

1 EigenFlux: A Stable Multi-Stream Radiative Transfer 2 Method for Strongly Scattering Media

3 Daniel P. Johnson^{1,*} and Matthew S. Johnson^{2,*}

4 ¹Retired, Aerospace Research Fellow, Fridley, MN, USA

5 ²Department of Chemistry, University of Copenhagen, Copenhagen Denmark

6 *drdpj@comcast.net, msj@chem.ku.dk

7 ABSTRACT

Radiative transfer in strongly scattering media remains computationally challenging, particularly for systems with highly asymmetric phase functions and large optical depths, where conventional discrete-ordinate approaches may suffer from numerical instability, slow convergence, or loss of accuracy. We present EigenFlux, a multistream radiative transfer framework based on eigenmode decomposition, natural-reflectance stabilization, and flexible mesh-based angular discretization. Unlike previous approaches relying primarily on global polynomial expansions, EigenFlux permits localized resolution of phase functions with strongly forward scattering or significant backward-scattering components while preserving flux conservation and numerical stability. The method is evaluated across 957 test cases spanning asymmetry factors from $g = -0.998867$ to $g = 0.998867$ and single-scattering albedos from $\omega = 0.0014660$ to $\omega = 0.9999995$, including extreme multiple-scattering regimes that are difficult for conventional solvers. Comparisons with DISORT show competitive accuracy and computational performance, with EigenFlux exhibiting particularly robust behavior for highly asymmetric scattering systems and large numbers of streams. EigenFlux maintained stable solutions for asymmetry factors exceeding $|g| > 0.99$, where conventional polynomial-based expansions became unstable or required substantially larger stream numbers. Analysis of the eigenspectrum further reveals the emergence of asymptotic diffuse transport regimes in optically thick systems and persistent direct-beam structure in semi-transparent media. These results suggest that EigenFlux provides a stable and flexible framework for radiative transfer calculations for atmospheres, snow and ice, ocean optics, pigments and coatings, remote sensing, and graphics rendering, particularly in cases involving extreme scattering asymmetry.

9 Introduction

10 The fundamental theory of light scattering in the atmosphere was developed by Lord Rayleigh in 1871⁴¹. Rayleigh scattering
11 remains fundamental to the field of radiative transfer today. The earliest known formulations of the modern radiative transfer
12 equation (RTE) were published by Eugen Von Lommel in 1887³⁰, and an integral version by Orest Chwolson in 1889²⁸.
13 However, neither publication spread to the general academic community⁸.

14 In 1905, Schuster used hemispheric isotropy to develop and publish a two-stream RTE and its analytical solution⁴² and has

15 been traditionally credited with originating the RTE, although a similar two-stream approximation was presented by Eddington
16 in 1916¹³. Papers by Schwarzschild in 1906 and 1914, and by Milne in 1921 on thermodynamic equilibrium within solar
17 and stellar atmospheres led to the establishment of the RTE in its general form^{29,43,44}. A full analytic theory of the RTE was
18 developed and published by Chandrasekhar in 1950⁷.

19 In the meantime, Kubelka and Munk developed a simplified two-constant RTE and its solution in 1931^{23,24} that is equivalent
20 mathematically to Schuster's. Whereas Eddington and Shuster's two-stream RTE and subsequent modifications^{26,34} have been
21 considered only appropriate for mediums without strong asymmetry, Kubelka-Munk's method is accurate for determining the
22 reflectance of materials with strong scattering. As a result, K-M and its modifications have become the standard for use by the
23 painting and coating industries²² where the most useful pigments tend to be those with extreme scattering properties. A modern
24 study which uses the K-M method is the Lawrence Berkeley National Laboratory's study into pigments for roofing materials
25 that show color in the visible spectrum, but are transparent in IR and UV so as to remain cool even under solar heating². The
26 study determined the scattering and absorbing properties of 85 candidate materials. Most materials were found to be strongly
27 forward scattering²⁵.

28 Researchers in atmospheric physics/chemistry and oceanographers were interested in solutions to the full RTE in order to
29 understand the effects of solar flux. The 1970's saw the development of a variety of RTE solvers starting from Chandrasekhar's
30 work⁷, including the popular DISORT solver⁴⁷ available as public source code, both as a stand-alone distribution²⁷ and as part
31 of the RadTranLib distribution¹⁶.

32 Astronomers and meteorologists were interested in the RTE as a way of understanding the albedo of the Earth and other
33 planets⁹. The Bi-Directional Radiation Field (BDRF) was formulated and standardized as part of this understanding^{32,52}.

34 Snow and ice are particularly important materials in determining the albedo of the Earth, and microwave sensing has
35 become an important tool for characterizing current snow and ice levels. Current algorithms such as the Discrete Ordinates
36 method are being supplied as part of RTE solvers with custom models for the highly forward scattering and low absorptency
37 features of snow and ice^{14,19,37}.

38 Application of the RTE to oceans began as early as 1922 when Raman⁴⁰ invoked scattering to explain the color of the
39 sea. Scattering due to suspended particles (turbidity) and water turbulence play a major role in determining the color⁴⁵. The
40 resulting mathematics was given a firm footing by Preisendorfer's 6 Volume *Hydrologic Optics*^{31,38,39}. The work of Akkaynak
41 and Treibitz provides an interesting example of the use of the RTE in color-correction of underwater imaging³. The Hydrolight
42 tool²⁰ is a commercial tool that can directly solve hydrological depth-varying absorbance and scattering problems, including
43 systems with strong forward scattering. It is coded specifically for hydrological problems and does not address atmospheric
44 radiative transfer or radiative transfer within pigmented materials.

45 A simplified form of the RTE was introduced by Blinn⁵ as an approach to rendering realistic scenes in computer graphics in
46 1984. This was expanded into a generalized Light Transport Theory a few years later by Kajiya²¹. This initial work focused
47 on models that were computationally light and resulted in realistic appearances, but were not necessarily physically accurate.

Advances in computer technology have allowed the increased use of physically-realistic models³⁶. The complexity of rendering lighting and atmospheric effects in computer-generated imagery means that the leading rendering technology is based on ray-tracing and Monte-Carlo sampling. These methods provide an important alternative to the more traditional RTE solvers. An example is the MYSTIC code¹⁵ which is included in the RadTranLib public source distribution¹⁶ along with the more traditional DISORT solver⁴⁷.

In addition to the pigments mentioned above, many key components of meteorological concern show strong forward scattering as well. Stamnes, et. al.⁴⁸ reports $g = 0.85, 0.89, 0.997$ for air bubbles, snow grains, and brine pockets respectively. Clouds are strongly forward scattering and have strong backward scattering components¹⁷ (see Figure 11 below). Materials with true negative asymmetry are less common, but $g < -0.4$ have appeared in theoretical studies of engineered materials⁵⁴.

The *Mesh Approximates* (MA) method presented here is closely related to the classic *Discrete Ordinates* (DO) method presented by Chandrasekhar⁷ (we follow the presentation by Goody and Yung¹⁸ and the paper by Stamnes, et al.²). Both methods start with the integro-differential equation (3) with boundary conditions for the diffuse intensity with an explicit expression for the direct intensity. The DO method first defines a finite-dimensional approximation of the integral terms to generate a linear ODE. That finite-approximation uses a Legendre approximation of the phase matrix, and Gaussian quadrature for the integrals, which is mathematically equivalent to using Legendre polynomial expansions for the integrands. To solve the resulting Ordinary Differential Equations (ODE), DO performs an eigenvalue decomposition to get a system of uncoupled ODEs, half of which are unstable. DO expresses the uncoupled ODEs and boundary conditions as an algebraic eigenvalue problem, which is then solved using specialized algorithms for that purpose. The MA method first approximates the original equation using a piecewise-linear approximation of the phase matrix and the diffuse intensity, with exact evaluation of the resulting integrands over each piece-wise linear interval.

As in the previous method, the next step is to use an eigenvalue decomposition to solve the resulting Ordinary Differential Equations (ODE) to get a system of uncoupled ODEs, half of which are unstable. It stabilizes the uncoupled ODEs by initializing their solution with a natural reflectance assumption (equivalent to the assumption of an semi-infinite atmosphere). Piecewise-linear mesh approximations are again applied along the depth axis and to the boundary conditions in order to generate a well-conditioned linear system which can be solved with standard algorithms.

The natural reflectance solution can then be used to generate the general two-boundary solution through a linear combination of the downward natural reflectance solution starting at the top boundary, and with an upward natural reflectance solution starting at the bottom boundary. The linear combination is chosen to satisfy the original boundary conditions at the two boundaries.

The DO method is limited in the fit that can be obtained using Legendre polynomials, which require high orders of approximation to avoid oscillations at the end-points, making it difficult to use for approximating those scattering phase functions which are strongly forward or have a significant backward scattering component. The MA approach allows for the use of any subdivision of the ordinates, both for the multi-streams and along the depth axis. This allows for the use of meshes

81 designed to resolve the underlying dynamics, for forward scattering problems with more than 0.99 asymmetry for the existing
82 implementations.

83 Like the DO, the base MA algorithm is limited to application to homogeneous media. Inhomogeneous media are managed
84 by introducing multiple homogeneous layers with varying characteristics which can be combined into an overall heterogeneous
85 solution. In its existing implementation, MA is limited to plane-parallel geometry, although the use of pseudo-spherical
86 geometry is contemplated for the future.

87 Based on these considerations, there remains a need for a radiative transfer method that is numerically stable, computationally
88 efficient, and accurate for both optically thick and semi-transparent systems, including systems with highly asymmetric
89 scattering phase functions while also promoting transparency and reproducibility through open implementation. In this paper
90 we introduce EigenFlux, a multistream radiative transfer model based on an eigenmode formulation combined with flexible
91 angular discretization and localized basis functions. The method is designed to preserve stability and conserve flux, while
92 accurately describing strongly forward-scattering systems. We evaluate the approach across a broad range of asymmetry factors
93 and single-scattering albedos, including extreme scattering regimes that are challenging for conventional discrete-ordinate
94 methods. Finally, we compare the behavior of EigenFlux with established approaches and discuss potential applications in
95 atmospheric science, ocean optics, remote sensing, material science, and graphics rendering.

96 **Methods**

97 **Radiative Transfer**

98 We investigate *radiative transfer* through a homogeneous media, illuminated at its top boundary and a reflective/absorptive
99 surface at its bottom boundary, that contains a uniform mix of particles which may absorb or scatter light particles that are
100 traveling through the media. We will limit this investigation to the plane-parallel situation, in which we only model the *depth* to
101 which a light particle has penetrated, (increasing as the light particle descends deeper), the *relative velocity* (the cosine of the
102 angle of travel relative to the vertical), and its *azimuth* (the angle of travel relative to the medium's "north").

103 The *intensity* function is interpreted here as the probability that a light particle is at depth y in the media, and has a relative
104 velocity of v , where $v = \cos(\theta)$. So $(v = 1, \theta = \pi/2)$ is straight down, $(v = 0, \theta = 0)$ is horizontal, and $(v = -1, \theta = -\pi/2)$
105 is straight up.

106 The particles may either absorb or scatter a light particle encountering them. The process of a light particle travelling until
107 it is absorbed or scattered out of the beam is known as *extinction*, and the expected path length of the process is the *extinction*
108 *path length*. Upon extinction, the fraction of the particles that are then scattered is the *single scatter albedo* also known as the
109 *scatter fraction*. EigenFlux currently does not consider thermal emission or inelastic scattering from the particles.

110 The scatter distribution is determined by a rotationally symmetric phase function $k(v)$ with *asymmetry* g measuring the
111 expected amount of back scatter vs. forward scatter, $g = \int 2\pi v k(v) dv$ where $g = 1$ is full forward scatter and $g = -1$ is full

backward scatter. The scattering matrix is given by

$$K(v, w; a - b) = k(vw + \cos(a - b)\sqrt{1 - v^2}\sqrt{1 - w^2})$$

Further information and background can be found in the references^{18,22,34}.

Key Variables and Functions

θ	Angle of travel of light particle, relative to vertical
ϕ	Azimuth of travel of light particle, relative to north
$v = \cos \theta$	Velocity relative to vertical
(v, a)	Polar cosine and azimuth angle of incident vector
(w, b)	Polar cosine and azimuth angle of scattered vector
x	Depth
y	Depth scaled to extinction path length
z	Exponential depth $z = e^{-y/\hat{y}_{05}}$
$\tilde{I}(v, x, \phi)$	Intensity distribution
$I(v, y, \phi)$	Intensity distribution with respect to y
$s(v, \phi) = I(v, 0, \phi)$	Intensity distribution at top boundary (source illumination)
$K(v, w, a - b)$	Normalized phase scattering distribution (parametrized by g)

Model Parameters

σ	Extinction path length for light to interact with particles
κ	Probability that upon interaction, light is absorbed by particle
α	Probability that upon interaction, light is scattered by particle
$\omega = \alpha / (\alpha + \kappa)$	Single scatter albedo
g	Average scattering asymmetry where $g = 1$ is full forward scatter and $g = -1$ is full backward scatter
$\hat{y}_{05}$	Two-stream estimate of the depth at which the transmission was reduced to 5% of the original source

Under stationary conditions, the intensity distribution (1) satisfies Schwartzchild's Equation³⁴. (Note that the emission term is not considered here.)

$$I(v, a; y) + v \partial_y I(v, a; y) = \omega \iint K(v, w; a - b) I(w, b; y) dw db$$

$$I(v, a; 0) = s(v, a)$$
(1)

Note that $K(v, w; a)$ is cyclic in a , i.e. $K(v, w; a + 2\pi) = K(v, w; a)$ and is the only term in the equation that is azimuth-dependent other than the boundary condition. As a result, the fundamental solution will be cyclically symmetric in azimuth

$$\Phi(v, a; w, b; y) = \Phi(v, a - b; w, 0; y) = \Phi(v, a - b + 2\pi; w, 0; y)$$

Natural Reflectance

Given a boundary at the top of the medium, the left-hand side of equation (1) is a first-order linear differential equation in y that is unstable for $v < 0$, i.e. for light traveling up to the top of the medium. To fix this problem, we use the notion of natural reflectance to find canonical solutions that can be combined to find two-boundary solutions to (1).

The *natural reflectance* of a material is the reflectance of a sample that is thick enough to be effectively opaque, e.g. adding additional depth does not change the reflectance significantly. In considering atmospheric radiation, this would be the assumption of an infinitely deep atmosphere (without the attendant pressure increase). In considering paints and coatings, this would be the assumption of a completely opaque film.

Let us write down the standard textbook solution for a first order differential equation with the initial boundary condition $s(v)$.

$$I(v, y, a) = s(v, a) e^{-y/v} + (\omega/v) e^{-y/v} \int_{\eta=0}^y \int_{w=-1}^1 \int_{b=0}^{2\pi} e^{\eta/v} K(v, w, a - b) I(w, \eta, b) db dw d\eta$$

However, for $v < 0$, $e^{-y/v}$ is unbounded in y , and under the natural reflectance condition, the light exiting the surface, $I(v, 0)$ for $v \leq 0$ should be solely determined by the light entering the surface, $I(v, 0)$ for $v \geq 0$.

By using a second boundary at depth M for the light moving up, we can get a two-sided equation in which we specify $I(v, 0)$ for $v \geq 0$ for light moving from the surface to the bottom, and $I(v, M)$ for $v \leq 0$ for light moving from the bottom to the surface.

For $v \geq 0$,

$$I(v, y, a) = s(v, a) e^{-y/v} + (\omega/v) e^{-y/v} \int_{\eta=0}^y \int_{w=-1}^1 \int_{b=0}^{2\pi} e^{\eta/v} K(v, w, a - b) I(w, \eta, b) db dw d\eta$$

For $v < 0$,

$$I(v, y, a) = s_M(v, a) e^{(M-y)/v} - (\omega/v) e^{-y/v} \int_{\eta=y}^M \int_{w=-1}^1 \int_{b=0}^{2\pi} e^{\eta/v} K(v, w, a - b) I(w, \eta, b) db dw d\eta$$

Now apply the natural reflectance condition by letting $M \rightarrow \infty$ under the condition that $s_M(v, a)$ is bounded, and split out the specific solution for $v = 0$, which results in

For $v > 0$,

$$I(v, y, a) = s(v, a) e^{-y/v} + (\omega/v) e^{-y/v} \int_{\eta=0}^y \int_{w=-1}^1 \int_{b=0}^{2\pi} e^{\eta/v} K(v, w, a-b) I(w, \eta, b) db dw d\eta$$

For $v = 0$,

$$I(v, y, a) = \omega \int_{w=-1}^1 \int_{b=0}^{2\pi} K(v, w, a-b) I(w, y, b) db dw \quad (2)$$

For $v < 0$,

$$I(v, y, a) = -(\omega/v) e^{-y/v} \int_{\eta=y}^{\infty} \int_{w=-1}^1 \int_{b=0}^{2\pi} e^{\eta/v} K(v, w, a-b) I(w, \eta, b) db dw d\eta$$

As desired, the light exiting the surface, $I(v, 0)$ for $v \leq 0$, is determined by the light entering the surface, $I(v, 0)$ for $v \geq 0$.

Figure 1 shows the intensities for a strongly backscattering media.

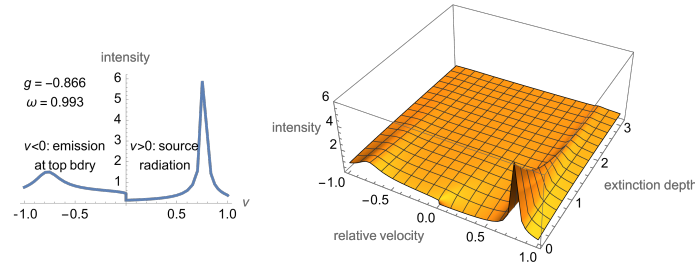


Figure 1. Intensities for strongly backscattering media: (left) emission ($v < 0$) and source ($v > 0$) radiation. (right) internal intensities. $v > 0$ shows particles descending deeper into the media at the different relative velocities, $v < 0$ are light particles ascending towards the top.

Now we turn our attention back to the basic equation (1). This can be decomposed into two parts, the *direct* component which is the intensity of the source rays before they are scattered or absorbed (also known as *extinction*), and the *diffuse* component which is the intensity of the scattered light. Furthermore, we can immediately determine the form of the direct component.

We accordingly define the two components of the intensity as

$$R(v, y, a) = e^{-y/v} s(v, a) \quad \text{Direct intensity distribution}$$

$$M(v, y, a) = I(v, y, a) - R(v, y, a) \quad \text{Diffuse intensity distribution}$$

with the boundary condition $\forall v > 0, I(v, 0) = s(v)$. Substituting these definitions into equation (1), we obtain the basic equation and side condition for the diffuse component.

$$M(v, y, a) + v \partial_y M(v, y, a) - \omega \int K(v, w, a - b) M(w, y, b) db dw = \omega \int K(v, w, a - b) R(w, y, b) db dw \quad (3)$$

$$\forall v > 0, M(v, 0, a) = 0$$

Figure 2 shows the internal direct intensity, which depends solely on the distribution of the source radiation and the extinction depth.

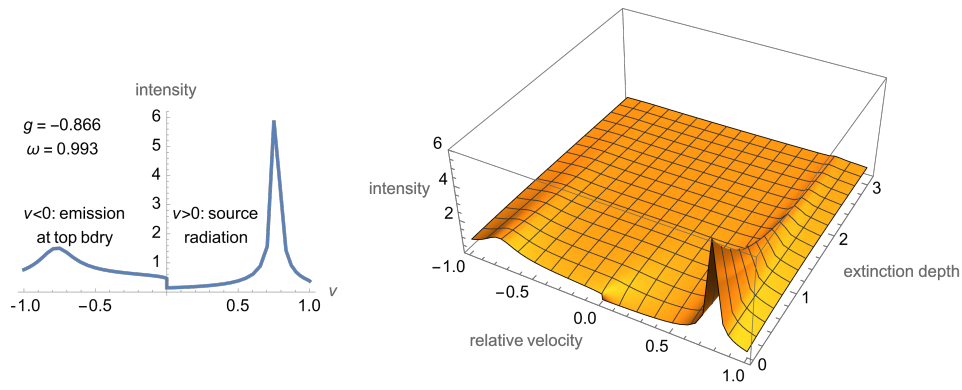


Figure 2. Internal direct intensity, showing the exponential decay of the source radiation based on the extinction depth.

Figure 3 shows the intensities for strongly forward scattering and backscattering media.

Mesh Approximation and Galerkin's Method

We use Galerkin's method¹ to solve the integral equations in (3). This method uses a framework of basis functions and test functions to generate a *mesh approximation* for the various functions that constitute the full solution.

v_i	Approximation points for relative velocity
$\phi_i(v)$	Basis functions
$\psi_i(v)$	Test functions
$\tilde{f}(v) = \sum f_i \phi_i(v)$	Approximating form for 1D functions
$\tilde{h}(v, w) = \sum h_{ij} \phi_i(v) \phi_j(w)$	Approximating form for 2D functions

When seeking an approximate $\tilde{f}(v) \approx g(v)$, we expand $\tilde{f}$ and integrate both against the test functions to get the linear equation which can be solved for the approximating coefficients.

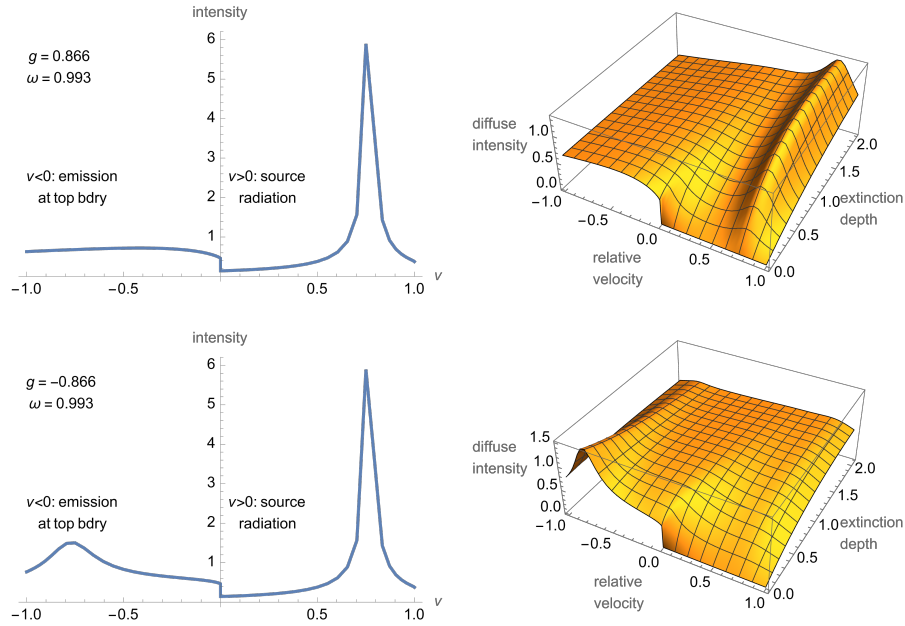


Figure 3. Internal diffuse intensities: (top) strongly forward scattering media, showing a diffuse emission and a strong internal peak at the source peak; (bottom) strongly backscattering media, showing a emission peak at the source peak, and a diffuse internal intensity.

$$\forall i, \sum_j f_i \int \psi_i(v) \phi_j(v) dv = \int \psi_i(v) g(v) dv$$

Any reasonable subdivision of points can be used for v_i . In this paper, v_i will be the concatenation of two sets of the Chebyshev points, one "arc" for $-1 \leq v \leq 0$ and another for $0 \leq v \leq 1$. The basis functions ϕ_i are triangular bump functions centered on the mesh points. We will be using two different choices for test functions in the course of this paper, either

1. $\psi_i = \phi_i$ where the test functions are the basis functions themselves, or
2. $\psi_i(v) = \delta[v - v_i]$ where the test functions are the Dirac delta functions, basically defining $\tilde{f}$ by sampling it at the mesh points.

Using (2) results in equations that are simpler, faster, and frequently better conditioned than (1), but using (1) preserves more of the symmetric properties of the original problem. So we use a mixture, (1) when additional symmetry is required, and (2) when expediency dictates the use of the simpler alternative.

Applying the Galerkin approximations to the basic equations (3), we get the mesh approximations:

$$\begin{aligned}
K(v, w; a - b) &= \sum_{jpc} K_{jpc} \phi_j(v) \phi_p(w) \tilde{\phi}_c(a - b) && \text{Phase function kernel} \\
p_0(v; a) &= \sum_{jc} p_{0jc} \phi_j(v) \tilde{\phi}_c(a) && \text{Intensity at surface} \\
M(v, y; a - b) &= \sum_{jc} M_{jc}(y) \phi_j(v) \tilde{\phi}_c(a - b) && \text{Diffuse intensity distribution} \\
\tilde{\phi}_c(a - b) &= \tilde{\phi}_c(a - b + 2\pi) && \text{Azimuth test function}
\end{aligned}$$

From this we derive the finite dimensional linear ODE.

$$\begin{aligned}
\sum_{jc} A_{ij} \tilde{B}_{fc} \partial_y M_{jc}(y) + \sum_{jc} B_{ij} \tilde{B}_{fc} M_{jc}(y) - \omega \sum_{jpc} B_{ij} \tilde{C}_{fdc} K_{jpd} B_{pq} M_{qc}(y) \\
= \omega \sum_{jpc} B_{ij} \tilde{C}_{fdc} K_{jpd} D_{pq}(y) p_{0qc}
\end{aligned} \tag{4}$$

where

$$\begin{aligned}
A_{ij} &= \int v \psi_i(v) \phi_j(v) dv \\
B_{ij} &= \int \psi_i(v) \phi_j(v) dv \\
C_{ij} &= \int \phi_i(v) \phi_j(v) dv \\
\tilde{B}_{fc} &= \int \tilde{\psi}_f(a) \tilde{\phi}_c(a) da \\
\tilde{C}_{fdc} &= \int \tilde{\psi}_f(a) \tilde{\phi}_d(a - b) \tilde{\phi}_c(b) da db \\
D_{ij}(y) &= \int e^{-y/v} \phi_i(v) \phi_j(v) dv
\end{aligned}$$

More succinctly,

$$A\tilde{B}\partial_y M(y) + (B\tilde{B} - \omega B\tilde{C}KC)M(y) = \omega B\tilde{C}KD(y)p_0 \tag{5}$$

Conservation Properties

One of the benefits of using Galerkin's Method is that it is an orthogonal projection from the Hilbert space of differentiable functions to the Hilbert space of piece-wise continuous functions, so it preserves conservation properties under the correct weights. This includes energy conservation, reciprocity, and flux closure.

The original scattering matrix $K(v, w, a - b)$, besides being symmetric in v, w and cyclic in $a - b$, also satisfies the conservation condition that $\forall w, b, \iint K(v, w, a - b) da dv = 1$. In order for the mesh approximate scattering matrix, $K(v, w; a, b) = \sum_{jpc} K_{jpc} \phi_j(v) \phi_p(w) \tilde{\phi}_c(a - b)$, to satisfy that condition, we must have

$$\forall p, b, \sum_{ja} K_{jpc} \int_{v=-1}^{v=1} \phi_j(v) dv \int_{a=0}^{a=2\pi} \tilde{\phi}_c(a - b) da = 1 \tag{6}$$

So the tensor $\tilde{K}_{jpab} = K_{jp(a-b)}$ must be doubly stochastic with respect to weights $\int \phi_j(v) dv$ and $\int \tilde{\phi}_b(a) da$. In general, the

192 simple choice of defining the approximation by simply sampling the kernel at the mesh points, $\tilde{K}_{jpc} = K(v_j, w_p, a_c)$ will yield a
 193 matrix that is close to, but is not doubly stochastic.

194 To ensure the problem remains conservative, EigenFlux uses a variation on the Sinkhorn-Knopp algorithm⁴⁶ suitable for
 195 re-scaling a matrix so that it is doubly stochastic with respect to the weights. The result is that the modified scattering matrix
 196 remains conservative in the mesh approximation.

197 Eigenvalue Decomposition

198 To solve (3), we use an *eigenvalue expansion* of the linear system generated by the mesh approximation.

199 The matrix A is near-singular at $v = 0$, but $(B - \omega BKC)$ is diagonally dominant and non-singular. So we can look at the
 200 eigenvalue decomposition of $(B - \omega BKC)^{-1}A$ for eigenvalues v_k and eigenvectors Q_k . The resulting ODE becomes

$$v_k \partial_y \mu_k(y) + \mu_k(y) = \rho_k(y) \quad (7)$$

201 where

v_k, Q_k	Eigenvalues and eigenvectors
$\mu_k(y)$	Eigenvector decomposition of $M_j(y)$
$\rho_k(y)$	Transformed boundary data

203 and

$$AQ_k = v_k(B - \omega BKC)Q_k$$

$$M_j(y) = \sum_k Q_k \mu_k(y)$$

$$\rho_k(y) = \omega Q^{-1}(B - \omega BKC)^{-1}BKD(y)s$$

207 Figure 4 shows the computed eigenvalues for varying parameter values. In general, there will be a continuous spectrum
 208 from -1 to 1, plus isolated eigenvalues at $v = \pm 1$ that correspond to the limiting distribution at increasing depths. As depth
 209 increases, the slowest decay of the intensity is governed by the isolated eigenvalues which can be quantitatively much slower
 210 than the extinction decay. See below for further details.

211 Figure 5 shows the computed eigenvectors for a single set of the parameter values. Note in particular the all-positive
 212 eigenvectors for $v = \pm 1.8$. These are the limiting distributions of the intensity.

213 We now have decomposed the problem into a set of one-dimensional first-order linear ODEs which have the general solution
 214 form

$$\mu_k(y) = \mu_k(0)e^{-y/v_k} + (1/v_k) \int_0^y e^{(\eta-y)/v_k} \rho_k(\eta) d\eta \quad (8)$$

215 There are additional considerations when the eigenvalue is zero or negative.

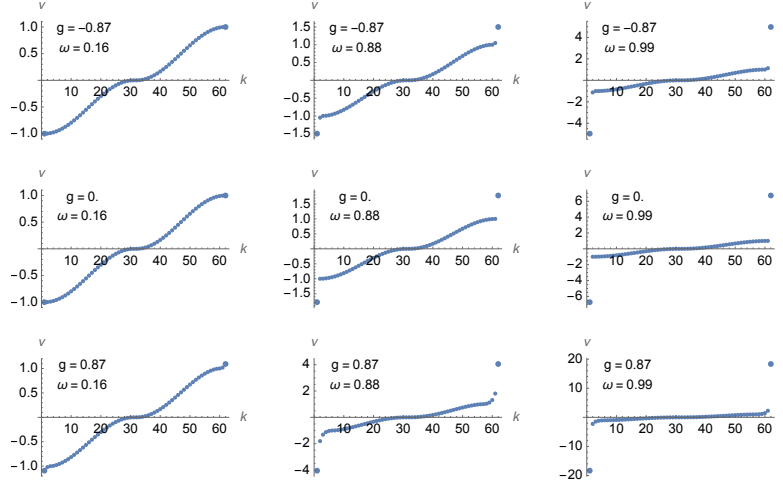


Figure 4. Eigenvalues for varying values of asymmetry g and scatter fraction ω , showing a continuous spectrum from $v = -1$ to $v = 1$ and two isolated eigenvalues. Note that the absolute value of the isolated eigenvalues increases with increasing ω .

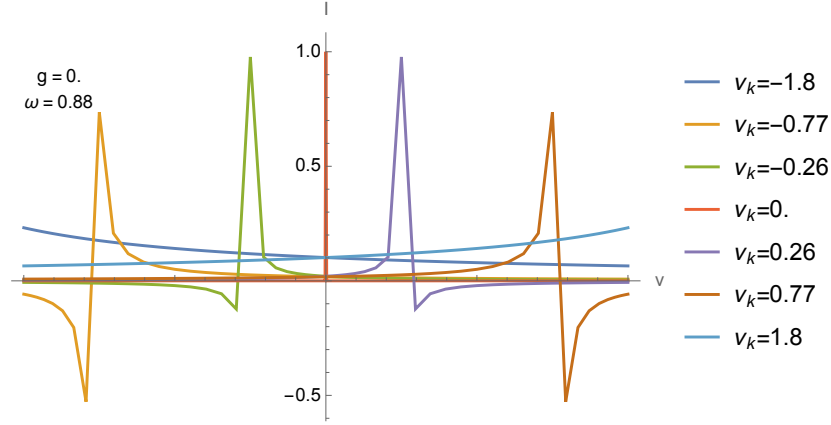


Figure 5. Sampling of eigenvectors for a single run. The eigenvectors for the isolated eigenvalues show as all-positive. The eigenvectors for the continuous spectrum are delta functions around the various relative velocities of the mesh.

One of the eigenvalues will be close to (or equal to) 0. In this case, we go back to (7) and use the resulting condition

$$\mu_k(y) = \rho_k(y).$$

When the eigenvalue is negative, (8) would imply that we have an unstable mode. In this case, we can apply the natural reflectance assumption discussed previously to the new ODEs.

With these considerations, we have the following more specific solution.

$$\begin{aligned} v_k > 0 &\implies \mu_k(y) = \mu_k(0)e^{-y/v_k} + (1/v_k) \int_0^y e^{(\eta-y)/v_k} \rho_k(\eta) d\eta \\ v_k = 0 &\implies \mu_k(y) = \rho_k(y) \\ v_k < 0 &\implies \mu_k(y) = -(1/v_k) \int_y^\infty e^{(\eta-y)/v_k} \rho_k(\eta) d\eta \end{aligned} \tag{9}$$

Note in particular that this implies that for $k : v_k \leq 0$, $\mu_k(0)$ is determined by ρ_k (and hence by p_0). For positive v_k ,

determination of $\mu_k(0)$ is slightly more complicated– they are determined by taking the side-condition $v > 0 \implies M[v, 0] = 0$ (see (3)), expanding by $M_j(0) = \sum_k Q_k \mu_k(0)$ (see (7)) and solving for the unknown $\mu_k(0)$.

Block Circulant

The eigenvalue decomposition of $\tilde{R} = (B\tilde{B} - \omega B\tilde{C}KB)^{-1}A\tilde{B}$ can be computationally costly. However, note that all functions/matrices (other than $p_0(v, a)$) that are dependent on azimuth are cyclically symmetric. As a result, the matrix $\tilde{R}$ has some special properties:

1. $\tilde{R}$ is block circulant, thus $\tilde{R}_{fcij} = \tilde{R}_{(f-c)0ij}$
2. The individual blocks of $\tilde{R}$ are symmetric, implying that $\tilde{R}_{ij}^{fc} = \tilde{R}_{ji}^{fc}$

Because of (1) and (2), the eigenvalues and eigenvectors of $\tilde{R}$ are real and can be determined from the number of blocks and the eigenvalue decomposition of a geometric sum of the individual blocks^{10,49,50}. Let the blocks of $\tilde{R}$ be given by R_{i-j} . Let ρ be a primitive root of unity of order n , the number of blocks, so that $\rho^n = 1$ and such that $\{\rho^i\}$ generates a complete list of all roots of unity of order n . Let $H(\rho) = \sum_j \rho^j R_{n-j}$. Then the eigenvalues of $\tilde{R}$ are the $n * m$ eigenvalues of $H(\rho^k)$, and the eigenvectors are the outer product of $\{\rho_k^j\}$ and the eigenvectors of $H(\rho^k)$.

Depth Model Approximation

Finding a good approximation mesh for the depth y can be problematic because y has an unbounded range, so instead we use the exponential depth z where $z = e^{-y}$, $0 \leq z \leq 1$ so that for a function of depth $f(y)$ we have $f(y) = f(-\ln(z))$.

Similar to Step One, we apply the following mesh approximation to (9), (but now with $\tilde{\psi}_i(z) = \delta[z = z_i]$, option (2) in the discussion on Mesh Approximation).

Depth Model

$$\begin{aligned} \mu_k(y) &= \sum_m \mu_{km} \phi_m(z) \text{ Transformed intensity} \\ \rho_k(z) &= \sum_m \rho_{km} \phi_m(z) \text{ Transformed boundary conditions} \\ \rho_{kh} &= \omega Q^{-1} (B - \omega BKB)^{-1} BKD(z_h) p_0 \\ D_{ij}(z) &= \int z^{1/v} \phi_i(v) \phi_j(v) dv \end{aligned}$$

From this and (9) we get the following.

$$\begin{aligned} v_k > 0 &\implies \mu_{km} = \mu_{0k} z_m^{1/v_k} + (1/v_k) \rho_{km} \int_{z_m}^1 z_m^{-1} (z_m/\zeta)^{1+1/v_k} \phi_m(\zeta) d\zeta \\ v_k = 0 &\implies \mu_{km} = \rho_{km} \\ v_k < 0 &\implies \mu_{km} = -(1/v_k) \rho_{km} \int_0^{z_m} z_m^{-1} (z_m/\zeta)^{1+1/v_k} \phi_m(\zeta) d\zeta \end{aligned}$$

This allow us to compute μ and M under the natural reflectance assumption.

Satisfying the General Two-Boundary Problem

The boundary conditions for a two-boundary radiative transfer problem specify the downward sources of illumination at the top boundary, and the upward sources of illumination at the bottom boundary.

$$I(w_j, 0) = r_0(w_j) \quad \text{downwards illumination at top boundary } (w_j \geq 0)$$

$$I(w_j, b) = r_b(w_j) \quad \text{upwards illumination at bottom boundary } (w_j \leq 0)$$

The general solution for radiative transfer for a medium with finite depth and two boundaries, top and bottom, can be expressed as the linear combination of the one-boundary solution for the top boundary with the one-boundary solution for the bottom boundary.

Let Φ be the fundamental solution for (3), so that $M = \Phi p_0$. To simplify the notation, we replace the indices by the underlying mesh points e.g. $M_i(y) = M(v_i, y)$. We then note that the solution for a system with a bottom boundary is given by a depth-reversal of the solution for a system with a top boundary.

$$\begin{aligned} \tilde{M}^{top}(v_i, y) &= \sum_{w_j \geq 0} \Phi(v_i, w_j, y) r_0(w_j) \\ \tilde{M}^{bot}(v_i, y) &= \sum_{w_j \leq 0} {}^R\Phi(v_i, w_j, b - y) r_b(w_j) \\ {}^R\Phi(v_i, w_j, b - y) &= \Phi(-v_i, -w_j, b - y) \end{aligned} \tag{10}$$

where

b depth of bottom boundary

$\tilde{M}^{top}$ solution to top-boundary problem under natural reflectance assumption

$\tilde{M}^{bot}$ solution to bottom boundary problem under natural reflectance assumption

${}^R\Phi$ depth-reversed fundamental solution

$r_0(w_j)$ downwards illumination of top boundary ($w_j \geq 0$)

$r_b(w_j)$ upwards illumination of bottom boundary ($w_j \leq 0$)

Both the downwards and upwards system satisfy the base integro-differential equation (3). A linear combination of the two sets of solutions has the same degrees of freedom as the two-boundary problem, so a linear combination of the two will span the solution set.

To find that solution, first let's decompose the systems into downwards flows ($v \geq 0$) and upwards flows ($v \leq 0$).

$$\begin{bmatrix} I_y^\uparrow \\ I_y^\downarrow \end{bmatrix} = \begin{bmatrix} R\Phi_{b-y}^\downarrow & \Phi_y^\uparrow \\ R\Phi_{b-y}^\uparrow & \Phi_y^\downarrow \end{bmatrix} \begin{bmatrix} r_b^\uparrow \\ r_0^\downarrow \end{bmatrix}$$

where

$I_y^\uparrow$ Intensity of flow upwards at depth y

$I_y^\downarrow$ Intensity of flow downwards at depth y

From this we can determine the boundary input and output flows.

$$\begin{bmatrix} S_b^\uparrow \\ S_0^\downarrow \end{bmatrix} = \begin{bmatrix} R\Phi_0^\downarrow & \Phi_b^\uparrow \\ R\Phi_b^\uparrow & \Phi_0^\downarrow \end{bmatrix} \begin{bmatrix} r_b^\uparrow \\ r_0^\downarrow \end{bmatrix}$$

$$\begin{bmatrix} O_0^\uparrow \\ O_b^\downarrow \end{bmatrix} = \begin{bmatrix} R\Phi_b^\downarrow & \Phi_0^\uparrow \\ R\Phi_0^\uparrow & \Phi_b^\downarrow \end{bmatrix} \begin{bmatrix} r_b^\uparrow \\ r_0^\downarrow \end{bmatrix}$$

And so we have found the two-boundary system.

$$\begin{bmatrix} O_0^\uparrow \\ O_b^\downarrow \end{bmatrix} = \begin{bmatrix} R\Phi_b^\downarrow & \Phi_0^\uparrow \\ R\Phi_0^\uparrow & \Phi_b^\downarrow \end{bmatrix} \begin{bmatrix} R\Phi_0^\downarrow & \Phi_b^\uparrow \\ R\Phi_b^\uparrow & \Phi_0^\downarrow \end{bmatrix}^{-1} \begin{bmatrix} S_b^\uparrow \\ S_0^\downarrow \end{bmatrix}$$

where

$S_b^\uparrow$ Intensity of source input at bottom boundary at depth b

$S_0^\downarrow$ Intensity of source input at top boundary at depth 0

$O_0^\uparrow$ Intensity of output from top boundary

$O_b^\downarrow$ Intensity of output from bottom boundary boundary

Results

Numerical Investigations of Analytical Features

For the numerical experiments, the mesh approximation for the relative velocity v have 61 sample points distributed as two arcs of shifted Chebyshev points, to give additional resolution around the three points $v = -1, 0, 1$. The mesh approximation for

the scaled depths $0 \leq z \leq 1$ has 67 sample points distributed as shifted Chebyshev points to provide additional resolution at $y = 0, \infty$. The actual scaling used is $z = e^{-y/\hat{y}_{05}}$ where $\hat{y}_{05}$ is the two-stream estimate of the depth at which the transmission was reduced to 5% of the original source. This provides better resolution by the numerical algorithm when the test case has strong forward scattering or a significant backward scattering component.

The test cases used the Henyey-Greenstein phase function parametrized by g the asymmetry parameter, which in this case is equal to the average scatter angle relative to an incident angle.

The 957 test cases used all pairs of 33 values of the asymmetry parameter ($g =$ average scattering angle) and 29 values of the scattering fraction ($\omega =$ probability of scatter given extinction $= 1 -$ probability of absorption given extinction).

Table 1. Test case parameters. v_i and z_i were fixed for all runs, so there were 33×29 test cases. These test cases span the range of asymmetry and single stage albedo, with increased density at the extremes of strong scattering and low absorptency, in order to cover the analytic features of the RTM. For v and z Chebyshev point of the second kind were used, remapped to the interval $[0, 1]$ (and $[-1, 0]$ for v .) Then g is distributed as the remapped Chebyshev points of the first kind. The strong sensitivity to low absorptency dictated that ω be the squares of the Chebyshev points of the first kind.

var	definition	distribution	number	min	max
v_i	relative velocity	double Chebyshev	61	-1	1
z_i	scaled exponential depth	Chebyshev	67	0	1
g_i	asymmetry factor	Chebyshev	33	-0.998867	0.998867
ω_i	single scatter albedo	modified Chebyshev	29	0.0014660	0.9999995

Table 1 shows the parameters for the test cases. The Fortran implementation took 0.0742 seconds per test case, the Python implementation took 2.45 seconds per test case, and the Mathematica implementation took 23.5 seconds per test case. More detailed timing studies are presented below.

The Asymptotic Radiance Distribution

Observations of radiance in deep waters show that the shape of the radiance distribution approaches a limiting distribution, and the rate of decay of that distribution is exponential³¹. This is known as the asymptotic radiance distribution. The maximum eigenvalue of Equation (5) characterizes this behavior.

As shown in Figures 4 and 5 and discussed below, each material has a unique largest eigenvalue v greater than 1 and a unique positive eigenvector. The rate of attenuation for each eigenvector is the reciprocal of the corresponding eigenvalue, so this positive eigenvector has the slowest rate of attenuation among the diffuse components of the intensity. Since the largest eigenvalue is also greater than 1, its rate of attenuation is also slower than the rate of attenuation of the direct component.

Hence the positive eigenvector represents the asymptotic limit of the distribution of the intensity as the optical depth increases, and the rate of convergence is given by the reciprocal of the eigenvalue. As shown in Figure 6, the maximum eigenvalue (and hence the slowest decay in diffusion) increases as absorption decreases ($\omega \rightarrow 1$) and as the forward scattering ratio increases ($g \rightarrow 1$). So the diffuse intensity decays slower than the extinction decay of the direct intensity.

However the maximum eigenvalue is close to one on the majority of the region. Such materials have a decay rate of

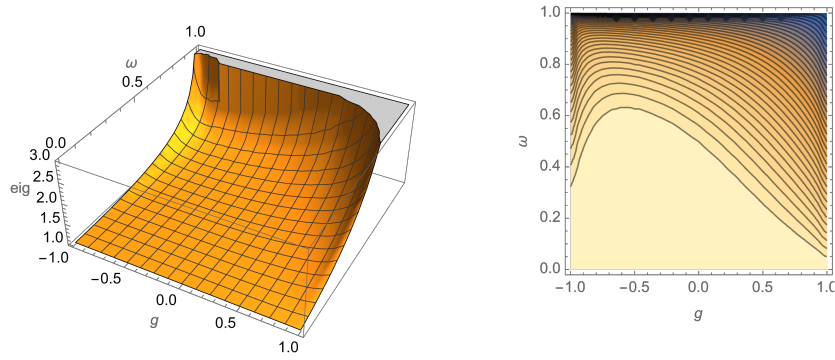


Figure 6. Maximum eigenvalues for varying asymmetry g and scatter fraction ω . The maximums increase as ω increases, i.e. as absorptency decreases.

diffusion very close to the extinction decay rate of the direct component, so are in a strong sense effectively transparent in that there is always a component of direct intensity relative to the diffuse intensity. Given the direct component source, Figure 7 shows the convergence of an opaque material to the diffusion limit, while Figure 8 shows a semi-transparent material where the direct component remains larger than the limiting diffuse component.

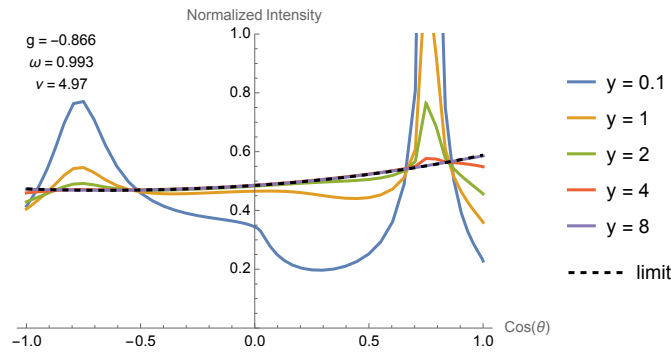


Figure 7. Asymptotic radiance distribution for a low absorptency media ($\omega = 0.993$). As depth y increases, the diffuse internal intensity dominates the direct source intensity (the peak at the right) and the normalized intensity converges to the diffusion limit.

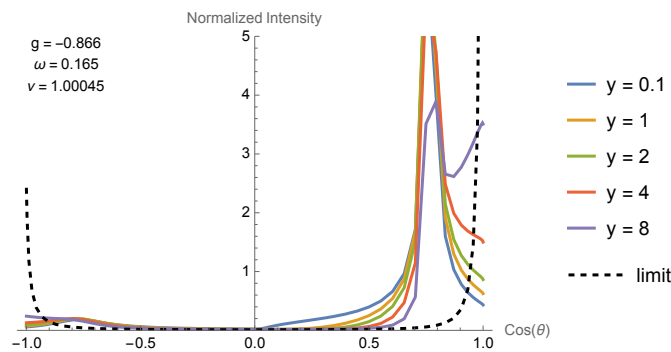


Figure 8. Asymptotic radiance distribution as depth y increases for a high absorptency media ($\omega = 0.165$). The direct source intensity (the peak at the right) dominates the diffuse limit.

Comparing Apparent Optical Properties to Two-Stream Approximation

The two-stream/Kubelka-Munk formulation provides simple analytic formulas for computing g and ω from R and η , and for the inverse. We use it as a reference baseline in our investigation of the properties of the multi-stream formulation.

The *Inherent Optical Properties*³¹ (IOP) are the properties of a media that characterize its optical behavior. For equation (1) they consist of the optical depth, the scatter fraction, and the scattering matrix. Since the numerical investigations here assume normalization by the optical depth and use the Henyey-Green one-parameter phase function, it is sufficient to use the scattering asymmetry g and the scattering fraction ω . This is also the common practice when using a two-stream approximation such as the Kubelka-Munk formulation.

The *Apparent Optical Properties*³¹ (AOP) are the observed optical properties of a media. Following common practice, we look at the measured reflectance R and attenuation coefficient η .

Figure 9 shows the reflectance and the attenuation coefficient at an optical depth of 0.75 for (a) $g = 0.85$ as ω varies from -1 to 1 , (b) $\omega = -1$ as g varies from 0 to 1 , and (c) $\omega = 1$ as g varies from 0 to 1 , for the numerical simulation and for the two-stream analytic approximation.

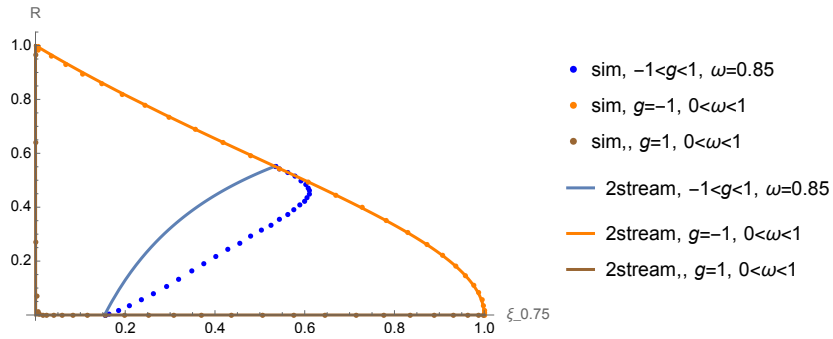


Figure 9. Reflectance and Attenuation Coefficient at 0.75 loss depth as computed by simulation and as given by the Kubelka-Munk two-stream approximation. There is agreement on the borders when $g = \pm 1$, but significant deviation in the interior when $-1 < g < 1$.

This illustrates the following:

1. The two-stream approximation agrees with the full system on the four boundaries, $\omega = \pm 1$ and $g = 0, 1$,
2. Overall error of the two-stream approximation is ≈ 0.15 .
3. The reflectance R and attenuation coefficient ξ_{75} (at transmission loss 0.75) do not uniquely determine the asymmetry g and scatter fraction ω for $g < -0.7$.

If we look at the scatter diagrams at differing transmission loss depths in Figure 10, we see that the difficulty of invertibility increases as the loss increases, the data lets us determine g and ω at loss depths of less than 50%, or for $g > -0.5$, while inversion becomes problematic for loss depths greater than 75% and $g < -0.7$.

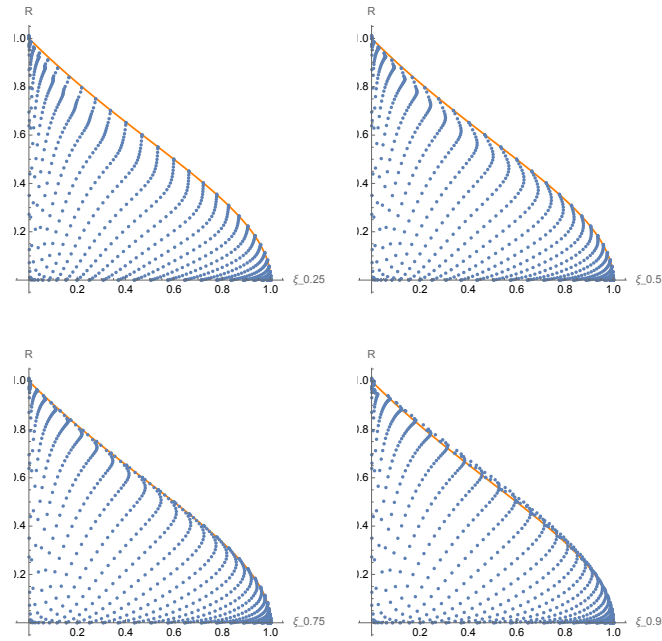


Figure 10. Scatter diagrams for reflectance R and attenuation coefficient ξ at loss depths of 25%, 50%, 75%, and 95%.

Comparison to Other Models

A choice was made as to which Radiative Transfer Models (RTMs) to compare against EigenFlux (See Table 2). The major concerns were: (1) Does the RTM explicitly model scattering? (2) Does the RTM include the visible spectrum? (3) Is it available as open access, and is it still supported? (4) Does it use its own solver or does it use a different RTM? (5) Is it mature (version > 1.0)?

These considerations led to two RTMs: DISORT and MYSTIC, of which DISORT was chosen due to its long maturity and the multiple RTMs that use it as their solver.

Table 2. Radiative Transfer Models (RTMs) considered in course of study. Does not include RTMs intended for spectrographic use which only implicitly consider multiple scattering. Does not include models that use other models as their solver. Includes only mature (version > 1.0) models under active support. List of models obtained from Wikipedia⁵⁵ and independent literature search.

Beginning of Table 2				
Name	UV/Visible?	Open Access?	Other Limitations?	Solver?
6S/6SV1 ¹	No	Yes		Successive Orders
ARTS ²	No	Yes		Discrete Ordinates Iterative, Monte Carlo

¹6S/6SV1, "Second Simulation of a Satellite Signal in the Solar Spectrum vector code", <https://salsa.umd.edu/6spage.html>, (accessed May 6, 2026)

²ARTS, "The Atmospheric Radiative Transfer Simulator", <https://www.radiativetransfer.org/about/>, (accessed May 6, 2026)

Continuation of Table 2				
Name	UV/Visible?	Open Access?	Other Limitations?	Solver?
CRTM ³	Yes	Not publicly released		Doubling-Adding, Successive Orders
DART ⁴	No	Yes for research with public funding		Transfer function iteration
DISORT ⁵	Yes	Yes		Discrete Ordinates
HydroLight ⁶	Yes	Commercial		Invariant Imbedding
libRadtran ⁷	Yes	Yes		Uses DISORT, MYSTIC
LinePak ⁸	Yes	On-line only		
MODTRAN ⁹	Yes	No		
MYSTIC ¹⁰	Yes	Yes (See libRadtran)		Monte Carlo
RTMOM ¹¹	Yes	No		Method Of Moments
SCIATRAN ¹²	Yes	Yes	Scattering limited to built-in functionality	Discrete Ordinates
SMART-G ¹³	Yes	Yes	Requires GPU	Monte Carlo
SMRT ¹⁴	No	Yes	Specialized for snow pack	Discrete Ordinates
VLIDORT/ LIDORT ¹⁵	Yes	By request		Discrete Ordinates
End of Table 2				

³CRTM, "Community Radiative Transfer Model (CRTM)", <https://www.jcsda.org/jcsda-project-community-radiative-transfer-model>, (accessed May 6, 2026)

⁴DART, "The Discrete Anisotropic Radiative Transfer Model", <https://dart.omp.eu/#/>, (accessed May 6, 2026)

⁵DISORT, "LLLab DISORT Website", <http://www.rtmocn.com/disort/>, (accessed May 6, 2026)

⁶HydroLight, "HydroLight", <https://www.numericaloptics.com/hydrolight.html>, (accessed May 6, 2026)

⁷libRadtran, "libradtran", <https://www.libradtran.org/doku.php>, (accessed May 6, 2026)

⁸LinePak, "Spectral Calc.com: High-resolution spectral modeling", <https://www.spectralcalc.com/info/about>, (accessed May 6, 2026)

⁹MODTRAN, "MODTRAN@", <http://modtran.spectral.com>, (accessed May 6, 2026)

¹⁰MYSTIC, "MYSTIC - the Monte Carlo code for the physically correct tracing of photons in cloudy atmospheres", <http://www.bmayer.de/index.html?mystic.html&1>, (accessed May 6, 2026)

¹¹RTMOM, "Radiative Transfer Model Comparison with Satellite Observations over CEOS Calibration Site Libya-4", <https://www.mdpi.com/2073-4433/13/11/1759>, (accessed May 6, 2026)

¹²SCIATRAN, "SCIATRAN: RADIATIVE TRANSFER MODEL AND RETRIEVAL ALGORITHM", <https://www.iup.uni-bremen.de/sciatran/>, (accessed May 6, 2026)

¹³SMART-G, "SMART-G: a Monte Carlo GPU Radiative Transfer code", <https://hygeos.com/en/smart-g/>, (accessed May 6, 2026)

¹⁴SMRT, "SMRT: Snow Microwave Radiative Transfer model", <https://smrt-model.science>, (accessed May 6, 2026)

¹⁵VLIDORT/LIDORT, "Overview of RT Solutions Products", http://www.rtslidort.com/about_overview.html, (accessed May 6, 2026)

Phase Function Limitations

Of the tools considered, the snow and ice models are intended for highly forward scattering problems. Since they use the DO method, they are subject to the instability problems that come with using Legendre expansions of a highly asymmetric phase function. They ameliorate those problems with the use of variations on a specific technique, called the $\delta - N$ method in Thomas-Stamnes⁵¹, which treat forward scattering light particles as non-scattering transmitted particles. But as we see below in Figure 16, the effect of this is limited.

Stamnes. et. al.⁴⁸ report that while snow grains have asymmetry $g = 0.9$, brine pockets have asymmetry $g = 0.997$. Their tool, CASIO-DISORT, derived from DISORT, was limited practically to $g_{max} \leq 0.9$. The higher g required for brine-snow mixtures was achieved through a reduced forward scattering transformation⁴⁸ which is essentially an externally applied $\delta - N$ method.

We can see some of the advantages of the mesh approximation over the Legendre decomposition in managing phase functions. Figure 11 shows the approximations of the cloud phase function defined in Garcia-Stewart¹⁷, which contains both strongly forward scattering and a significant backward scattering component. Approximations used are those used in the case of $n = 56$ streams.

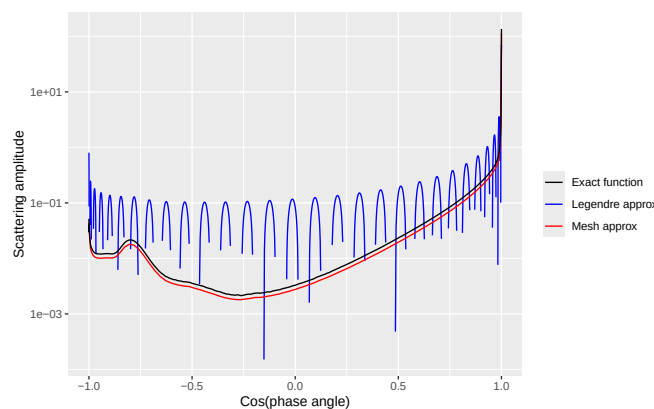


Figure 11. Cloud phase function and approximations for $n=56$. The original phase function is strongly forward scattering, but also has a significant backward scattering component. The gaps in the Legendre approximation are due to the approximation going negative.

Accuracy and Timing Studies

To establish the accuracy of the EigenFlux algorithm, numerical investigations were conducted on a MacBook Pro with 2.6 GHz 6-Core Intel Core i7, 16Gb of RAM, running Tahoe V26.3.1. The final algorithm was coded in GNU Fortran 2008. The accuracy of the implementation was first verified by hand comparisons to published tables (see Table 35 in Van Hulst⁵³).

The distribution for DISORT4 was downloaded from the *Light and Life Lab* website²⁷, along with its standard test suite, and compiled with the same compiler and options as Eigenflux was.

To provide a more general coverage of accuracy over a range of conditions, the error between the computed solution and the reference equation was computed. The integral formulation (2) was used as the reference equation because it is a numerically stable exact form. A Schlick phase distribution^{4,35} was used as the reference phase kernel for two reasons 1) it is very similar to the popular Henyey-Greenstein phase distribution, 2) its kernel function $K(v, w)$ has a simple analytic form, allowing the exact kernel to be used in the reference equation.

Runs were performed for varying number of streams ranging from 14 to 280, for a Chebyshev mesh and for a linear mesh. Each run included 49 test cases varying scattering fractions from 0.012 to 0.987 and for asymmetry varying from -0.975 to +0.975.

Figure 12 shows the accuracy as a function of the number of streams for the Chebyshev mesh and for the linear mesh. It shows that the Chebyshev mesh is more accurate by a range of 1 to 2 orders of magnitude. There is significant variance in the accuracy across the 49 test cases of differing scattering fraction and asymmetry. Roughly speaking, an increase in number of streams of 30 times results in one order of magnitude increase in accuracy.

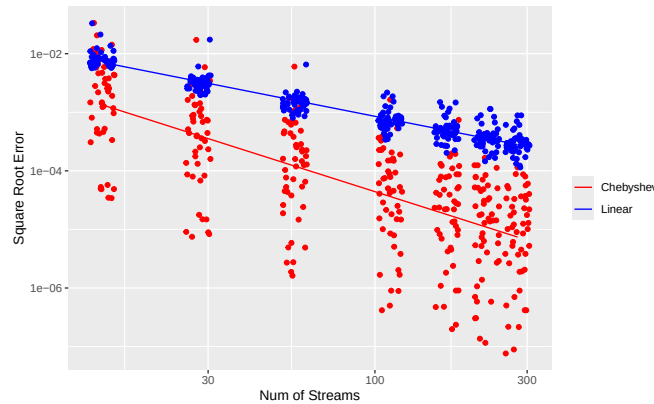


Figure 12. Error as a function of number of streams for Chebyshev spacing and for linear spacing, plotted on a log-log scale. The error is the integration of the squared error between the intensity and its reference equation. Fitting was made to a log-log curve. Jitter added to number of streams to expand point cloud.

The change in accuracy for EigenFlux across the test cases is largely a function of the scatter fraction- the lower the absorption, the lower the accuracy as in Figure 13. Figure 14 shows that there is a weak tendency for the method to be more accurate at the extreme points of asymmetry.

The change in accuracy for DISORT across the test cases is similar in behavior to EigenFlux as a function of the scatter fraction- the lower the absorption, the lower the accuracy as in Figure 15. However unlike EigenFlux, Figure 16 shows DISORT is less accurate at the extreme points of asymmetry.

The same input parameters were used to directly compare the EigenFlux and DISORT results and timing. The Henyey-Greenstein phase function was used for these comparisons.

One issue in the comparison is that EigenFlux always computes across a spanning set of source functions, whereas DISORT

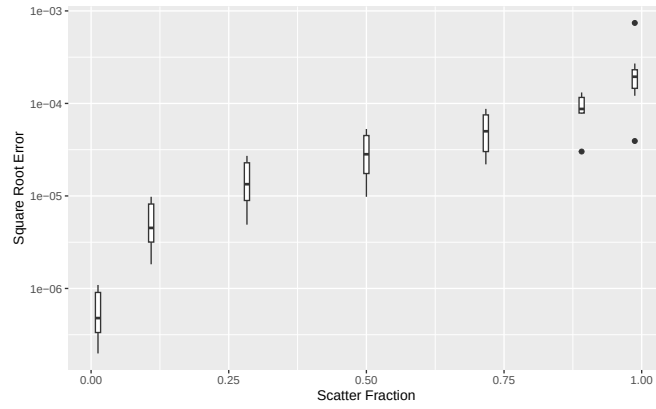


Figure 13. Boxplot of EigenFlux error as a function of scatter fraction. Data is for the run with $nn = 168$. Lower absorptency increases error.

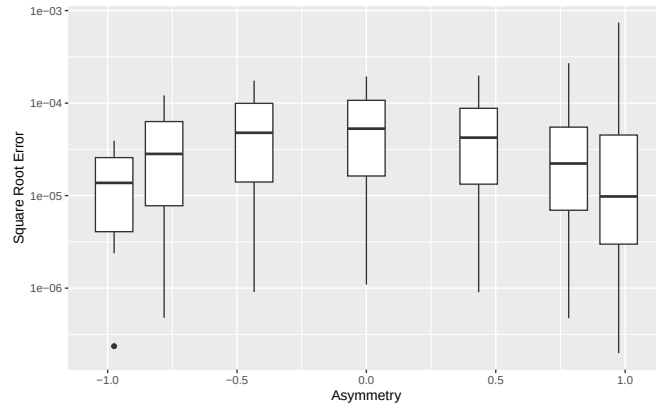


Figure 14. Boxplot of EigenFlux error as a function of asymmetry. Data is for the run with $nn = 168$. Strong asymmetry decreases error slightly.

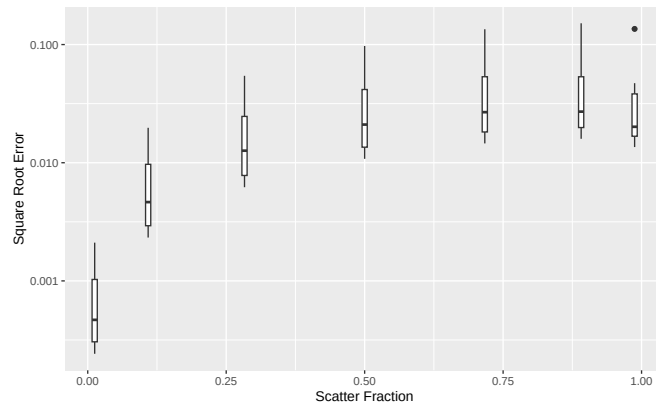


Figure 15. Boxplot of DISORT error as a function of scatter fraction. Data is for the run with $nn = 168$. Lower absorptency increases error.

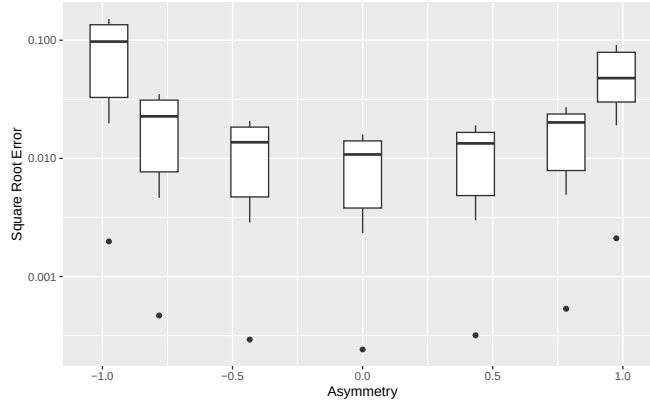


Figure 16. Boxplot of DISORT error as a function of asymmetry. Data is for the run with $nn = 168$. Strong asymmetry increases error.

374 computes a single source function at a time. As a result, the DISORT times in Figure 17 were scaled to correspond to the
 375 EigenFlux usage. The result shows that DISORT is faster for lower numbers of streams, whereas EigenFlux is faster for higher
 376 numbers of streams, with a crossover at $n = 56$.

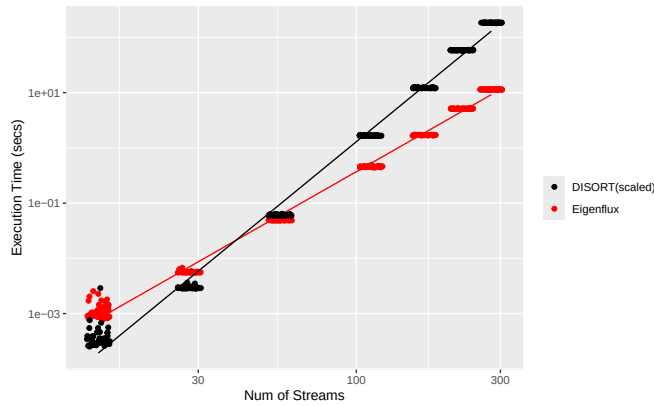


Figure 17. Execution time for EigenFlux vs. DISORT, plotted on a log-log scale. DISORT times have been scaled by number of source beams since EigenFlux always computes multiple source beams.

377 The difference between the intensities computed by EigenFlux versus DISORT show considerable variance, as seen in
 378 Figure 18. Figures 20 and 19 show that this is largely a factor of the asymmetry- DISORT's solution deteriorates for strongly
 379 scattering problems.

380 Conclusions

381 EigenFlux is a novel approach to solving the radiative transfer problem, using a natural reflectance structure and a Galerkin
 382 mesh approximation scheme that allows for flexible calculation points including linear and Chebyshev point distributions,
 383 which in turn allows for accurate reduced order approximations of phase functions which are strongly forward scattering or

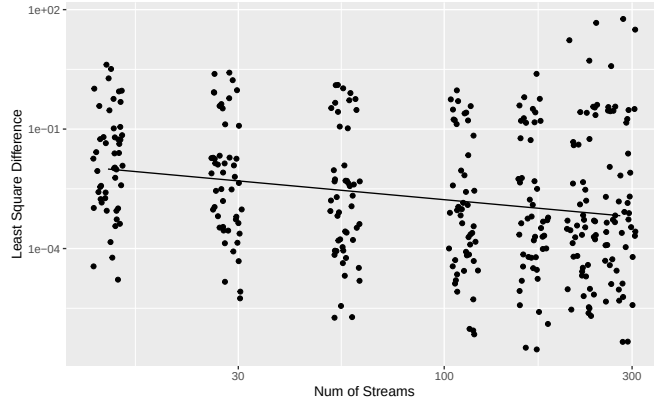


Figure 18. Least square difference between intensities computed by EigenFlux vs. DISORT, plotted on a log-log scale. Jitter added to number of streams to expand point cloud.

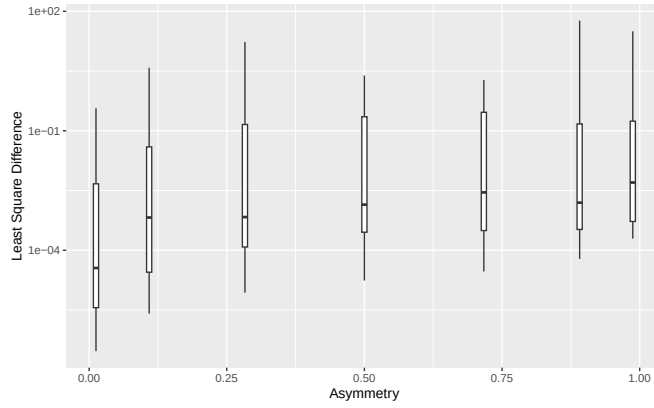


Figure 19. Least square difference between EigenFlux and DISORT as a function of scattering fraction, plotted on a log scale. Lower absorbency increases the difference, very slightly.

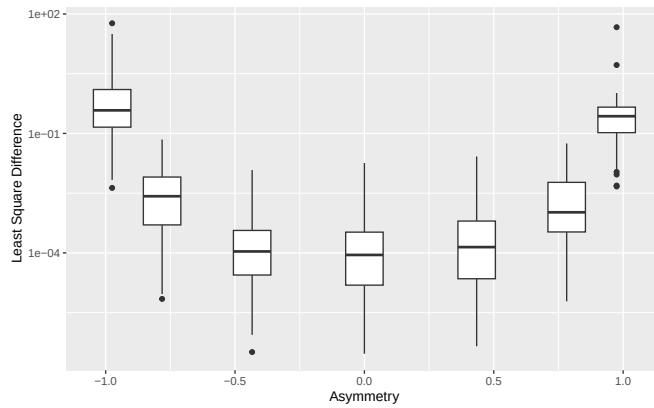


Figure 20. Least square difference between EigenFlux and DISORT as a function of asymmetry, plotted on a log scale. Strong asymmetry increases the difference.

have significant backward scattering components. The resulting implementation shows strong numerical accuracy and favorable computational scaling in comparison with DISORT across the test cases investigated here. The primary novelty of EigenFlux lies in its combination of natural-reflectance stabilization, localized mesh approximations, and eigenmode decomposition, allowing stable treatment of highly asymmetric scattering regimes that are difficult for conventional discrete-ordinate methods.

Figure 14 shows that EigenFlux is more accurate for extreme scattering points while Figure 20 shows that the comparable DISORT code is less accurate for the same extreme points. Figure 17 shows that EigenFlux is faster than DISORT for larger numbers of streams, with an even breakpoint at about 56 streams.

Analytically, EigenFlux provides insights into the nature of RTM intensity structures. The max eigenvalue determines the limiting distribution of the intensity, and dictates the degree to which the diffuse intensity overcomes (or fails to overcome) the direct intensity as depths increase. In a low-absorbency system such as snow and ice, the diffuse intensity quickly overcomes the direct intensity.

The analysis here also shows that for low absorbance systems such as snow and ice, the use of two-stream approximation as an inverse model to infer the asymmetry and single stage albedo from measured transmission and reflectance can be problematic as multiple values for the asymmetry and single stage albedo can result in identical transmission and reflectance measures.

The present implementation of EigenFlux is limited to scalar radiative transfer in plane-parallel geometries and does not currently include polarization, thermal emission, or fully spherical atmospheric effects. Inhomogeneous systems are represented through combinations of homogeneous layers rather than through fully continuous spatial variation. These limitations define important directions for future development. Future work could include extension to pseudo-spherical geometries, inclusion of polarization and thermal emission, adaptive mesh refinement, and optimization for specific architectures. The flexible mesh and eigenmode structure of EigenFlux may also prove useful for inverse retrieval applications and coupling to atmospheric, oceanographic, and graphics-rendering systems.

Data Availability

Materials described in the manuscript are available from the University of Copenhagen Electronic Research Data Archive at address: <https://doi.org/10.17894/ucph.cfd8e267-97f3-496d-b434-e29984b931c8>

References

1. Adjerd, S. & Baccouch, M. "Galerkin methods", *Scholarpedia*, Vol. 5, pp. 10056, 10.4249/scholarpedia.10056 2010
2. Akbari, H., *et al.* "Cool colored materials for roofs" *Proceedings of American Council for an Energy Efficient Economy* Asilomar Conference Center in Pacific Grove, CA., Aug. 2004
3. Akkaynak, D. & Treibitz, T. "Sea-Thru: A Method for Removing Water From Underwater Images," *2019 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*, Long Beach, CA, USA, 2019, pp. 1682-1691, 2019

- 414 4. Blasi, P., Le Saec, B. and Schlick, C., "A Rendering Algorithm for Discrete Volume Density Objects" *Computer Graphics*
415 *Forum*, 12: 201-210, <https://doi.org/10.1111/1467-8659.1230201>, 1993
- 416 5. Blinn, J. F. "Light reflection functions for simulation of clouds and dusty surfaces" *Computer Graphics*, 16(3), 21-29, 1982
- 417 6. Buras, R. & Mayer, B. "Efficient unbiased variance reduction techniques for Monte Carlo simulations of radiative transfer in
418 cloudy atmospheres: The solution", *J. Quant. Spectrosc. Radiat. Transfer*, 112,434–447, 2011
- 419 7. Chandrasekhar, S. *Radiative Transfer*, Oxford Publications, Oxford, 1950, (reprinted Dover Publications, New York, NY,
420 1960.)
- 421 8. Chwolson, O. D. "Grundzüge einer mathematischen Theorie der inneren Diffusion des Lichtes". *Bull. Acad. Imp. Sci. St.*
422 *Petersburg*, Nouvelle Série I (XXXIII), 221-256. 1889.
- 423 9. Coakley, J. A. "Reflectance and Albedo, Surface" , *Encyclopedia of Atmospheric Sciences*, Elsevier, 2003
- 424 10. Davis P.R. *Circulant Matrices*, John Wiley, New York. 1979.
- 425 11. Davis P.R. *Linear Operators and their Spectra*, Cambridge Studies in Advanced Mathematics 106, Cambridge University
426 Press, Cambridge, UK. 2007.
- 427 12. d'Eon, E. *A Hitchhiker's Guide to Multiple Scattering*, <https://eugenedeon.com/hitchhikers>
- 428 13. Eddington, A.S. "On the radiative equilibrium of the stars", *Monthly Not. of the Royal Astro. Soc.*, 77, 16-35, 1916
- 429 14. Ehn, J. K., T. N.Papakyriakou, and D. G.Barber "Inference of optical properties from radiation profiles within melting
430 landfast sea ice", *J. Geophys. Res.*, 113, C09024, 2008, <https://doi.org/10.1029/2007JC004656>
- 431 15. Emde, C., Buras, R., Mayer, B., & Blumthaler, M. "The impact of aerosols on polarized sky radiance: model development,
432 validation, and applications", *Atmos. Chem. Phys.*, 10, 383–396, 2010.
- 433 16. Emde, C., *et al.* "The libRadtran software package for radiative transfer calculations (version 2.0.1)", *Geosci. Model Dev.*,
434 9, 1647–1672, 2016
- 435 17. Garcia, R. & C. Siewert, "Benchmark Results in Radiative Transfer" *Transp. Theory and Stat. Physics*, 14, 437-484, 1985
- 436 18. Goody, R. M. & Yung, Y. L. *Atmospheric Radiation, Theoretical Basis, 2nd Ed.*, Oxford University Press, New York, 1989
- 437 19. Hamre, B., J.-G.Winther, S.Gerland, J. J.Stamnes, and K.Stamnes "Modeled and measured optical transmittance of
438 snow-covered first-year sea ice in Kongsfjorden, Svalbard", *J. Geophys. Res.*, 109, C10006, 2004, [https://doi.org/10.1029/](https://doi.org/10.1029/2003JC001926)
439 [2003JC001926](https://doi.org/10.1029/2003JC001926).
- 440 20. HydroLight, *Radiative Transfer Software*, <https://www.numericaloptics.com/hydrolight.html>, 2020.
- 441 21. Kajiya, J. T. & Von Herzen, B. P. "Ray tracing volume densities", *Computer Graphics (Proceedings of SIGGRAPH '84*,
442 Vol. 18, 165-74 1984
- 443 22. Koleske, J. V. (ed.), *Paint and Coating Testing Manual*, ASTM, Philadelphia, PA, 14th Edition, 1995.

- 444 **23.** Kubelka, P. & Munk, F. "Ein Beitrage zur Optik der Farbenstriche", *Zeitschrift Fur Technische Physik*, #12, p. 593, 1931
- 445 **24.** Kubelka, P. "New Contributions to the Optics of Intensely Light Scattering Materials– Part I", *Journal Optical Society of*
446 *America*, #38, p448, 1948
- 447 **25.** Levinson, R., Berdahl, P., & Akbari, H. "Solar spectral optical properties of pigments—Part I: model for deriving scattering
448 and absorption coefficients from transmittance and reflectance measurements", *Solar Energy Materials and Solar Cells*,
449 Volume 89, Issue 4, Pages 319-349, 2005
- 450 **26.** Liou, K. N. , *An Introduction to Atmospheric Radiation*, 2nd Ed., Academic Press, 2002
- 451 **27.** LLLab, "LLLab DISORT Website", Accessed July 21, 2023, <http://www.rtatmocn.com/disort/>
- 452 **28.** Lommel, E. "Die Photometrie der diffusen Zurückwerfung" , *Sitzungsberichte der mathematische und physikalische Classe*
453 *der Königlichen Bayerische Academie zu München*, 17, 95-132, 1887.
- 454 **29.** Milne, E. A. "Radiative Equilibrium in the Outer Layers of a Star: the Temperature Distribution and the Law of Darkening".
455 *Monthly Notices Royal Astron. Soc.* 81(5), 361-375. 1921.
- 456 **30.** Mishchenko, M.I. "125 years of radiative transfer: Enduring triumphs and persisting misconceptions". *Radiation Processes*
457 *in the Atmosphere and Ocean*. AIP Conf. Proc. 1531, 11-18. doi 10.1063/1.4804696. 2013.
- 458 **31.** Mobley, C.D. *Light and Water: Radiative Transfer in Natural Waters* Academic, San Diego. 1994
- 459 **32.** Nicodemus, F.E., Richmond, J.C., Hsia, J.J., Ginsberg, I.W. & Limperis, T. , *Geometrical Considerations and Nomenclature*
460 *for Reflectance*, National Bureau of Standards, October, 1977
- 461 **33.** NIST, *Digital Library of Mathematical Functions*, <https://dlmf.nist.gov>, Oct. 19, 2020.
- 462 **34.** Petty, G. W. *A First Course in Atmospheric Radiation*, Sundog Publishing, Madison, WI, 2nd edition, 2006.
- 463 **35.** Pharr, M. & Humphreys, G., *Physically Based Rendering: From Theory to Implementation*, MIT Press, 2004
- 464 **36.** Pharr, M., Jakob, W. & Humphreys, G., *Physically Based Rendering, Fourth Edition: From Theory to Implementation*,
465 MIT Press, 2023
- 466 **37.** Picard, G., Sandells, M., and Löwe, H.: "SMRT: an active–passive microwave radiative transfer model for snow with
467 multiple microstructure and scattering formulations (v1.0)", *Geosci. Model Dev.*, 11, 2763–2788, 2018, [https://doi.org/10.](https://doi.org/10.5194/gmd-11-2763-2018)
468 [5194/gmd-11-2763-2018](https://doi.org/10.5194/gmd-11-2763-2018)
- 469 **38.** Preisendorfer, R. W. "A survey of theoretical hydrologic optics", *Journal of Quantitative Spectroscopy and Radiative*
470 *Transfer*, Vol. 8, Issue 1, Pages 325-338, 1968, [https://doi.org/10.1016/S0022-4073\(68\)80116-5](https://doi.org/10.1016/S0022-4073(68)80116-5).
- 471 **39.** Preisendorfer, R. W. *Hydrologic Optics*, in 6 volumes: *Vol. 1: Introduction*, NTIS PB-259 793/8ST; *Vol. 2: Foundations*,
472 NTIS PB-259 794/6ST; *Vol. 3: Solutions*, NTIS PB-259 795/3ST; *Vol. 4: Imbeddings*, NTIS PB-259 796/1ST; *Vol. 5:*
473 *Properties*, NTIS PB-259 797/19ST; *Vol. 6: Surfaces*, NTIS PB-268 704/4ST; Pacific Mar. Environ. Lab/NOAA, Seattle,
474 WA. 1976

- 475 **40.** Raman, C.V. "On the molecular scattering of light in water and the colour of the sea", *Proc. R. Soc. Lond. A*, 101:64–80,
476 <https://royalsocietypublishing.org/doi/10.1098/rspa.1922.0025>, 1922
- 477 **41.** Rayleigh, Lord., "On the light from the sky, its polarization and colour", *Phil. Mag.*, 41:107-120. 274-279. 1871.
- 478 **42.** Schuster, A., "Radiation through a foggy atmosphere". *Astrophys. J.* XXI(I), 1-22. 1905.
- 479 **43.** Schwarzschild, K., "Ueber das Gleichgewicht der Sonnenatmosphäre". *Nachrichten von der Königlischen Gesellschaft der*
480 *Wissenschaften zu Göttingen, Mathematische-Physikalische Klasse*, 195, 41-53. 1906.
- 481 **44.** Schwarzschild, K., "Über Diffusion and Absorption in der Sonnenatmosphäre". *Sitzungsberichte der Königlischen Preussis-*
482 *chen Akademie der Wissenschaften*, 47, 1183-1202. 1914.
- 483 **45.** Shoulejkin, W. "On the Color of the Sea", *Phys. Rev.* 22, 85, 1923
- 484 **46.** Sinkhorn, R., and Knopp, P., "Concerning nonnegative matrices and doubly stochastic matrices", *Pacific Journal of*
485 *Mathematics*, 21(2):343–348, 1967
- 486 **47.** Stamnes, K., Tsay, S., Wiscombe, W. & Jayaweera, K., "Numerically stable algorithm for discrete-ordinate-method
487 radiative transfer in multiple scattering and emitting layered media", *Applied Optics*, Vol. 27 page 2502, 1988
- 488 **48.** Stamnes, K., Hamre, B., Stamnes, J.J., Ryzhikov, G., Biryulina, M., Mahoney, R., Hauss, B., Sei, A., "Modeling of
489 radiation transport in coupled atmosphere-snow-ice-ocean systems", *Journal of Quantitative Spectroscopy and Radiative*
490 *Transfer*, Volume 112, Issue 4, 2011, Pages 714-726, ISSN 0022-4073, <https://doi.org/10.1016/j.jqsrt.2010.06.006>
- 491 **49.** Tee, G.J. "A novel finite-difference approximation to the biharmonic operator", *The Computer Journal*, 6 (2), 177–192.
492 MR29 #6646. 1963.
- 493 **50.** Tee, G. J. "Eigenvectors of Block Circulant and Alternating Circulant Matrices", *New Zealand Journal of Mathematics*, 36:
494 195–211. 2007.
- 495 **51.** Thomas, G. E., & Stamnes, K. *Radiative Transfer in the Atmosphere and Ocean*, Cambridge University Press, Cambridge,
496 UK, 1999. 2005
- 497 **52.** Torrance, K.E. & Sparrow, F.M. "Theory for Off-Specular Reflection From Roughened Surfaces" *J. OSA*, Vol. 57, #9,
498 1105-1114, Sept. 1967
- 499 **53.** Van De Hulst, H. C., *Multiple Light Scattering, Tables, Formulas, and Applications*, Vol 2, Academic Press, New York,
500 1980.
- 501 **54.** Varytis, P., & Busch, K., "Negative asymmetry parameter in plasmonic core-shell nanoparticles", *Opt. Express* 28,
502 1714-1721, 2020, <https://doi.org/10.1364/OE.380181>
- 503 **55.** Wikipedia contributors, "Atmospheric radiative transfer codes," *Wikipedia, The Free Encyclopedia*, [https://en.wikipedia.](https://en.wikipedia.org/w/index.php?title=Atmospheric_radiative_transfer_codes&oldid=1350763300)
504 [org/w/index.php?title=Atmospheric_radiative_transfer_codes&oldid=1350763300](https://en.wikipedia.org/w/index.php?title=Atmospheric_radiative_transfer_codes&oldid=1350763300), (accessed May 6, 2026).