 1 nm in the 280-1600 nm range and 5 nm in the 1600-3000 nm range. In this calculation we have used the temperature, the pressure, and the gas composition values of the US Standard Atmosphere 1976 model (NOAA and Force, 1976). For the calculation, we have used the Monte Carlo method simulation as implemented by Geant4 toolkit (Collaboration et al., 2003, 2019 [Online]). Geant4 is a Monte Carlo simulation toolkit of the passage of particles through matter, developed and maintained by an international collaboration at the CERN. For the solar radiation spectrum at the top of the atmosphere, we have used the recent reference solar spectrum named SOLAR-ISS built by (Meffah et al., 2018, 2020) from SOLAR/SOLSPEC data (Thuillier et al., 2009; Bolsée et al., 2016). The computation of optical photon's transport in Geant4 requires the implement of the mean free paths of the radiation interaction processes of absorption and scattering in addition to the medium refractive indices and the boundary conditions for all 32 atmospheric layers (see section 3.1 for more details).

The calculation of the different photons mean free paths was based on the formulas of the absorption coefficient, the Rayleigh and the Mie Scattering coefficients, respectively in subsection 2.2.

2. Data and Methods

2.1. The atmosphere model

The atmospheric temperature, pressure and its gas composition values are taken from the US Standard Atmosphere 1976. The US Standard Atmosphere 1976 model provides the vertical profiles for the following reference atmospheres: MLS (Mid Latitude Summer), MLW (Mild Latitude Winter), SAS (Sub Arctic Summer), SAW (Sub Arctic Winter), TRL (Tropical), STS (Sub Tropical Summer), STW (Sub Tropical Winter), AS (Arctic Summer), AW (Arctic Winter). The atmospheric profiles consist of the pressure, temperature, and number densities of H_2O , CO_2 , O_3 , N_2O , CO , CH_4 , O_2 , and N_2 vs. altitude. Data were originally derived from (McClatchy et al., 1972). The atmosphere is represented by a superposition of 32 discrete layers where the two lowest layers are assumed to be filled with a mixture of gas molecules and, rural aerosols, and the rest of the upper layers are filled with gas molecules only. The most upper layer ends at an altitude of 100 km considered as the top of the atmosphere. Each atmospheric layer j is characterized by an altitude z_j , temperature T_j , pressure P_j , volume density ρ_j , constituent mass fraction f_j , etc.. The atmosphere is assumed to be tropical and the physical properties of its layers (T_j , P_j , ρ_j , f_j , etc..) are defined according to the US Standard Atmosphere 1976 model for the TRL (Tropical) reference atmosphere. The atmosphere from the bottom to the top in this model is composed of 25 layers of one kilometer thick, 5 layers of five kilometers thick, one layer of 20 kilometers thick and one layer of 30 kilometers thick. Characteristics of rural aerosols (concentration, mode radius, etc..) are defined according to (Shettle and Fenn, 1979).

2.2. Atmospheric optical properties

The optical photon transport computation in Geant4 Monte Carlo toolkit requires the implementation of both the mean free path of the scattering process and the absorption process, as well as the medium refractive indice. The absorption and scattering mean free paths for the 32 layers are defined as the inverse values of the absorption coefficient and the scattering coefficient, respectively. We have calculated these optical properties with a step interval of 1nm for the 280 to 1600 nm wavelength range and a step interval of 5 nm for the 1600 to 3000 nm wavelength range. For a given atmospheric layer, the total extinction coefficient k^j is defined by:

$$k^j = k_{gas}^j + k_{aerosols}^j \quad (1)$$

2.2.1. Gas molecules extinction coefficient

For a layer between an altitude of z_j and z_{j+1} , the gas molecules extinction coefficient can be expressed as follows (Grau, 2012):

$$k_{gas}(\lambda, z_j) = \frac{\tau_{gas}(\lambda)}{\Delta z} \left(e^{-\frac{z_j}{H_{gas}}} - e^{-\frac{z_{j+1}}{H_{gas}}} \right) \quad (2)$$

Where τ_{gas} is the total gas optical depth, H_{gas} is a gas molecules scaling factor ($H_{gas} = 8$).

The contribution of elastic scattering from gas molecules much smaller than the wavelength is given by the Rayleigh scattering coefficient (Bucholtz, 1995):

$$k_{gaz}^{diff}(\lambda, z_j) = \sigma_s N_s(z_j) 10^5 \quad (3)$$

Where N_s is the molecular number density at an altitude z_j and σ_s is the Rayleigh scattering cross-section in cm^2 given by:

$$\sigma_s(\lambda) = \frac{24\pi^3 (n_s^2 - 1)^2}{\lambda^4 N_s^2 (n_s^2 + 2)^2} F_k \quad (4)$$

$F_k = \frac{6+3\rho_n}{6-7\rho_n}$ is the king correction factor taking into account the anisotropy of air, and depends on the air depolarization factor ρ_n . n_s and N_s are the refractive index and molecular number density of air at standard condition of temperature and pressure. The values of F_k for the US Standard Atmosphere 1976 are given by (Bucholtz, 1995) for 36 wavelengths from 0.2 to 1 μm and for the rest of the wavelength range, it is assumed to be constant and equal to 1.047.

2.2.2. Aerosols extinction coefficient

Mie scattering occurs when the incident wavelength is of the same order as the aerosol size. Aerosol extinction, scattering, or absorption coefficients are defined by the (Eq. 5), where p denotes the absorption when $p = ab$, the scattering when $p = sc$, and the extinction coefficient when $p = ex$:

$$k_{aer}^p(\lambda) = \int_{r_{min}}^{r_{max}} \sigma_p(m(\lambda, r))n(r) dr \quad (5)$$

The r_{min} and r_{max} in equation (5) are the minimum and the maximum radius of the aerosol particles population. $n(r)$ is the aerosol particle size distribution function, and σ_p is the Mie process cross-section ($\sigma_p = Q_p \pi r^2$) where r is the aerosol radius.

For homogeneous uncoated spherical aerosols, the extinction efficiency Q_{ex} , the scattering efficiency Q_{sc} , as well as the absorption efficiency Q_{ab} can be calculated using the Mie theory of (Bohren and Huffman, 2008). These optical parameters are functions of the aerosol size parameter $x = \frac{\pi r}{\lambda}$ and its refractive index m .

To include the altitude dependence of aerosols absorption and scattering coefficients, we have used the so-called the normalized absorption and scattering coefficients obtained by dividing absorption and scattering coefficient by the extinction coefficient for $\lambda = 550nm$ and multiplying it by the altitude dependent aerosol concentration profile $s(z_j)$ as given by the (Eq. 6) and (Eq. 7) (Carr, 2005):

$$k_{aer}^{ab}(\lambda, z_j) = \frac{k_{aer}^{ab}(\lambda)}{k_{aer}^{ex}(550nm)} s(z_j) \quad (6)$$

$$k_{aer}^{sc}(\lambda, z_j) = \frac{k_{aer}^{sc}(\lambda)}{k_{aer}^{ex}(550nm)} s(z_j) \quad (7)$$

$$s(z_j) = s_0 \exp^{-\frac{z_j}{H_{aer}}} \quad (8)$$

With H_{aer} is the aerosol scaling factor and $s_0 = s(z_j = 0)$ is related to the surface meteorological range via the Koschmieder law (Koschmieder, 1924, 1930; Douglas and Booker, 1977).

2.3. The Solar Spectrum at the top of the atmosphere

For the solar radiation entering the atmosphere, we have used a recent reference spectrum named SOLAR-ISS obtained by (Meftah et al., 2018) from the measured data of the SOLAR/SOLSPEC instrument on board of the International Space Station (ISS). This solar spectrum covers the wavelength range 165-3000nm and has a resolution better than 0.1 nm below 1000 nm, and 1 nm in the wavelength range of 1000-3000 nm. It is also considered to be a representative spectrum of the 2008 solar minimum where no sunspot was observed during the 266 days of this year. Although the measured data have been obtained on the board of the ISS in the outer space at the distance about 400 km from the earth, the effect on the solar radiation is usually neglected before it enters the atmosphere at the 100 km altitude and can be considered as the solar spectrum at the top of the atmosphere. In order to put the SOLAR-ISS spectrum at the same spectral resolution used in our Geant4 calculations, a convolution with Gaussian slit functions has been applied using QDOAS software convolution tool as follows (Danckaert et al., 2012):

$$(SOLAR - ISS)_c = (SOLAR - ISS) * f(FWHM) \quad (9)$$

Where f is the slit Gaussian function and $FWHM$ is the Full Width at Half Maximum. The $FWHM$ is set equal to 1 nm for the wavelength range of 280-1600 nm and 5 nm for the wavelength range of 1600-3000 nm.

2.4. Methods

2.4.1. Monte Carlo simulation Geant4 toolkit

The Monte Carlo approach for atmospheric radiative transfer involves the use of probabilistic methods to simulate the transport of radiation in the atmosphere. First, a large number of photons are emitted from a source at a given position on the top of the atmosphere. On their way to the earth, these photons travel following the initial direction set by the user then they can undergo random events, namely random numbers are used to determine whether a photon is scattered or absorbed (Premuda et al., 2012).

In this work, we have used the Geant4 toolkit with the US Standard Atmosphere 1976 model with the atmospheric optical properties cited above which means: Refractive index, gas absorption mean free path, Rayleigh scattering mean free path, and Mie scattering mean free path to calculate the solar radiation spectral transmittance of the atmosphere and the spectral irradiance received at the ground with a spectral resolution of 1 nm for the wavelength range of 280-1600 nm and 5 nm for the wavelength range of 1600-3000 nm. For the solar radiation input at the top of the atmosphere, we have used the reference spectrum SOLAR-ISS.

Geant4 is a Monte Carlo simulation toolkit of the passage of particles through matter, developed and maintained by an international collaboration at the CERN. All the interaction processes of solar radiation with the atmosphere are being treated with this code (Collaboration, 2019; Collaboration et al., 2016). In addition to the medium refractive indices and the boundary conditions for all 32 atmosphere layers, the computation of optical photon's transport in Geant4 requires the implementation of the mean free paths of the interaction processes of the absorption and the scattering. The calculation of the different photons mean free paths was based on the formulas of the absorption coefficient, the Rayleigh and the Mie Scattering coefficients, presented in the previous subsection 2.2. The absorption and scattering mean free paths are defined as the inverse values of the absorption coefficient and the scattering coefficient, respectively.

2.4.2. Comparison with other methods

For a comparison purpose of our result obtained by Geant4 with other results, we have calculated the solar radiation transmittance of the atmosphere and the solar spectrum at the ground under the same atmospheric model and conditions using two (2) models, namely, Beer-Lambert law model and the MYSTIC Monte Carlo code model.

Beer-Lambert Law

Despite its simplicity, till now the Beer-Lambert law stills widely used in some important applications such as the ER-2 NOAA Dual-Beam UV Absorption Ozone Photometer to estimate the ozone number density in the sample chamber described by (Gao et al., 2012). According to Beer-Lambert law, the direct irradiance is given by:

$$IR_d = (SOLAR - ISS)_c e^{-\tau_r AM} d_c \quad (10)$$

Where τ_r is the total atmospheric optical depth defined as the sum of gas and the aerosols optical depth where ($AM = \frac{1}{\cos(\theta_{zenith})}$), and d_c is the distance correction factor.

The Angstrom approach was used to estimate the optical depths of aerosols as given by Eq.11 (Ångström, 1930) :

$$\tau_a = \beta \left(\frac{\lambda}{\lambda_0} \right)^\alpha \quad (11)$$

Where $\lambda_0 = 1\mu m$, β is the Angstrom coefficient (turbidity parameter), and α is the exponent coefficient. The corresponding Angstrom coefficient to each meteorological range *Vis* value that has been obtained using the formula here below (Iqbal, 2012):

$$\beta = 0.55^\alpha \left(\frac{3.916}{Vis} - 0.01162 \right) [0.002472(Vis - 5) + 1.132] \quad (12)$$

MYSTIC

MYSTIC stands for Monte Carlo code for the physically correct Tracing In Cloudy Atmospheres, MYSTIC is a radiative transfer code developed by the Institute of Atmospheric Physics of the German Aerospace Center. A free version is available at the official Libradtran website (Mayer and Kylling, 2005).

3. Results and discussion

In the calculation of the transmittance of solar radiation of the earth atmosphere by Geant4, we have used the Monte Carlo simulation method to follow the track of each photon from its entrance to the atmosphere to the surface of the earth using the 32 atmospheric layers model and their optical properties presented in the previous section. MYSTIC is also a Monte Carlo code which traces photons on their individual random paths through the atmosphere. In the calculation of the atmospheric transmittance by Beer-Lambert law, we have used the total atmospheric optical depth for a normal incidence of solar radiation. The spectral transmittance of the atmosphere has been calculated by these three methods for the same atmosphere model and the same input parameters. The spectral transmittance of the atmosphere is defined as:

$$T(\lambda) = \frac{N_g(\lambda)}{N_0(\lambda)} \quad (13)$$

Where N_0 is the number of photons with a wavelength λ entering normally the top of the atmosphere or the number of Monte Carlo simulations for a given wavelength. In our calculation of the spectral transmittance of solar radiation we have chosen N_0 to be 10^7 . In order to verify that this number of simulations is sufficient to have good and reproducible results, we have considered $N_0 = 10^9$ in some small intervals of light wavelength just to check that the spectral transmittance results within these intervals did not change. N_g is the number of photons having a wavelength λ and reaching the ground after their passage through all the 32 atmosphere layers. In the case of the Beer-Lambert law, for $\theta_{zenith} = 0$, the spectral transmittance is defined as follows:

$$T(\lambda) = e^{-\tau_t(\lambda)} \quad (14)$$

τ_t is the total atmospheric optical depth for a normal incidence of solar radiation at the top of the atmosphere.

3.1. Geant4 Simulation Results

3.1.1. The spectral transmittance of the atmosphere

The spectral transmittance of the atmosphere as defined by equation (13) has been calculated by the Geant4 code for an atmosphere supposed to be without aerosols and an atmosphere having aerosols. Fig. 1 shows the calculated spectral transmittance of the atmosphere without aerosols and with aerosols for two different visibilities. The spectral resolution has been taken to be 1 nm over the 280 -1600 nm range and, 5 nm over the 1600 -3000 nm range.

The absorption bands shown in Fig. 1 are due to the molecules of the gases constituting the atmosphere which are well known (Rothman et al., 2009, 1987). Oxygen molecules have their most prominent bands in the visible spectrum at 761 nm, and most of the important absorption bands are located in the infrared and UV as shown also in Table 1

Table 1

Absorption bands and picks of the atmosphere without aerosols.

Gases	Absorption Bands/picks
O_3	283 – 302 nm
O_2	761 nm
H_2O	810 – 840 nm, 715 – 740 nm, 890 – 1000 nm, 1100 – 1200 nm, 1300 – 1500 nm, 1750 – 2000 nm, 2200 – 3000 nm
CO_2	1900 – 2100 nm, 2700 – 2900 nm
CH_4	2100 – 2450 nm, 1600 – 1750 nm

3.1.2. Spectral irradiances and total irradiance at the ground

The spectral irradiance at the ground is given by the product of the reference spectral irradiance at the top of the atmosphere multiplied by the spectral transmittance given by the (Eq. 13)

$$I_g(\lambda) = (SOLAR - ISS)_c(\lambda)T(\lambda) \quad (15)$$

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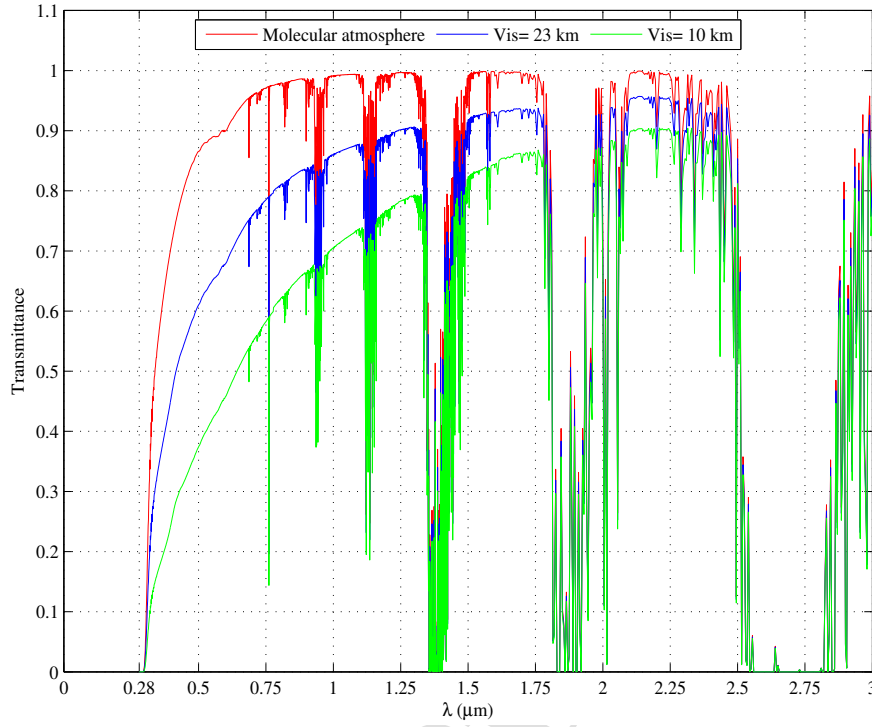


Figure 1: The spectral transmittances of the atmosphere for molecular gas only and for the mixture of gasses and aerosols for 23 km visibility (Vis=visibility) and 10 km visibility obtained by Geant4.

Fig. 2 shows the reference solar spectral irradiance ($SOLAR - ISS$)_c(λ) at the top of the atmosphere and the direct normal irradiances received at the ground calculated by Geant4, in the cases of an atmosphere without aerosols and in the presence of aerosols for atmosphere visibilities 23 km, the most common experienced visibility for clear days, and 10 km as an important indicator of haze (Fu et al., 2018).

As expected, the presence of aerosols causes an important attenuation in the spectral irradiance as shown in Fig. 2, Table 2, and Table 3. This attenuation is generally more important in the UV and the visible compared to the infrared. It can be more severe when the meteorological conditions cause an increase in the concentration of aerosols in the atmosphere.

The total irradiance in a given wavelength range of $\Delta[\lambda_{min}, \lambda_{max}]$ is the sum of the spectral irradiance for each wavelength λ_i within this wavelength range, so the total reference solar irradiance in a given wavelength range $\Delta\lambda$ can be expressed as follows:

$$I_{TSR\Delta\lambda} = \sum_{\lambda_i}^{\Delta\lambda} I_{SR}(\lambda_i) \quad (16)$$

and the total solar irradiance at the ground in the range of $\Delta\lambda$ is given by (Eq.18)

$$I_{Tg\Delta\lambda} = \sum_{\lambda_i}^{\Delta\lambda} I_g(\lambda_i) \quad (17)$$

The percentage of the attenuation of the solar irradiance by the atmosphere in a wavelength range of $\Delta[\lambda_{min}, \lambda_{max}]$ can be also calculated by the following equation:

$$Att_{\Delta\lambda} = \frac{I_{TSR\Delta\lambda} - I_{Tg\Delta\lambda}}{I_{TSR\Delta\lambda}} \times 100\% \quad (18)$$

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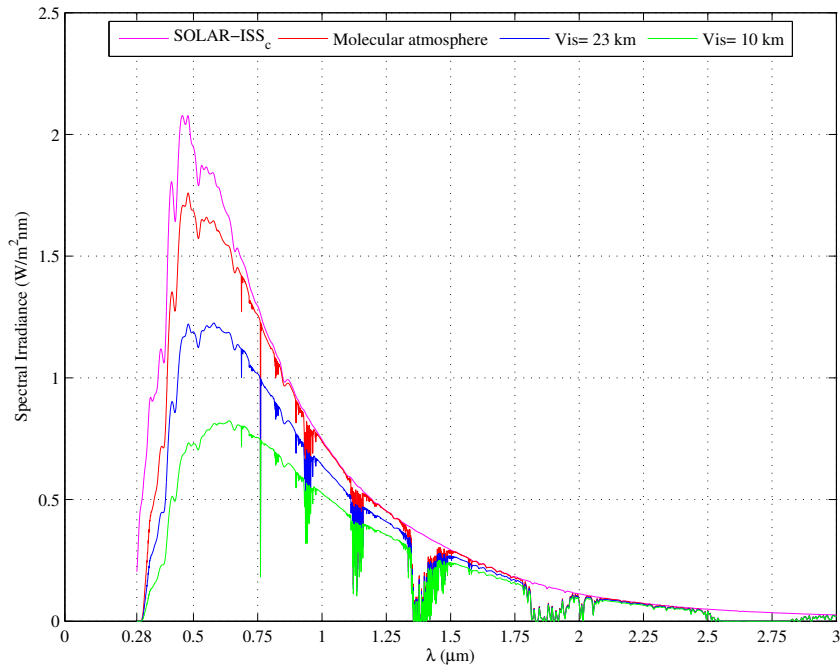


Figure 2: The reference solar spectral irradiance ($SOLAR-ISS_c$) at the top of the atmosphere and the calculated spectral irradiance at the ground by Geant4 for aerosol-free atmosphere and in the presence of aerosols at 23 km and 10 km visibility.

Table 2

Total irradiance calculated for different domains of the solar spectrum.

Range $\Delta\lambda$ (nm)	Reference total irradiance (Wm^{-2})	Ground total irradiance without aerosols (Wm^{-2})	Ground total total irradiance Vis = 23 km (Wm^{-2})	Ground total irradiance Vis = 10 km (Wm^{-2})
UV 280 – 400 nm	100.737	49.921	30.861	15.761
VIS 400 – 800 nm	663.804	590.101	439.642	293.260
IR 800 – 3000 nm	573.923	492.927	438.017	372.579
280 – 3000 nm	1338.466	1132.951	908.522	681.601

Table 3 shows the percentage of the attenuation of the total irradiance by the atmosphere without and with aerosols in the spectral domains of UV, VIS, and IR and in the entire range of our reference spectrum.

Table 3

Percentage of attenuation of solar radiation by the three different atmosphere cases.

Range $\Delta\lambda$ (nm)	$Att_{\Delta\lambda}$ atmosphere without aerosols	$Att_{\Delta\lambda}$ atmosphere with aerosols Vis= 23 km	$Att_{\Delta\lambda}$ atmosphere with aerosols Vis= 10 km
UV 280 – 400 nm	50.44 %	69.36 %	84.35 %
VIS 400 – 800 nm	11.10 %	33.76 %	55.82 %
IR 800 – 3000 nm	14.11 %	23.68 %	35.08 %
280 – 3000 nm	15.36 %	32.12 %	49.08 %

3.2. Comparison of results

In the following of this section, we will compare the results obtained by Geant4 with those obtained by MYSTIC code and Beer-Lambert law with the same atmospheric conditions and the same input parameters. We will limit ourselves to the comparison between the three obtained spectral transmittances which are presented in Fig. 3, Fig. 4 and Fig. 5, in an atmosphere without aerosols and with aerosols for 23 km and 10 km visibility, respectively.

The average of the relative difference (ARD) between the transmittances of the Geant4 and MYSTIC codes in a given wavelength range can be written as:

$$\bar{\Delta T}_{G4-M} = \frac{1}{n_\lambda} \sum_i^{n_\lambda} \frac{T_{G4}(\lambda_i) - T_M(\lambda_i)}{T_{G4}(\lambda_i)} \quad (19)$$

and (ARD) between transmittances of Geant4 code and Beer-Lambert law can also be written as:

$$\bar{\Delta T}_{G4-BL} = \frac{1}{n_\lambda} \sum_i^{n_\lambda} \frac{T_{G4}(\lambda_i) - T_{BL}(\lambda_i)}{T_{G4}(\lambda_i)} \quad (20)$$

Where n_λ is the number of wavelengths and λ_i is in the considered spectrum range.

Table 4

Average of the relative difference between the spectral transmittance obtained by Geant4 code, by the MYSTIC code and Beer-Lambert law.

Range $\Delta\lambda$ (nm)	atmosphere without aerosols		atmosphere with aerosols Vis= 23 km		atmosphere with aerosols Vis= 10 km	
	$\bar{\Delta T}_{G4-M}$ (%)	$\bar{\Delta T}_{G4-BL}$ (%)	$\bar{\Delta T}_{G4-M}$ (%)	$\bar{\Delta T}_{G4-BL}$ (%)	$\bar{\Delta T}_{G4-M}$ (%)	$\bar{\Delta T}_{G4-BL}$ (%)
UV 280 – 400 nm	5.02	3.71	7.48	0.28	0.27	-34.94
VIS 400 – 800 nm	0.81	0.76	3.31	-3.24	-0.57	-28.56
IR 800 – 3000 nm	0.59	0.24	1.19	0.41	0.63	-5.68

Fig.3, Fig. 4 and Fig. 5 show the spectral atmospheric transmittance obtained by Geant4, MYSTIC and Beer-Lambert law for the three studied cases as functions of small wavelength intervals. For the purpose of qualitative visual comparison only, Table 4 shows the average of the relative differences between the spectral transmittance obtained by Geant4 and MYSTIC (ΔT_{G4-M}); Geant4 and Beer-Lambert law (ΔT_{G4-BL}) in the UV, visible and infrared domains, respectively, for the three studied atmospheric cases. The average of the relative difference between the spectral transmittance T_{G4} obtained by Geant4 code and that transmittances T_M and T_{BL} of MYSTIC code and Beer-Lambert law, respectively are presented in Table.4 calculated by equations (19) and (20).

As shown in Fig. 3, in the case of an atmosphere without aerosols, the results obtained by these three models are almost the same except for 300 – 500 nm range where MYSTIC spectral transmittance is slightly lower than that of Geant4; as shown in Table 4, over the UV band, the average relative difference between Geant4 and MYSTIC code is about 5.02%. Whereas the difference between Geant4 and Beer-Lambert law is about 3.71%. For the rest of the spectral domain the average relative difference between Geant4 and the two models does not exceed 1%. As shown in Fig. 4 and Fig. 5, in the presence of aerosols in the atmosphere, the difference between Geant4 and MYSTIC, Geant4 and Beer-Lambert law transmittances become a little more important. These differences spread over the UV and VIS domains, and partially on the IR domain. They do not always have the same sign; They are sometimes either positive or negative.

For 23 km visibility, the most important average relative difference is between Geant4 and MYSTIC transmittance which is about 7.5% and 3% in the UV and in the visible domain, respectively. Between Geant4 and Beer-Lambert law, the most important difference is -3% in the VIS domain whereas it is less than 1% elsewhere. One can notice that the transmittance obtained by the Geant4 code has its values intermediaries between those obtained by MYSTIC and Beer-Lambert especially in the visible range. For the visibility of 10 km, the average relative difference

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between Geant4 and MYSTIC is negligible over all the solar radiation range, in contrast to the results obtained by Geant4 and Beer-Lambert law which is about -35% for the UV domain, -29% for the visible domain and -5.6% for the infrared domain. This important difference is due to the limitation of validity of Beer-Lambert law for high aerosols concentrations in the atmosphere.

4. Conclusion

In this work we have calculated the atmosphere spectral transmission of the solar radiation at the earth surface using the Geant4 Monte Carlo simulation toolkit, the reference spectrum SOLAR-ISS and the US Standard Atmosphere 1976 model. This atmospheric spectral transmission is obtained in three cases; in an atmosphere without aerosols and in an atmosphere with aerosols at 23 km and 10 km visibility. The main results can be summarized as follows:

- The direct normal irradiance received at the ground with a spectral resolution of 1 nm in the range of 280 to 1600 nm and 5 nm in the range of 1600 to 3000 nm.
- The total direct normal irradiance in the three spectral domains of solar radiation which are the ultraviolet (UV), the visible (VIS) and the infrared (IR).
- The percentage of the attenuation of the solar irradiance by the three cases of the atmosphere, and over the three spectral domains UV, VIS and IR.

The simulation results show that there is a strong attenuation of the UV irradiance in the presence of aerosols which can reach 84% for the visibility of 10 km as compared to IR irradiance which is about 35.08%.

In the absence of aerosols, the mean relative transmittance differences between Geant4 and MYSTIC, and between those of Geant4 and Beer-Lambert are of the order of a few percent in the UV, while in the VIS and IR domains they are less than 1%.

For the visibility of 23 km, the most important average of the relative differences is that between Geant4 and MYSTIC transmittances in the UV domain which is about 7.5%, and 3% in the visible, and about 1% in the infrared. Between Geant4 and Beer-Lambert law this difference is about -3% in the visible and less than 1% elsewhere. For the visibility of 10 km the average relative difference of the transmittances between Geant4 and MYSTIC is less than 1% over all the solar radiation spectrum range. However, between Geant4 and Beer-Lambert law, this difference is about -35% in the UV domain, -29% in the visible domain, and -5.6% for the infrared domain. These important differences were expected and are explained by the known limitation of validity of the Beer-Lambert law for high aerosols concentrations. In these two cases of visibilities, the values of the transmittance of Geant4 remain intermediate between those of MYSTIC and Beer-Lambert law in the visible range.

To conclude, for a clear sky and in the case of atmosphere without or with aerosols, the spectral irradiance obtained by Geant4 is slightly higher than that obtained by MYSTIC code. Their maximal difference is about 7.5% in the UV and 3% in the visible, respectively. The difference between Geant4 and Beer-Lambert law is only a few percent for an atmosphere without or with small concentrations of aerosols but it can increase drastically with the increase of aerosol concentrations in the atmosphere, especially in the UV and the visible domains.

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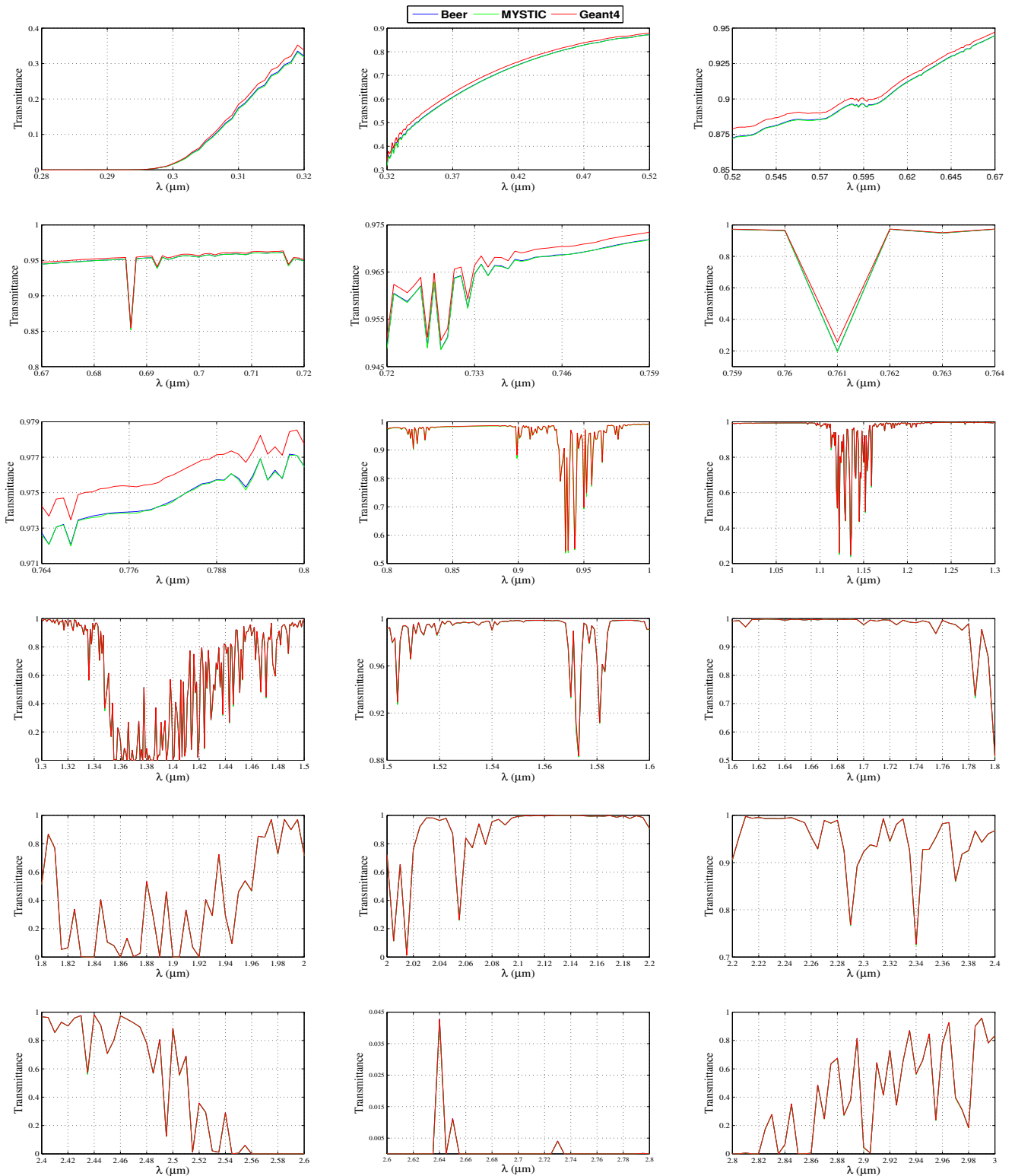


Figure 3: Comparison between the spectral atmospheric transmittance for atmosphere without aerosols, calculated by Geant4, MYSTIC and Beer-Lambert law.

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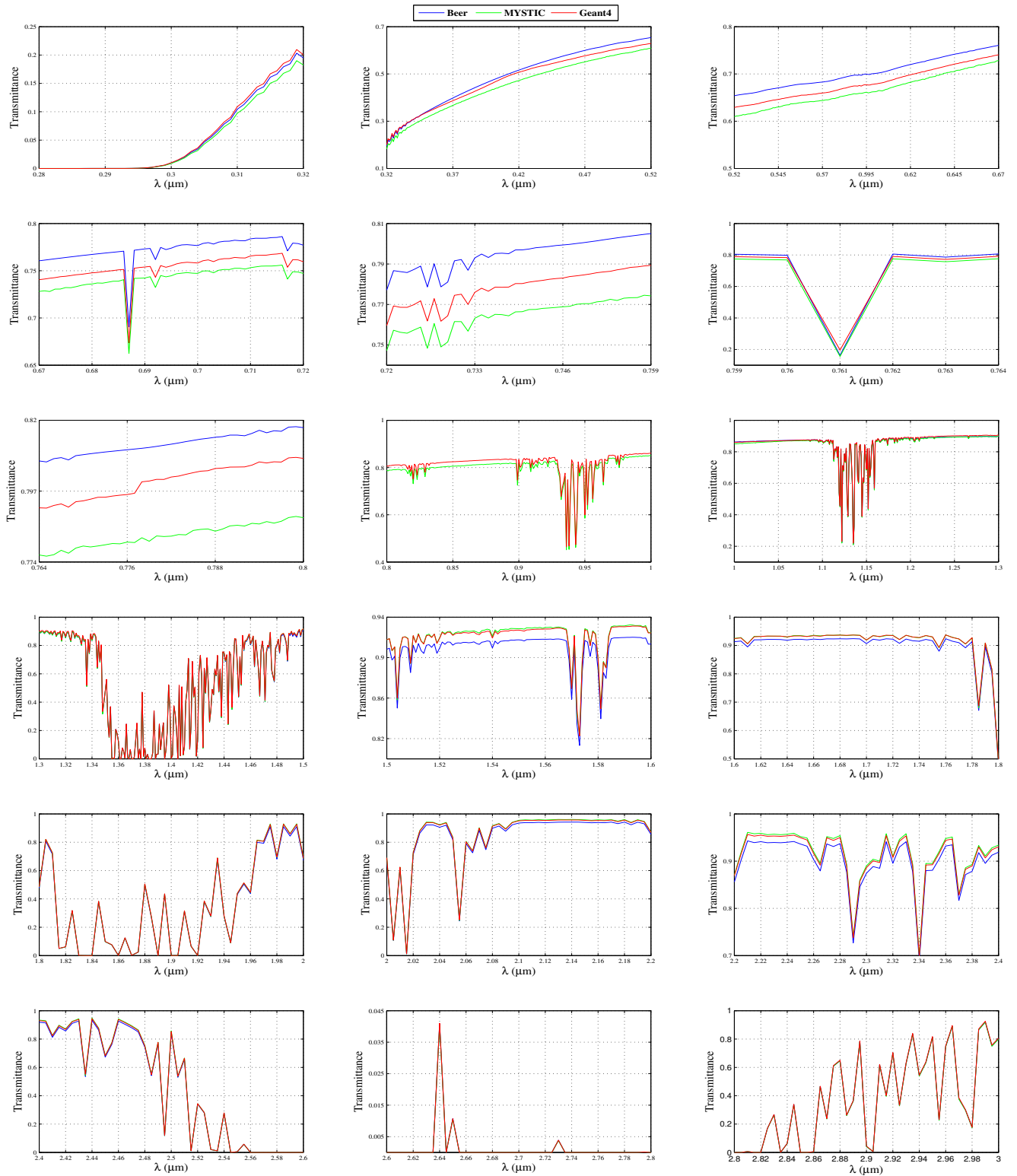


Figure 4: Comparison between the spectral transmittances of the atmosphere in the presence of aerosols with a visibility of 23 km calculated by Geant4, MYSTIC and Beer-Lambert law respectively.

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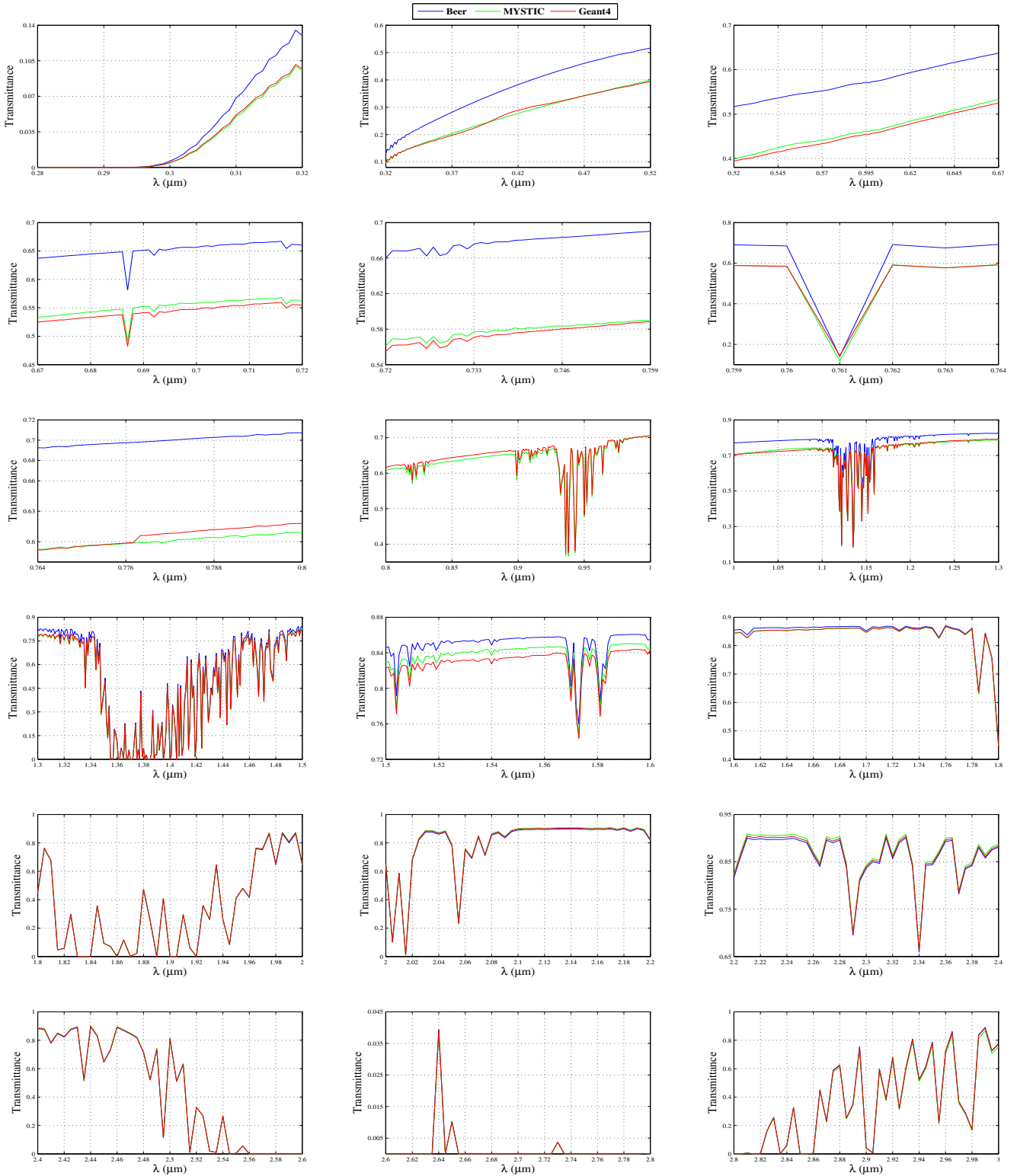


Figure 5: Comparison between the spectral transmittances of the atmosphere in the presence of aerosols with a visibility of 10 km calculated by G4, MYSTIC and Beer-Lambert law.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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