A Fast Two-Stream-Like Multiple-Scattering Method for Atmospheric Characterization and Radiative Transfer

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ABSTRACT

Multiple-scattering effects can significantly impact radiative transfer calculations for remote sensing and directed-energy applications. This study describes the development and implementation of a fast-calculating two-stream-like multiple-scattering algorithm that captures azimuthal and elevation variations into the Air Force Institute of Technology Center for Directed Energy’s Laser Environmental Effects Definition and Reference (LEEDR) atmospheric characterization and radiative transfer code. LEEDR is a fast-calculating, first-principles, worldwide surface-to-100-km, atmospheric characterization package for the creation of vertical profiles of temperature, pressure, water vapor content, optical turbulence, atmospheric particulates, and hydrometeors as they relate to line-by-line layer transmission and radiance from the ultraviolet to radio frequencies. The newly implemented multiple-scattering algorithm fully solves for molecular, aerosol, cloud, and precipitation single-scatter layer effects with a Mie algorithm at every atmospheric layer. A unique set of asymmetry and backscattering phase-function parameter calculations accounts for radiance loss due to the molecular and aerosol constituent reflectivity within a layer and accurately characterize diffuse layers that contribute to multiple-scattered radiances in inhomogeneous atmospheres. LEEDR is valid for spectral bands between 200-nm and radio wavelengths. Accuracy is demonstrated by comparing LEEDR results with published sky radiance observations and experimental data. Determining accurate aerosol loading via an iterative visibility/particle-count calculation method is ultimately essential to achieve agreement between observations and model results for realistic atmospheres.

1. Introduction

Atmospheric effects are critical for simulating the performance of sensor systems in operational conditions. The Air Force Institute of Technology’s Center for Directed Energy (AFIT/CDE) High Energy Laser End-to-End Operational Simulation is perhaps the first directed-energy weapon (DEW) simulation package to fully incorporate a correlated, probabilistic climatological database (Fiorino et al. 2005). The necessity for realistic, accurate, and correlated vertical profiles extends far beyond DEW given that one of the primary factors affecting the analysis and processing of remote sensing multi-, hyper-, and ultra-spectral sensor data is the wavelength-dependent total atmospheric effect on the particular parts of the spectrum considered, with scattering in optically thick media presenting one of the greatest challenges. Corrections for these effects require detailed knowledge of atmospheric variability, which in
turn requires an expanded environmental database beyond the typical deterministic or “standard” atmospheric type data utilized by many modern radiative transfer models. Thus, AFIT/CDE has produced an atmospheric effects definition and reference, the Laser Environmental Effects Definition and Reference (LEEDR; Fiorino et al. 2008b), that allows the export of the first-principles atmospheric characterizations. LEEDR contains both an internally consistent line-by-line and correlated-\( k \) distribution radiative transfer algorithm capable of assessing path transmittance, path radiance, and celestial contributions to an observed signal level in true three-dimensional (3D) geometry on a spherical Earth with any relationship between the target and observer.

To accurately analyze the radiative transfer process through a realistic vertical atmospheric profile, multiple-scattering (MS) effects on radiance calculations must be considered. Single-scattering (SS) theory provides a computationally simple method for incorporating an approximate solution. However, the method is not robust in scenarios where scattering dominates and subsequent results compare well to measurements only in a narrow set of circumstances. Many radiative transfer codes operate under this simplifying assumption as scattering is either unimportant in the spectral domain of interest or not relevant to the particular application. Others employ various MS algorithms with varying degrees of complexity and accuracy. Two of the most widely used methods for incorporating MS effects are the two-stream approximation and the Discrete Ordinate Radiative Transfer model (DISORT; Stamnes et al. 1988). DISORT is a stand-alone Fortran module that accurately solves the radiative transfer equation in a vertically inhomogeneous plane-parallel atmosphere and has been incorporated into numerous radiative transfer codes as a separate module called upon for MS calculations. The two-stream approximation is a discrete ordinate method with the simplifying assumption that radiation only travels in two discrete directions or streams. This assumption significantly reduces the complexity and computational cost at the expense of directional accuracy and is found in various forms with varying simplifying assumptions.

This paper seeks to describe the development of an integrated internal LEEDR algorithm for fast-calculating two-stream-like MS that captures azimuthal and elevation variation and provides accurate results with minimal computational expense. The technique presented herein is unique as it calculates MS effects with a quasi-cumulative diffusivity method that considers the initial solar radiance contribution. A brief description of the LEEDR code and calculations are presented in section 2. The SS algorithm inherent to LEEDR is discussed in section 3, and the two-stream-like MS algorithm addition is described in section 4. Multiple-scattering results from LEEDR in comparison with various published sky radiance observations and experimental data for both up- and down-looking scenarios while accounting for atmospheric conditions with LEEDR’s unique atmospheric characterization features are presented in section 5. A brief summary of the findings and future research directions are given in section 6.

2. LEEDR description and calculations

LEEDR is a verified and validated, fast-calculating, first-principles atmospheric characterization package (Hall et al. 2016). It enables the creation of vertical profiles of temperature, pressure, water vapor content, optical turbulence, and atmospheric particulates and some hydrometeors as they relate to line-by-line layer extinction coefficient magnitude at any wavelength from the ultraviolet to radio frequencies. In addition to its broad spectrum of consideration, LEEDR uniquely allows for a temporally and spatially varying atmospheric boundary layer through the use of its correlated, probabilistic thermodynamic databases in the production of its vertical profiles of data. This allows LEEDR to produce profiles of meteorological data and effects that could actually occur or have actually occurred at particular locations and time periods, and attach a statistical likelihood of such occurrences. This differs significantly from using “standard” atmospheric profiles (e.g., U.S. Standard Atmosphere, 1976; COESA 1976) in engineering analyses or simulations (Fiorino et al. 2008b). Additionally, a National Oceanic and Atmospheric Administration (NOAA) Operational Model Archive Distribution System (NOMADS) data feed has been incorporated to supply gridded observations or real-time, correlated weather forecasts (out to 180 h) for use in profile generation (Fiorino et al. 2014). This technique has been shown to significantly increase the predictive performance of LEEDR when coupled with surface observations (Shirey 2016).

In general, LEEDR defines the well-mixed atmospheric boundary layer with a worldwide, probabilistic surface climatology (when more accurate definition via direct observations and/or numerical weather modeling is not available) based on season and time of day, and then computes the radiative transfer and propagation effects from the vertical profile of meteorological variables. Worldwide seasonal, diurnal, and geographical spatial–temporal variations in meteorological parameters in LEEDR are organized into databases of probability density function through the use of multiple climatological databases, including the Extreme and Percentile Environmental Reference Tables (ExPERT; Squires et al. 1995) database, the Master Database for
Optical Turbulence Research in Support of the Airborne Laser (Bussey et al. 2000), and the Global Aerosol Dataset (Koepke et al. 1997). This results in a model capable of defining atmospheric conditions at any user-defined wavelength from 0.2 μm to 8.6 μm for any location from the surface to any user-specified altitude. Within the boundary layer, atmospheric conditions are characterized through a novel approach utilizing the ExPERT climatological surface conditions for the selected site or by user-defined surface data input through the “ground level” tab and fast-calculating dry and moist adiabatic relationships. Above the boundary layer, six upper-air regions—polar north, midlatitude north, tropical, desert, midlatitude south, and polar south—are used to characterize meteorological parameters when numerical weather prediction (NWP) data are not accessed with the NOMADS input tool. The U.S. Standard Atmosphere, 1976 is also available for selection (Fiorino et al. 2008b).

For the 573 land surface sites available from ExPERT in LEEDR the user can select 1 of 9 relative humidity (RH) percentile conditions (ranging from 1st to 99th percentiles) to model, with the default being 50th percentile conditions. The time of day can be selected as a 24-h average, as well as eight 3-h local time (LT) blocks throughout the diurnal cycle for both summer and winter seasons. When ocean sites are selected, regional data are utilized. If a 3-h time block is selected, the height of the top of the atmospheric boundary layer is dynamically adjusted as indicated in Table 1. The 573 land sites and upper-atmosphere regions are depicted in Fiorino et al. (2014).

LEEDR uses RH as the key parameter for correlation between atmospheric parameters as it is critically important in the growth and scattering effects of aerosols. When coupled with temperature, it yields correlated values of all other moisture parameters. LEEDR’s atmospheric databases and probabilistic correlation method have been extensively described in earlier publications (Fiorino et al. 2005, 2008a, 2014).

An important consequence of employing adiabatic lapse rates is that the RH varies dramatically within the boundary layer, usually increasing from the surface to approximately 100% near the top of the boundary layer. This has a very strong effect on the aerosol size distribution—because of the RH-driven water uptake by water soluble aerosols—that in turn strongly affects the vertical extinction structure through the boundary layer, primarily because of scattering at wavelengths less than 2 μm. This effect is not captured when modeling with standard atmospheric data as the moisture (dewpoint) does not lapse realistically in standard atmospheres. Thus, RH does not necessarily increase with height in a standard atmosphere boundary layer. This is illustrated in Fig. 1, which graphically depicts absorption and scattering of 355-nm radiation between the surface and 4000 m for U.S. Standard Atmosphere, 1976 conditions with constant aerosol concentration through the lowest 1250 m and the LEEDR representation of an observed Dayton, Ohio, summer atmosphere at 1400 eastern daylight time 25 Jul 13 are shown with solid lines (Fiorino et al. 2015).

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### Table 1. Overland boundary layer height (m) as a function of season and local time of day.

<table>
<thead>
<tr>
<th>Time of day (local)</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000–0259</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>0300–0559</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>0600–0859</td>
<td>1000</td>
<td>500</td>
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<tr>
<td>0900–1159</td>
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<td>1200–1459</td>
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</tr>
<tr>
<td>1800–2059</td>
<td>1524</td>
<td>1000</td>
</tr>
<tr>
<td>2100–2359</td>
<td>1000</td>
<td>500</td>
</tr>
</tbody>
</table>

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**FIG. 1.** Absorption and scattering effects modeled by LEEDR compared with Raman lidar profile data points shown in blue. The 355-nm radiation extinction profiles from 4000-m altitude to the surface in a U.S. Standard Atmosphere, 1976 where the boundary layer is only defined with a constant aerosol concentration through the lowest 1250 m are shown by dashed lines. LEEDR-modeled absorption and scattering effects for the same vertical path and boundary layer aerosol concentration but applying an observed Dayton, Ohio, summer atmosphere at 1400 eastern daylight time 25 Jul 13 are shown with solid lines (Fiorino et al. 2015).
Coupling the boundary layer effects on atmospheric particulates (aerosols and hydrometeors) is accomplished internally within LEEDR. Molecular absorption calculations are made by combining line strength data from the high-resolution transmission (HITRAN) 2008 database with temperature, dewpoint, and pressure vertical profiles derived from ExPERT for the top 13 atmospheric constituents. LEEDR treats both Rayleigh scatter for atmospheric molecules as well as aerosol scattering via Mie scattering theory and returns Mie extinction, scattering, and absorption efficiencies via the Wiscombe Mie scattering module (Wiscombe 1980).

To model the aerosol distribution appropriately, a lognormal size distribution of the form

\[ \frac{dN(r)}{d(\log r)} = \frac{N}{(2\pi)^{1/2}(\sigma)^2} \exp \left[ -\frac{(\log r - \log r_M)^2}{2(\log \sigma)^2} \right] \]  (1)

is utilized for the aerosol type defined for a particular scenario, location, altitude, season, and RH. The quantity \( N \) is the total particle number density per unit volume and is normalized to 1. The \( r_M \) value is the modal (or median) radius, and \( \sigma \) is the standard deviation for the aerosol species. The wavelength-specific normalized extinction, scattering, and absorption coefficients \( \beta_{e,s,a}(\lambda) \) or cross sections \( \sigma_{e,s,a}(\lambda) \), are obtained by integrating over the range of radii (not shown). For moist aerosol calculations, one must consider that humidity causes aerosol particle growth, even at RH values far below saturation. This is handled by allowing the modal radius and the refractive index for each aerosol species to vary with RH, solving for the number density using the dry modal radius and standard deviation, and then solving Eq. (1) for the humidity-altered radius value \( r(a_w) \) using the humidity-altered modal radius. Noting that the complex index of refraction changes with humidity, the Wiscombe Mie scattering module is reinvoked with the humidity-altered parameters.

Hydrometeors in LEEDR currently include raindrops, drizzle drops, cloud droplets, ice spheres (ice fog), and ice crystals (cirrus clouds). These hydrometeors are distributed with type specific distributions and assumed to be spheres with the exception of cirrus ice crystals, which are considered hexagonal columns. The Wiscombe Mie scattering module is applied in the same manner as for aerosols. Further details on the humidity-altered aerosol and hydrometeor size distributions can be found in previously published work (Fiorino et al. 2005, 2014).

### 3. LEEDR’s single-scattering algorithm

The SS assumption is possibly one of the simplest scattering approximations used in modern radiative transfer models. The underlying assumption stipulates that only the first scattering event is accounted for or tracked in the solution. If the scatter event is directed along the line of sight of the observer, then it contributes to the final radiance calculation; if not, that event and all subsequent scatters of the photon are ignored. This approximation is only valid in optically thin media where very few scattering interactions are expected to occur or where even small deviations from the initial vector are sufficient to prevent scattering effects as could occur with scattering heavily weighted close to the source. Since the number of influential scatters is capped at one, any medium with a small mean path is poorly simulated. Thus, it is inappropriate for most terrestrial applications in the shortwave regime; however, in certain regions of the longwave regime, the results often prove useful because of relatively weak scattering. Despite these limitations, SS often forms the basis for MS algorithms as much of the necessary physics is captured in the single-scatter parameter and resulting phase function, and the results prove useful for further calculations.

Radiance in or along an observation path comes primarily from two sources: surface and atmospheric emissions in the infrared and scattered ultraviolet to near-infrared energy from the sun or other celestial objects. Emissions from the sky and the surface are often referred to as the thermal or longwave component of path radiance, respectively, and the solar radiation is typically called the shortwave component. Both components are reflected and/or scattered by Earth’s surface and by atmospheric particulates such as aerosols, water and ice cloud particles, and precipitation. Rayleigh scattering caused by air molecules is significant at shorter wavelengths (<1 \( \mu \)m) and is an important consideration for solar scattering and laser propagation. LEEDR models the single-scattered solar radiation by accounting for the top-of-the-atmosphere solar spectrum, the curvature of Earth, and geometry-specific distribution scattering phase functions based on Rayleigh and Mie theory. Figure 2 is a schematic description of the radiative transfer geometry for LEEDR, simplified for demonstration purposes to a plane-parallel atmosphere. In reality, LEEDR employs a spherical shell model that accounts for Earth’s curvature and shell clouds/overcast conditions. Each computational point is located in the appropriate shell and straight line geometry is employed as defined by the appropriate atmospheric conditions. Refractive bending is available within LEEDR but not discussed in this context. The atmosphere is broken into \( n \) number of layers from the surface to the 100 km top of the atmosphere. All calculations are performed for each layer, and all nonvertical pathlengths are accounted for before integrating (summing) over pathlengths. Earth’s
surface is considered to be a separate source layer: an emitter in the longwave and a scatterer-reflector in the shortwave (Fiorino et al. 2016).

Direct path transmittance \( t \) refers to the radiation that is directly transmitted without scattering and is calculated monochromatically via Beer’s law. For the plane-parallel assumption this is expressed as a function of optical depth, \( t(\tau) = e^{-\tau |\cos \theta|} \), (2)

where \( \tau \) is the optical depth (unitless), \( \theta \) is the source angle of incidence upon a parallel plane, \( z \) is the geometric height (m), and \( \beta(z) \) is the layer volume extinction coefficient (sum of absorption and scattering) in dimensions of inverse length (m\(^{-1}\) or cm\(^{-1}\)) as shown in Eq. (3) (Fiorino et al. 2016):

\[
\tau(z_1, z_2) = \int_{z_1}^{z_2} \beta(z) \, dz.
\]

Total SS spectral path radiance (W cm\(^{-2}\) sr\(^{-1}\) \( \mu \)m\(^{-1}\)) is calculated in a manner similar to the scheme implemented in MODTRAN (Acharya et al. 1999; Cusumano et al. 2011). LEEDR first defines the atmosphere in a user-specified number of layer slabs \( n \) based on the vertical profile conditions for the site, time of season, time of day, surface visibility, and boundary layer height of interest. The path radiance contribution of a slab \( (\Delta L) \) with lower and upper boundaries \( a \) (nearer to the observer) and \( b \) (farther from the observer), as shown in Fig. 2, is given by

\[
\Delta L_{\text{path}} = \int_{t_a}^{t_b} J(t) \, dt = \int_{t_a}^{t_b} \mathcal{J}(t_a - t_b) \, dt_a \mathcal{J}(1 - t_L) = t_a \mathcal{J} \int_{t_a}^{t_b} J(t) \, dt,
\]

where \( t_a \) and \( t_b \) are transmittances from the observer to the slab \( a \) and \( b \) boundaries along the line of sight (LOS), \( t_L \) is the transmittance of the slab, and the integration is along the LOS and all values are spectral. Integration with respect to transmission is preferred as it is defined with respect to the observer as a point of reference. For LEEDR, \( J \) is the total source term including the SS solar and thermal components. The quantity \( \mathcal{J}(1 - t_L) \) is the radiance attributed to the individual slab at the slab location, while \( \Delta L \) is the slab radiance contribution at the observer location. Thus the path radiance, without additions for surface terms, is the sum of the self-radiance of each layer slab weighted by the transmission between the slab and the observing sensor. For up-looking scenarios not considering MS effects, the total source \( J \) consists of two terms as shown below for the self-radiance of layer \( L \):

\[
\int_{t_L}^{1} J(t) \, dt = J(t)_{\text{thermal}} + J(t)_{\text{sss}}.
\]

The thermal source term is computed via the following:

\[
J_{\text{thermal}} = (1 - \omega) \int_{t_L}^{1} L(T) \, dt = \sum_{t_L}^{1} (1 - \omega_L) [L(T)(1 - t_L)],
\]

and the single-scattered solar source term is

\[
J_{\text{sss}} = \omega p(\theta) I_0 \int_{t_L}^{1} t_0(t) \, dt = \sum_{t_L}^{1} \omega_L p(t_L)(1 - t_L)[L_0(1 - t_L)],
\]

where \( \omega_L \) is the slab SS albedo, which is the ratio of the scattering coefficient to the extinction coefficient; \( L_0(T) \) is the Planck function at the slab temperature \( T \); \( I_0 \) is the solar irradiance at the top of the atmosphere; \( p(t_L)(\theta) \) is the

![FIG 2. General schematic of the radiative transfer geometry internal to LEEDR.](image-url)
scattering phase function, dependent on the scattering angle $\theta$; $t_0$ is the transmittance from the sun via the scattering point (on the LOS) to slab boundary $a$ along the LOS; $t_{a}$ is transmittance from the scattering point to slab edge $a$ along the LOS; and $t_{aL}$ is a function of position along the LOS as is the angle $\theta$. For a celestial object such as the sun, this angle remains nearly constant for LOS positions in the terrestrial atmosphere but could vary significantly for a different source object located in the terrestrial atmosphere (Acharya et al. 1999; Cusumano et al. 2011).

Molecular, aerosol, and hydrometeor scattering are handled simultaneously in the LEEDR’s scattering algorithms. This is accomplished by combining normalized phase functions via a weight proportional to the scattering amount expressed by

$$W_{m,a,w} = \beta_{s(m,a,w)}/\beta_c.$$  

(8)

The combined molecular, aerosol, and weather phases for the solar or source term normalized along the angular dimension $\mu$ per observer path altitude $z$ are weighted by the associated scattering per given altitude $z$ expressed by

$$C = P_m W_m + P_a W_a + P_w W_w,$$  

(9)

where $\beta_{s(m,a,w)}$ is the volume scattering coefficient for molecular, aerosol, and hydrometeor, respectively. $\beta_c$ is the sum of these three terms and represents the volume extinction (absorption + scattering) coefficient, $P(z)_m$ is the molecular phases per altitude, $P(z)_a$ is the aerosol phases per altitude, and $P(z)_w$ is the hydrometeor phases per altitude. LEEDR’s SS algorithm has previously been compared with MODTRAN’s SS algorithm and shown to produce consistent results (Cusumano et al. 2011). While SS is computationally cheap and a relatively simple method to implement, it fails to sufficiently characterize radiative transfer processes through inhomogeneous atmospheric layers for mediums with any appreciable optical thickness (because of scattering). Accounting for MS effects has historically been computationally expensive and thus prohibitive, but highly desired for absorption and scattering effects through inhomogeneous mediums such as clouds and aerosol haze at wavelengths $< 2 \mu$m. Stand-alone modules such as DISORT are often used in radiative transfer models, yet optimizing interfaces and configurations between models can present a significant challenge (Berk et al. 2014). Two-stream methods have long been widely used as rapid and relatively cheap approximations to solve for important features of MS effects. LEEDR’s internal implementation is built on the SS algorithm and leverages its unique atmospheric characterization capabilities with a cumulative diffusivity approach in an algorithm appropriate for modeling radiative transfer through realistic clouds and aerosol layers.

4. LEEDR’s multiple-scattering algorithm

LEEDR’s MS algorithm is a source-to-observer cumulative diffusivity method that fully solves for molecular, aerosol, cloud, and precipitation single-scatter layer effects with a Mie algorithm at every calculation point/atmospheric layer rather than an interpolated value from a precomputed lookup table. This cumulative diffusivity method first considers the incident solar radiation contribution to a given layer accounting for solid angle and elevation. It then measures the contribution of diffused energy from previous layers based on the transmission of the current level to produce a cumulative radiance that is reflected from a surface and measured at the observer location. A unique set of asymmetry and backscattering phase-function parameter calculations accounts for the radiance loss due to the molecular and aerosol constituent reflectivity within a level. This allows for a more accurate characterization of diffuse layers that contribute to multiple-scattered radiances in inhomogeneous atmospheres (Fiorino et al. 2016).

The algorithm treats the direct and the scattered radiation separately, where direct transmission is modeled via Beer’s law according to Eq. (2) and indirect or scattered radiation is modeled through a diffuse scattering assumption. The total observed scattered radiance from multiple sources $J_{mscat}$ is the sum of the solar SS source term along the observer path $J_{ss}$, the diffusivity model $J_{diff}$ source term, and the thermal source term $J_{thermal}$ written as

$$J_{mscat} = J_{diff} + J_{ss} + J_{thermal}.$$  

(10)

The multiple-scatter component is summed with the direct transmission to yield a final radiance. The SS and thermal algorithms remain unchanged from those previously described. Each atmospheric layer possesses an intrinsic radiation that can be summed to provide the cumulative contribution of radiation from other layers. At each layer, the intrinsic radiation is determined by subtracting the absorbed radiation from the direct solar radiation incident at that layer, as well as a loss term calculated from a layer specific albedo or reflection term. Intrinsic radiation values are added cumulatively along the LOS from source to observer to produce a final radiance solution.
Direct transmission to each point along the LOS is calculated as described in the SS procedure. For each layer along the LOS, the intrinsic scattered radiation is determined by

\[ I_{\text{int}} = I_0 [1 - t_{\text{slab}}(z)] \omega(z)_{\text{slab}}, \]  

(11)

where \( I_{\text{int}} \) is the intrinsic irradiance of the slab, \( t_{\text{slab}} \) is the transmission of the slab layer, and \( \omega_{\text{slab}} \) is the single-scatter albedo of the slab. This calculation is accomplished for each layer of the atmosphere along the LOS.

Iteratively calculating the diffusivity at each layer of the atmosphere is key to the two-stream-like modeling of MS effects. Starting at the farthest layer from the observer and moving toward the observer along the LOS, the intrinsic diffuse component is cumulatively summed along the path. The sum of two layers is then treated as a new layer that is iteratively summed with the next layer. However, not all diffuse energy of the adjacent layer is retained in each iterative step. This is due to reflection off the adjacent layer in a direction away from the observer. In this sense, the algorithm resembles a typical two-stream approach that divides the radiation propagation into two streams or directions. Here the radiation is divided into two hemispherical directions separated by the local horizontal plane and the amount of radiation scattered off the adjacent layer and away from the observer is determined by

\[
I(z)_{r,\text{int}} = \frac{1}{4\pi} \int_0^\pi \int_0^{2\pi} I(z - 1)_{\text{int}} \omega(z)_{\text{slab}} \rho(z, \theta)_{\text{slab}} \times I_0 [1 - t_{\text{slab}}(z)] \omega(z)_{\text{slab}} \, d\theta \, d\phi, \]

(12)

with \( I(z - 1)_{\text{int}} \) being the intrinsic solar irradiance incident from the first layer onto the second layer. This is considered a loss term because of reflection or scattering. The resulting diffuse radiation for two layers being considered a loss term because of reflection or scatter-

\[
I_u(z) = I(z - 1)_{\text{int}} - I(z)_{r,\text{int}}. \]

(13)

The process of iteratively summing two layers and then summing another layer with the previously combined layer yields the total cumulative diffusivity summation as described by

\[
J_{\text{diff}} = \sum_{z} \left[ \frac{I(z)}{4\pi} \frac{\mu}{4\pi} + J_{\text{diff}}(z - 1) \right] \omega(z)T(z)_{\text{abs}}, \]

(14)

where \( J(z = 1)_{\text{diff}} \) is equal to zero. Here, \( T(z)_{\text{abs}} \) is the transmission at altitude \( z \) along the observer path accounting for absorption only. For these calculations, the diffusivity for \( z = 1 \) is assumed to be zero because of the assumption that the initial MS radiance is equal to zero prior to the first scattering layer.

Since Earth’s surface is considered to be a separate source layer, a valid surface albedo–reflectance is necessary to determine the amount of diffuse radiance reflected from the surface back into a given atmospheric layer. Additionally, the presence of clouds along the observer path must be considered. If clouds are present along the path, the surface albedo of the layer encompassing the cloud is defined as the single-scatter albedo. Otherwise, the LEEDR default albedo of the surface of Earth where the observer is located is used. The diffusivity value used from \( R(z)_{\text{diff}} \) at the \( z \) index of the valid surface level is thus defined as

\[
R(z)_{\text{diff}} = \{R_{\text{diff}} + R_{\text{diff}}\}p\pi \text{ for no clouds and}
\]

\[
R(z)_{\text{diff}} = [R_{\text{diff}} + R_{\text{diff}}\alpha(z)] \text{ with clouds}. \]

(15)

### 5. Comparative multiple-scattering results

To assess the performance of the implemented MS algorithm, LEEDR was compared with several different sources of data as reported in literature, as well as experimental radiance data publically available through database collections. LEEDR demonstrated the ability to closely match experimental data, which we attribute to its thorough accounting of realistic atmospheric conditions to include observed aerosols and clouds. Without the accurate atmospheric characterization, LEEDR’s results qualitatively agreed with other two-stream models but failed to predict actual radiance observations. To accurately model the atmosphere, aerosol loading had to be matched to current conditions. This was accomplished by first obtaining the reported visibility conditions for the test locations as recorded by the nearest permanent weather observation stations. Visibility conditions can be matched by scaling the surface layer extinction coefficient but this fails to account for any scaled aerosol effect at other layers in the atmosphere and is only valid strictly at 550 nm. A more accurate way of scaling the visibility to match observed conditions is to iteratively alter the climatological surface aerosol number concentration until the calculated visibility at the surface matches the reported value such that the effect is consistent across wavelengths. Utilizing the Global Aerosol Dataset (GADS; Koepeke et al. 1997) database for aerosol content, number concentration, and optical properties (200 nm to 40 \( \mu \)m), the aerosol content was scaled by a constant factor so that visibilities at the surface agreed with reported observations. The following comparisons describe various data sources and LEEDR simulations in detail.
a. HSI data comparisons

In 2012 the Institute for Meteorology and Climatology (IMuK) at the University of Hanover, Germany, performed a sky radiance case study as reported by Tohsing et al. (2014). Upwelling spectral sky radiances for a variety of zenith and azimuthal orientations were measured using a hemispherical sky imager (HSI). The HSI, designed by the IMuK, consists of a Canon PowerShot G10 compact camera, a Dörr DHG fish-eye lens, along with a commercial compact charge coupled device (CCD) sensor with three channels; red, green, and blue. Data collection occurred in late October 2012 at 52.39° N, 9.70° E, 59 m above sea level. Because of the nonlinear behavior of the camera sensor, a nonlinear regression approach was used to calculate all of the spectra in the visible region and validate HSI data against a CCD spectroradiometer (Tohsing et al. 2014). Tohsing’s previously published results for a relatively clear sky on 21 October as well as LEEDR simulations are shown in Fig. 3.

To make valid comparisons with the HSI-collected and CCD spectroradiometer-collected data, atmospheric parameter inputs in LEEDR were matched for each dataset. This was accomplished by obtaining the nearest METAR weather observation report to include temperature, dewpoint, visibility, wind speed, and cloud-cover conditions. For the 21 October 2012 case, the ExPERT database for the winter season at 1200–1500 local time for the nearest ExPERT site (Hamburg, Germany) along with the observed surface conditions were used to define the atmospheric state (e.g., temperature and dewpoint temperature) and to adiabatically scale the vertical profile through the boundary layer. GADS aerosol concentrations were set at 0.4 to match observed visibility conditions as determined through an iterative investigation of surface visibility at 550 nm under various aerosol conditions (Fiorino et al. 2016).

LEEDR simulations depict a blue sky without cloud cover that shows noticeable variation in intensity with elevation and azimuth variations. These values present the same spectral shape and relative magnitude as Tohsing’s observations. The large peaks seen near 400 nm in the LEEDR results are examples of atmospheric effects that may be smoothed by the instrument.
response function and thus not seen to the same extent in the observations. LEEDR provides radiative transfer results without any filtering because of instrument effects or equipment, which leaves the data relevant to all instruments. Furthermore, the spectral resolution of the two datasets do not necessarily align.

For the overcast case of 22 October 2012, the IMuK group collected spectral radiance measurements in the same manner. Their results are reproduced for comparison in Fig. 4 along with LEEDR simulations. LEEDR was configured in the same manner as the 21 October scenario with the exception of the time period of interest (0900–1200 LT) and the addition of a 2850-m stratus continental cloud layer (150–3000 m) as estimated by ground and satellite based observations of cloud cover and thickness. Additionally the GADS aerosol concentration was set at 1.9 to match the observed visibility conditions. LEEDR outputs are shown in Fig. 4 where simulations depict an overcast sky as evidenced by the relatively white–gray color balance. Additionally, there is minimal variation in intensity with elevation and azimuth variations. These values again present the same spectral shape and relative magnitude as Tohsing’s observations where the large relative minimum radiance values appear to be smoothed by the instrument response function. These spectral radiance results aid in demonstrating LEEDR’s ability to model MS effects of radiant energy while accounting for realistic atmospheric conditions. Azimuthal variations are accounted for in both cloudy and clear environments. The large shift in visibility between 21 and 22 October and the resulting shift in aerosol concentrations used to model these conditions can potentially be explained by the near coastal location of the observations and the shifting wind directions. It is impossible to ascertain the exact state of the atmosphere from climatology and surface data from various nearby locations; thus exact matches of data to the model are unlikely. Despite this limitation, simple corrections provide realistic model outputs that match the spectral response and order of magnitude for clear and overcast conditions for a measurement that is highly variable.

Figure 5 displays all-sky 500-nm radiance measurements from both the CCD spectroradiometer and HSI instruments as reported by Tohsing et al. (2014). The solar position as calculated by LEEDR is approximately 70.2° zenith and 214.1° azimuth. Because both instruments become saturated on account of limited dynamic range when directly viewing the direct solar region, measurements in the circumsolar region were not included in the aforementioned regression model used to train the CCD algorithm. It was also reported...
that a 2%–5% overestimation of radiance arises when internal reflections of direct sunlight create ghost images in parts of the HSI image (Tohsing et al. 2014).

LEEDR simulates consistent results along the edge of this saturated region. Inside the saturated region, LEEDR’s results remain unsaturated and follow expected behavior to include a slightly reddish sky when viewing the sun low in the atmosphere. LEEDR’s ability to predict values in the parts of the sky where there is strong aerosol forward scattering (about 10°–20° from the sun position) exceeds the HSI and CCD’s measurement capability for this particular scenario. Note that LEEDR accounts for realistic angular diameter and solid solar angle of the sun for a given date and time. The data suggest LEEDR’s potential to provide physically accurate radiance simulations when instrumentation is hindered by inherent collection limitations.

b. LABLE comparisons

A second dataset containing downwelling radiance collected during the Lower Atmospheric Boundary Layer Experiment (LABLE) was used to assess the performance of LEEDR’s MS algorithm. The LABLE campaign was conducted at the U.S. Department of Energy’s (DOE) Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site in Oklahoma during 2012 and 2013 by a plethora of collaborating organizations. The Atmospheric Emitted Radiance Interferometer (AERI) instrument was used to measure downwelling infrared (3–19 μm) radiance along with vertical profiles of temperature and dewpoint (water vapor content). The dataset presented (Klein et al. 2015) provides radiance data for the following three distinct atmospheric profiles: 1125 UTC 7 November 2012, and 1132 and 1731 UTC 27 June 2013, as displayed in Fig. 6. Note that all three datasets were collected under cloud-free conditions (Fiorino et al. 2016).

For the most accurate LEEDR comparison, NWP Global Forecast System (GFS) output was obtained from the NOMADS database for the dates and times corresponding to the three AERI-collected datasets. The 0.5°-resolution GFS data were used to define the atmosphere and vertical profile within LEEDR. LEEDR generated path radiance for all three cases, seen in the top right of Fig. 6 as compared with measurements depicted in the top left of Fig. 6, show a
discrepancy with the 1132 and 1731 UTC 27 June 2013 spectral signatures. The differences in the 1132 case are primarily due to the lack of vertical resolution in the GFS data to resolve the higher water content present during the morning time frame within the lower boundary layer, while the 1731 differences are attributable to inaccurate estimates of local surface temperature from the GFS model.

Path radiance was recalculated via LEEDR using the same atmospheric parameters with the additional consideration of surface observations, thus utilizing LEEDR’s unique boundary layer characterization coupled with the NWP data in the atmosphere above the boundary layer and the MS algorithm. The results, seen in the bottom left of Fig. 6, provide an accurate comparison to the AERI-observed radiance values in the top left of Fig. 6. Absolute differences are shown in the bottom right of Fig. 6 where the black lines show the error when using the uncorrected data and the colored lines show the error when using NWP corrections. The results show improvement for both 27 June 2013 cases when corrected surface observations are utilized. While significant differences still exist at a few wavelengths, they are likely due to different spectral resolutions of the model and instrument collection and the overall error across the band is centered on zero. It is worth noting that the atmospheric conditions in the boundary layer were not adiabatic at 1132 UTC 27 June 2013; however, simply applying an accurate surface observation of temperature and dewpoint more accurately matched measurements than solely utilizing NWP data. Coupled with accurate atmospheric characterization the results support the utility of the MS algorithm in the longwave regime.

c. MODIS comparisons

To further evaluate LEEDR’s MS algorithm, radiance data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra and Aqua satellites were collected and analyzed for comparison with LEEDR path radiance simulations (MODIS Characterization
MODIS continuously acquires radiance measurements in 36 different spectral bands along its polar orbit. Pixel measurements are georeferenced to points on the ground, as well as satellite position, enabling direct comparison for down-looking simulations from space with LEEDR simulations. For the purposes of algorithm development and evaluation, potential MODIS datasets were sorted and filtered to obtain correlated inputs into LEEDR. MODIS datasets were filtered to determine the existence of cloud layers and to estimate the respective cloud parameters (Platnick et al. 2015).

LEEDR, like most operational radiative transfer models, employs a modified plane-parallel atmosphere approximation where clouds are defined by layers or slabs that wrap completely around a spherical Earth. MODIS atmospheric products provide cloud parameters estimates including cloud-top height (or pressure) and cloud droplet effective radius with respect to the water phase; however, the number of distinct layers and their composition is not known with certainty without additional measurements, such as lidar or radar. For this reason, this analysis considered single-phase cloud conditions, as determined by MODIS cloud-phase products. Additionally, to ensure the cloud parameters employed along the engagement pathlength were correlated with the ground position under the cloud structure of interest, the sensor zenith angle (from ground to satellite) was limited so that the path from the ground to the top of the path layer did not exceed the 1-km pixel resolution of the sensor (Fiorino et al. 2016).

For MODIS-observed radiances and LEEDR simulation comparisons, geolocation information from the calibrated MODIS data—including sensor zenith and azimuth, solar zenith and azimuth, cloud droplet effective radius, cloud-top height, and cloud optical thickness—were extracted and used as model inputs. Points of interest were limited to corresponding upper-atmosphere sounding sites. Cloud-base heights were obtained from corresponding METAR weather observations, and atmospheric parameters were defined using the linear interpolation between the closest GFS data points at the corresponding time. Clouds were manually input into LEEDR by selecting one of the predefined cloud particle distributions [defined by Hess et al. (1998)] and setting the upper and lower limits based on cloud-top height and cloud-base estimates. It should be noted that this process was relatively subjective as cloud parameters lie on a continuum and rarely match nominal cloud particle distributions exactly. Figure 7 depicts the swath of data collected by the MODIS sensor on 15 December 2014 where the location meeting the described criteria is circled.

Figure 8 depicts the results of a LEEDR simulation for 15 December 2014. The red marks indicate the observed MODIS data collected in several different spectral bands, while the various lines each represent a separate LEEDR simulation. The green line depicts a cloud-free line-of-site SS simulation with a surface composed of deciduous forest for the atmospheric and geometric conditions occurring at 1810 UTC 15 December as the satellite passed over the eastern United States. The gray line represents a SS simulation with a stratus cloud layer between 900 and 3800 m. It can be seen that the SS approximation significantly lowers the observed radiance at the sensor, especially in the shortwave portion of the spectrum (0–2 μm).

The blue line represents the spectral output from a multiple-scattering simulation using the same cloud parameters. This simulation is observed to more closely match the observed data across the spectrum but with particular improvement in the shortwave.

d. SASZE comparisons

For further comparison, an upwelling radiance dataset was obtained from the ARM at the SGP location. The instrument used to collect the data was the Shortwave Array Spectroradiometer—Zenith (SASZE). The SASZE measures the zenith sky shortwave radiance in the ultraviolet to infrared band at a sampling frequency of approximately 1 Hz (Flynn 2016).

Zenith spectral data for 1730 UTC 5 December 2014 were compared with LEEDR simulations using the same date, time, and location. Cloud parameters are necessary inputs to be considered by LEEDR to accurately simulate the same spectral profile. Cloud properties
from various sources, including the Geostationary Satellite (GOES) derived products via NASA’s Langley Cloud and Radiation Research Group, were considered when subjectively determining input parameters. For this date and time, a stratus continental cloud layer was estimated to exist between the altitudes of 731 and 1500 m at the ARM SGP site. Three-hour, 0.5° GFS forecast data from the 1200 UTC cycle were used to define the atmospheric vertical profile via linear interpolation to the SGP site and solar position was obtained from the DOE ARM spectroradiometer data. Figure 9 shows the LEEDR-simulated radiance (red) in comparison with the ARM SASZE-measured radiance (blue) (Fiorino et al. 2016).

Large variations in the ARM data around 1.0–1.1 μm may result from system noise during collection. Additionally, the resolution of the simulation and the instrument do not necessarily align one-for-one, and the instrument response function is not considered in the LEEDR outputs. Despite these limitations, the consistency of the simulation with the collected data suggests LEEDR’s MS algorithm can sufficiently simulate the effects of a realistic atmosphere including cloud layers, particularly in the shortwave regime when accurate atmospheric conditions are known.

6. Summary and future work

Multiple-scattering effects can significantly impact radiative transfer calculations for remote sensing and directed-energy applications. This study described the development and implementation of a fast-calculating two-stream-like multiple-scattering algorithm that captures azimuthal and elevation variations into the Air Force Institute of Technology Center for Directed Energy’s Laser Environmental Effects Definition and Reference atmospheric characterization and radiative transfer code. The cumulative diffuse technique borrows concepts from the two-stream approximation but simplifies and integrates them in a fashion that couples and exploits the novel boundary layer characterization technique essential for accurate atmospheric characterization. A unique set of asymmetry and backscattering phase-function parameter calculations accounts for radiance loss due to the molecular and aerosol constituent reflectivity within a layer and accurately characterize diffuse layers that contribute to multiple-scattered radiances in inhomogeneous atmospheres.

Advanced atmospheric characterization must translate to increases in simulation accuracy of observed radiance values. Several sources of radiance observations were simulated with LEEDR and compared with diverse observations by various researchers. Included were downwelling radiance values in clear and cloudy conditions with various aerosol loadings at multiple locations. Longwave and shortwave performance were both considered and accurately modeled. These results applied to multiple instruments including spectrometers, CCD cameras, satellite sensors, and stationary radiometers at a dedicated site. The favorable comparisons of this new technique serve to establish the accuracy and utility of the cumulative diffuse approach as applied in LEEDR. Determining accurate aerosol loading via an iterative visibility/particle-count calculation method is
ultimately essential to achieve agreement between observations and model results for realistic atmospheres.

Initial implementation of the MS algorithm was solely applied to the solar source term. The technique described is applicable to all source radiation and therefore should be integrated to operate on thermal radiance contributions from the atmosphere itself. This will ensure that LEEDR’s approach is consistent for all sources considered. Despite this current limitation in design, the results suggest acceptable agreement in the longwave where this term would contribute most significantly.

In conclusion, LEEDR’s MS algorithm allows an accurate atmospheric characterization of solar radiance through inhomogeneous atmospheres including clouds and aerosols at wavelengths from 200 nm to 8.6 m. This enables accurate atmospheric compensation and correction for a variety of remote sensing applications. Additionally, the research demonstrates the impact of utilizing NWP data and in situ observations to accurately account for nonstandard conditions that impact radiance calculation in complex ways and ultimately improves the ability to model remote sensing performance.

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