RADIATIVE TRANSFER AND SPECTROPHOTOMETRIC CHARACTERIZATION OF MINERAL DUST OPTICS ON PHOTOVOLTAIC CELLS

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Atmospheric Science

by

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ABSTRACT

Efficiency of solar cells is degraded by deposition of mineral dust as well as other particles, and experiments reveal that losses can be significant (up to \( \sim 85\% \)) depending on various factors. However, little is known about the role of light scattering and absorption in reducing optical transmission to the solar cell semiconductor. This dissertation first develops a fundamental model of optical losses due to particle-on-substrate scattering for light propagating into the forward direction. We use discrete dipole approximation with surface interaction (DDA-SI), which is a numerical solution of light scattering for an arbitrarily shaped particle-on-substrate. Using DDA-SI, we studied transmission losses due to hemispheric backward scattering (HBS) and absorption. A parameter called the fraction of power lost, defined as the ratio of HBS efficiency plus absorption efficiency to extinction efficiency, was found appropriate to describe optical losses into the forward direction. We found that fine particles lead to higher losses (per optical depth or layer optical thickness) than coarser ones. Losses into the forward direction are maximized when the ratio of skin depth to particles diameter approaches unity.

In addition, we conducted a resuspension-deposition experiment with two types of mineral dust, optically absorbing and non-absorbing dust. The dust samples were suspended and deposited onto glass slides, acting as surrogates for solar cells. Dust-deposited glass slides with increasing amounts of mass per area were spectroscopically characterized using a spectrophotometer with an integrating sphere (SIS) detector system. The SIS device allowed us to measure forward-hemisphere scattering, HBS, and direct beam transmission. Transmission into the forward direction was found to decrease as function of optical depth, depending on the absorptivity of the dust. Multiple-scattering radiative transfer theory, specifically the two-stream model as well as Monte Carlo stochastic calculations, were used.
to describe transmission as function of optical depth for both absorbing and non-absorbing dust, yielding good agreement with experimental results within ~5%.

Two-stream model and Monte Carlo techniques yield a multiple-scattering transmission calculation that depends on the single-scattering parameters of albedo and asymmetry parameter.

This study has the potential to help with solar energy forecasting, aiding smart power grids in predicting and adapting to variations in solar cell energy output due to aerosol deposition. In addition, this study can help optimize cleaning procedures and schedules to save water in desert and semi-arid regions by describing transmission losses as function of dust type.
This dissertation is dedicated to my family, especially to my loving wife, Carissa, and my sweet baby daughter, Emiliana. Both of you are my source of strength and my daily supply of endurance.
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CHAPTER 1
MOTIVATION AND INTRODUCTION

1.1 Photovoltaic Cells and Optical Effects Of Particles Deposited on Them

Due to the increasing global concentration of carbon dioxide over the last century (Brown and Keeling, 1965; Pales and Keeling, 1965; Stocker, 2014), the need for non-carbon-emitting, sustainable energy has favored solar energy as one key source to replace energy produced from fossil fuels. Solar energy has the potential of being clean, inexpensive, with an enormous output; for instance, Mekhilef et al. (2012) note that "energy received from the Sun on the Earth’s surface in one hour equals to the amount of approximately one year energy needs of the Earth.” Solar energy is mostly produced by the use of photovoltaic (PV) cells, which are exposed to solar radiation and use semiconductors to convert solar radiation into electric energy. However, although costs of PV technology have decreased over time, PV solar energy remains cost-prohibitive, with reports indicating that PV energy can be nearly 50% more expensive than energy generated by fossil fuels (Reichelstein and Yorston, 2013). For this reason, one of the most important current aims of the U.S. Department of Energy (DoE) is the reduction of cost of PV solar energy to less than $0.08 per kW-h (Fu et al., 2017; Initiative, 2012). There are many factors that influence the cost of PV cell technology. One factor of important consideration is the cost of deterioration of the PV cell as function of environmental conditions, with one of the most significant factors being the loss of efficiency as function of accumulation of particles on the PV cell surface. Efficiency losses of the PV cell due to deposition of particles, can potentially incur added costs per kW-h due to
maintenance and water costs. Particularly problematic for PV cell technology is the fact that many PV cells are located in desert regions where water is scarce and thus cell cleaning by washing can considerably impact PV energy cost.

1.2 Particles on Remote PV Cells: Earth, Mars, and Beyond

The deposition of particles on PV cells also affects costs of solar energy for remote locations that are usually off-grid (i.e., areas which are too remote to be connected to grid-connected electric circuits). However, remote areas of the world can benefit substantially from PV solar energy since it does not require large infrastructures. Still, recent estimates of costs for these locations (Centeno Brito et al., 2014) suggest PV solar energy can average $\sim$0.08 dollars per kW-h, in addition to being the energy source with the lowest environmental footprint. Other types of energy such as wind and hydroelectric energy are estimated at $\sim$0.05 and $\sim$0.04 dollars per KW-h, being cheaper than solar but having larger environmental footprint and requiring large infrastructures. Hence, reducing costs of solar energy production in maintenance and cleaning can benefit expansion of PV solar energy making it cost-competitive with other types of energy. In this study, we have examined PV efficiency losses due to particle deposition to help with solar forecasting and with optimizing cleaning procedures and schedules. For example, Chapter 3 shows that transmission losses on PV cells due to non-absorbing particles can be approximately half of those due to absorbing particles. Hence, understanding the type of particles that deposit onto PV cells in a particular area, can lead to selectively cleaning PV cells depending on the optical characteristics of the particles expected for a specific PV cell location.
Dust deposition is a very significant factor for energy forecasting and PV cell efficiency in planetary exploration. Perhaps there is no better example of a remote location that epitomizes the need to understand how particles deteriorate PV cells as Mars. Energy for land probes and space stations on Mars is going to be largely supplied by solar cells. A NASA memorandum on Mars exploration explicitly states that “there is little doubt that photovoltaic arrays [i.e., solar cells] will play an important role” (Gaier and Perez-davis, 1991). Martian dust deposition on solar cells is further enhanced because Martian dust is electrostatically charged and adheres strongly to surfaces such as those of solar cells (Mazumder et al., 2006). Studies on PV cells deposited with Lunar dust reveal that just a small amount of dust (∼30 g/m²) reduces optical transmission of PV cells by 50% (Katzan et al., 1991). As shown by our experiments in Chapter 3, Martian dust being largely composed of hematite Fe₂O₃ (McSween et al., 1999) would reduce transmittance by > 50%. Furthermore, the difficulty of performing ad-hoc experiments in these remote locations highlights the importance for developing analytical methods that can be used to estimate PV cell efficiency in these environments.

1.3 Current State of Research

From the physics perspective, when particles such as dust, smoke, and/or biological particles deposit onto PV cells, they can scatter and absorb radiation and reduce the transmittance of radiation onto the PV cells semiconductor. Studies on PV cells efficiency deterioration due to deposition of particles report deteriorations ranging from ∼1% to ∼90% depending on loading, composition of the deposited particles, varying exposure time, angle tilt, wind and humidity (Sulaiman et al., 2014; Mani and Pillai, 2010). With few exceptions, the majority of PV cell studies
consider deterioration of the PV cell as function of time under varying experimental setups, taking in consideration the number of days, hours, or months that a PV cell was exposed to its environment (Maghami et al., 2016). Although these studies are important for understanding deterioration of PV cells at a particular location, it is not the time but the number of particles deposited in the PV cell as well as the optical characteristics of the particles that determine the optical efficiency loss of the PV cell. This is an idea that has not widely been studied and that requires more attention in the research community. For example, Al-Hasan (1998) notes that “...most of the [previous] research work was based on the number of days, weeks or months that the panels were exposed to sand dust accumulation... It is the amount of sand dust accumulated on the panels which should be correlated with light or solar radiation.” Adding complication to this issue is the fact that many particles can scatter radiation into the hemispheric forward direction, leading to the nuance factor that radiation can penetrate into the PV cell semiconductor despite the presence of particle scattering. In fact as shown in Chapter 2, transmission of solar radiation into the PV cell can be deteriorated by intensive factors independent of the number of particles on the PV cell as well as by extensive factors that depend on the number of particles. This consideration shows that deposition of non-optically absorbing particles onto a PV cell can potentially be tolerated while deposition of optically absorbing particles can deteriorate the PV cell output to a much greater extent. Hence, given an efficiency deteriorating tolerance (e.g., 10%), the number of deposited particles is not the only deteriorating factor, but the type of particles (i.e., size, morphology, composition) greatly contributes. Studies on the effects of soiling of PV cells that solely consider time as a deteriorating factor do not adequately generalize their results to different locations, where deposition rates and types of deposited particles may vary significantly. This work is an at-
tempt to find some generalized patterns that can be used to understand optical losses by particles regardless of location.

1.4 A Brief Description of Photovoltaic Technology

PV solar energy is produced using the photovoltaic effect, a process that is analogous to the photoelectric effect (Einstein 1965). The photovoltaic effect is the generation of electric current when light interacts with a semiconductor. To understand how this process functions, we must review some basic notions of diodes and electron-hole pairs. Diodes are formed by combining properties of two semiconductors in what is known as a PN-junction. The first semiconductor, namely P (for positive), has the property of leaving some of the semiconductor material unoccupied by electrons; this is known as electron-holes. The second semiconductor material, the N (for negative), has the property of having a number of electrons free. When the two materials are contacted side by side into the PN-junction, electron-holes act as charged positive particles and disperse randomly in the same manner that electrons do. Eventually, both electron-holes and electrons reach an equilibrium when there is an electric potential difference sufficiently large to prevent further dispersion of electrons and electron holes. The net effect of this charge polarization is that when an electric field is applied into the diode, depending on its direction, the voltage will tend to either polarize the junction further or decrease the level of charge polarization. This means that charge will preferentially flow in the direction that the PN junction becomes less charge polarized, and that a state of permanent charge polarization (i.e., voltage potential) has been reached by the PN-junction. Upon this configuration, if an electromagnetic wave interacts with the PN-junction, it will excite some of the electrons of the N material. The net ef-
fect is that if electrons are allowed to flow, for instance through an electric cable, they will generate a current. Most PV systems have strong spectral response within the spectral range from $\sim 400 \text{ nm}$ to $\sim 1500 \text{ nm}$ (Green et al., 2015; Kinsey and Edmondson, 2009). The current conversion efficiency (i.e., the fraction of light converted to electric energy) record holder is a multi-junction solar cell semiconductor developed by Soitec and the Fraunhofer Institute of Solar Energy (Dimroth et al., 2014). This system has the strongest spectral response from 300 nm to 1750 nm, converting approximately one quarter of all incident solar power into electrical power.

1.5 Outline of this Dissertation

This dissertation is a compilation of two manuscripts that were submitted to Solar Energy, which is the official journal of the International Society of Solar Energy and is published by Elsevier Publishing company. The first article has been published and is


This article comprises a fundamental light scattering approach to understand how particles deposited onto a PV cell scatter introduce optical losses. The basic premise of this study is that optical losses to a PV cell by particles are due to backward hemispheric scattering and absorption, while forward hemispheric scattering is not part of such optical losses since this light will still reach the PV semiconductor.
However, this study is limited to low optical depths much less than one (i.e., density of particles per unit area is very low), and assumes that incoming radiation is scattered only once (i.e., single-scattering approximation).

The second manuscript expands on the first. This study includes a suspension-deposition experiment using two types of dust: optically absorbing and non-absorbing. Furthermore, this study includes the multiple-scattering regime and studies deposition with larger, often more realistic optical depths.


This article was submitted for publication and is currently under review.

This dissertation includes the first manuscripts in Chapter 2 and the second one in Chapter 3.
CHAPTER 2

OPTICAL LOSSES OF PHOTOVOLTAIC CELLS DUE TO AEROSOL DEPOSITION: ROLE OF PARTICLE REFRACTIVE INDEX AND SIZE

by

Patricio G. Piedra and Hans Moosmüller

Abstract

Field experiments have revealed that deposition of dust particles plays a significant role in optical degradation of photovoltaic (PV) cell performance. Such experiments have been performed as a function of tilt angle of the cells, exposure time, and other environmental factors. However, very little is known about cell degradation as function of intensive particle parameters such as size and complex refractive index. This paper shows that, for normally incident solar radiation, deposited aerosols degrade PV cell performance due to particle absorption and due to scattering into the backward hemisphere. The fraction power lost ($FL$), together with the optical depth of the deposited particles, determines the fraction of power lost from the incident light beam. We have performed scattering calculations simulating the interaction of light with particles on substrates that analyzed $FL$ as function of particle size and particle complex refractive index. We have found that for small particles and a relatively large imaginary part of their refractive index, absorption losses dominate while for large particles and a relatively small imaginary part of the refractive index, backscattering losses dominate. Per optical depth, fine particles result in higher optical losses than coarse ones due to their larger absorption and hemispheric backscattering. Overall, our work quantifies optical losses
caused by deposited aerosols toward the goals of estimating PV cell performance for energy forecasting, informing PV cell designers about potential efficiency losses caused by particle deposition, and optimizing cleaning schedules.

2.1 Introduction

The need for energy forecasting has become a pressing issue in supporting smarter grids that can predict fluctuations, reduce or eliminate outages, and charge flexible prices. In recent years, significant efforts have been dedicated to create systems that allow for solar power forecasting [Pelland et al., 2013]. One of such forecasting factors is the power loss due to aerosol deposition such as dust, pollen, carbonaceous particles, etc.

From the fundamental physics perspective, the goal of PV energy harvesting is simple: to maximize the conversion of solar electromagnetic (EM) energy into electrical energy. Aerosol deposition on PV cells adds complexity to this goal. Aerosol particles deposited on PV cells absorb and backscatter part of the incident optical power and thereby reduce the optical power transmitted to the PV cell itself. This problem is significant since a large number of PV cells are located in sunny, semi-arid regions, where they can be subject to frequent deposition of mineral dust and other particles (e.g., soot in polluted areas). Field studies of PV cell degradation by dust deposition reveal that deposited aerosols significantly reduce the efficiency of PV cells, with studies reporting up to 85% losses [Sulaiman et al., 2014].

Many experiments on this subject report power transmission losses as function of time of exposure of the PV cell to its environment [Mani and Pillai, 2010; Maghami et al., 2016]. However, there exists little work on understanding trans-
mission losses that depend on the intrinsic optical characteristics of the deposited particles. Here, we study the transmittance properties of aerosols deposited on PV cells. We deviate from approaches that consider solely light extinction (Al-Hasan, 1998). Instead, we distinguish hemispherical forward scattering from hemispherical backward scattering, include absorption, and also consider the optical interaction between the PV cell surface and the deposited particles.

Table 2.1: Overview of assumptions of this study and future work needed.

<table>
<thead>
<tr>
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<th>This paper</th>
<th>Future work needed</th>
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<tr>
<td><strong>Incoming Radiation</strong></td>
<td>-direction normal to PV cell</td>
<td>-as function of incident angle</td>
</tr>
<tr>
<td></td>
<td>-only direct radiation</td>
<td>-consider diffuse/direct radiation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-consider polarization effects</td>
</tr>
<tr>
<td><strong>Particles</strong></td>
<td>-homogeneous spheres</td>
<td>-other shapes</td>
</tr>
<tr>
<td></td>
<td>-fixed real ref. index, varying imaginary ref. index</td>
<td>-inhomogeneous particles</td>
</tr>
<tr>
<td></td>
<td>-low optical depth</td>
<td>-as function of real refractive index</td>
</tr>
<tr>
<td></td>
<td>-homogeneous spatial distribution</td>
<td>-high/any optical depth</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-inhomogeneous spatial distribution</td>
</tr>
<tr>
<td><strong>Surface</strong></td>
<td>-calculates surface interaction, but only for thick surface with ref. index n=1.5</td>
<td>-consider thin layered surfaces (e.g., anti-reflective coatings)</td>
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<tr>
<td></td>
<td></td>
<td>-varying complex ref. index</td>
</tr>
<tr>
<td><strong>Experimental Work</strong></td>
<td>-none</td>
<td>-needed</td>
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2.2 Power Losses due to Particle Deposition on PV Cells

In order to develop the following theoretical framework, let us consider a very simple scenario of a PV cell with low particle loading (e.g., particles have not deposited onto other particles). Furthermore, let us assume that particles have deposited sparsely and homogeneously (i.e., particles do not form clusters), and light is normally incident. A summary of simplifying assumptions of this study and future work needed is shown in Table 2.1.

The power incident at normal incidence onto a clean PV cell and converted to electricity is $P_0$. If the PV cell is dirty, the power of the direct beam is reduced to $P$ by particle scattering and absorption according to Beer-Lambert’s law (e.g., Moosmüller et al. (2009))

$$P = P_0 e^{-\tau_{ext}}, \quad (2.1)$$

where $\tau_{ext}$ is the extinction optical depth caused by aerosols deposited on the substrate. The extinction optical depth is a measure of the amount of light that is removed from the incident beam due to scattering and absorption. The conventional term “optical depth” is misleading as it implies units of length, while $\tau_{ext}$ is unitless. For $\tau_{ext} \ll 1$, it can be written as the sum of scattering and absorption optical depths as

$$\tau_{ext} = \tau_{sca} + \tau_{abs}. \quad (2.2)$$

Here, we consider only the simplest case of light at normal incidence where we further distinguish between optical depth from scattering into the forward hemisphere $\tau_{fs}$ and from scattering into the backward hemisphere $\tau_{bs}$ by writing
\[ \tau_{sca} = \tau_{fs} + \tau_{bs}, \] yielding the identity

\[ \tau_{ext} - \tau_{fs} = \tau_{bs} + \tau_{abs}, \quad (2.3) \]

Dividing the identity of equation (2.3) by \( \tau_{ext} \), we obtain

\[ 1 - \frac{\tau_{fs}}{\tau_{ext}} = \frac{\tau_{bs} + \tau_{abs}}{\tau_{ext}}. \quad (2.4) \]

Let us define the power fraction lost \( FL \) as the fraction of extinction optical depth that is due to absorption and scattering into the backward hemisphere direction as

\[ FL \equiv \frac{\tau_{bs} + \tau_{abs}}{\tau_{ext}} = \frac{\sigma_{bs} + \sigma_{abs}}{\sigma_{ext}}, \quad (2.5) \]

where \( \sigma \) represents optical cross section instead of optical depth \( \tau \) so that \( \sigma_{abs} \) is the absorption cross section, \( \sigma_{ext} \) is the extinction cross section, and \( \sigma_{bs} \) is the hemispherical backward scattering cross section. For the PV cell surface being normal to the direction of the incident solar radiation, the power from extinction due to hemispherical forward scattering still reaches the semiconductor material and produces electrical power, while the extinction due to absorption heats the absorbing particles and the extinction due to hemispherical backward scattering is lost from the system. Therefore, the optical power \( P_{sc} \) reaching the semiconductor material after interacting with deposited particles can be written as

\[ P_{sc} = P_0 e^{-(\tau_{abs} + \tau_{bs})} = P_0 e^{-\tau_{ext}FL}. \quad (2.6) \]

For \( \tau_{ext}FL \ll 1 \), we can approximate equation (2.6) using the identity \( e^\beta \approx 1 + \beta \) for \( \beta \ll 1 \) as

\[ P_{sc} \approx P_0 (1 - \tau_{ext}FL). \quad (2.7) \]

For the simplest case of \( N \) identical particles with extinction cross-sections \( \sigma_{ext} \) deposited onto a surface area \( A \), the deposited particle layer has an optical depth \( \tau_{ext} \)
with
\[ \tau_{\text{ext}} = \frac{N}{A} \sigma_{\text{ext}}, \quad (2.8) \]
and the fraction lost is given by equation (2.5). However, in reality aerosol particles have a size distribution \( n(x) = \frac{dN}{dx} \), where \( \int_{x_1}^{x_2} n(x) dx = N \); for spherical particles, the size parameter \( x \) is the ratio of the particle circumference \( \pi D \) (with \( D \) being the particle diameter) to the EM wave’s wavelength \( \lambda \) with \( x \) defined as
\[ x = \frac{\pi D}{\lambda}. \quad (2.9) \]

If the sample is polydisperse with size parameters \( x \) between \( x_1 \) and \( x_2 \), equation (2.8) must be replaced by
\[ \tau_{\text{ext}} = \frac{1}{A} \int_{x_1}^{x_2} n(x) \sigma_{\text{ext}}(x) dx, \quad (2.10) \]
while the numerator of equation (2.5) is given by
\[ \tau_{\text{bs}} + \tau_{\text{abs}} = \frac{1}{A} \int_{x_1}^{x_2} n(x)[\sigma_{\text{bs}}(x) + \sigma_{\text{abs}}(x)] dx. \quad (2.11) \]

Thus, for polydisperse particles, equation (2.5) becomes
\[ FL = \frac{\int_{x_1}^{x_2} n(x)[\sigma_{\text{bs}}(x) + \sigma_{\text{abs}}(x)] dx}{\int_{x_1}^{x_2} n(x) \sigma_{\text{ext}}(x) dx}. \quad (2.12) \]

### 2.2.1 Intensive vs. Extensive Optical Parameters

A subtle but important distinction arises from describing light attenuation in the manner described in Section 2.2. Equation (2.1) has been modified to equation (2.6) through the definition of \( FL \) in equation (2.5). This modification allow us to describe power transmission into the PV cell semiconductor as
\[ P_{\text{sc}} = P_0 e^{-\tau_{\text{eff}}}, \quad (2.13) \]
where the effective (photovoltaic) optical depth $\tau_{\text{eff}}$ is

$$
\tau_{\text{eff}} = \frac{N}{A} \sigma_{\text{ext}} FL = \rho_N \sigma_{\text{ext}} FL.
$$

(2.14)

The quantity $\rho_N \equiv \frac{N}{A}$ is the number density of particles per unit area on the PV cell with units of m$^{-2}$. Alternatively, we can use the mass extinction cross section $k_{\text{ext}}$ (i.e., the extinction cross section per unit mass) with units of m$^2$/kg to describe $\tau_{\text{eff}}$ as

$$
\tau_{\text{eff}} = \rho_M k_{\text{ext}} FL,
$$

(2.15)

where $\rho_M$ is the sample mass density per unit area with units of kg/m$^2$. $\tau_{\text{eff}}$ is proportional to the particle number density $\rho_N$ or the sample mass density $\rho_M$. These quantities are extensive in the sense that they proportional to the amount of particles deposited. The quantities $\sigma_{\text{ext}} FL$ and $k_{\text{ext}} FL$ are intensive; they are dependent on the optical properties, but not on the quantity of the deposited particles.

The mass extinction cross section $k_{\text{ext}}$ is related to the extinction cross section $\sigma_{\text{ext}}$ as

$$
k_{\text{ext}} = \frac{\sigma_{\text{ext}}}{M} = \frac{Q_{\text{ext}} \sigma_{\text{geo}}}{M},
$$

(2.16)

where $Q_{\text{ext}}$ is the extinction efficiency (i.e., the extinction cross section divided by the geometric cross section), $\sigma_{\text{geo}}$ is the particle geometric cross section and $M$ is the particle mass. If we assume that all particles are spherical and the sample is mono-disperse, $M = \frac{\pi}{6} \rho D^3$ (where $\rho$ is particle mass density), and also $\sigma_{\text{geo}} = \frac{\pi}{4} D^2$. Expressing $D$ in terms of size parameter $x$ yields

$$
k_{\text{ext}} = \frac{3\pi}{2\rho\lambda x} Q_{\text{ext}}.
$$

(2.17)

Hence, equation (2.15) can be written as

$$
\tau_{\text{eff}} = \frac{3\pi \rho_M}{2\rho\lambda x} [Q_{\text{ext}} FL].
$$

(2.18)
The fraction $\rho_M/\rho$ has dimension of length and is a measure of the average thickness of the particle layer. The intensive particle optical properties determine $[Q_{\text{ext}}FL]$ in equation (2.18), and quantify the hemispherical backward scattering and absorption efficiency, or BSAE for short

$$BSAE \equiv Q_{\text{ext}}FL.$$ (2.19)

We explore the behavior of $FL$ and BSAE in Section 2.4.

Equation (2.18), which yields $Q_{\text{ext}}FL$ as an important factor determining $\tau_{\text{eff}}$, is simple and arises from our assumptions that all particles are spherical and that all particles are of the same size. While this is a very simplistic model, it allows us to investigate the optical effects of particles on PV cells with respect to their size and complex refractive index. In a more general approach, abandoning mono-disperse assumptions, the mass extinction cross section must be integrated over all sizes $x$ with $x_1 \leq x \leq x_2$, yielding

$$k_{\text{ext}} = \frac{\int_{x_1}^{x_2} \sigma_{\text{ext}}(x)n(x)dx}{\rho \int_{x_1}^{x_2} v(x)n(x)dx},$$ (2.20)

where $v(x)$ is the particle volume with size parameter $x$ and $n(x)dx$ is the number of particles with size parameter $x$. Substituting $\sigma_{\text{ext}}(x) = Q_{\text{ext}}(x)\frac{\pi}{4}D^2$ and $v(x) = \frac{\pi}{6}D^3$, and replacing $D = \frac{vl}{\pi}$, yields

$$k_{\text{ext}} = \frac{3\pi}{2\rho \lambda} \int_{x_1}^{x_2} Q_{\text{ext}}(x)x^2n(x)dx \int_{x_1}^{x_2} x^3n(x)dx.$$ (2.21)

Hence,

$$\tau_{\text{eff}} = \frac{3\pi\rho_M}{2\rho \lambda} \left[ \frac{\int_{x_1}^{x_2} Q_{\text{ext}}(x)x^2n(x)dx}{\int_{x_1}^{x_2} x^3n(x)dx}FL \right]$$ (2.22)

While equation (2.22) is more complex than (2.18), it contains the same physics, just integrating it over a particle size distribution.
2.3 Calculation of Particle Optical Properties

In this section, we briefly describe two approaches to calculating particle optical properties. The first one is the well-known Mie theory (Mie, 1908) and the second one is the discrete dipole approximation (DDA) method (Draine and Flatau, 1994). Mie theory is widely used for calculating optical properties of homogeneous, spherical particles in a homogeneous medium, while DDA can be used for particles with more complex morphology (including irregular shapes) and to calculate electromagnetic (EM) scattering of particles on surfaces. An alternative and more efficient method to calculate EM scattering of spheres or spheroids with substrate interaction is the T-matrix method (Videen, 1995; Mackowski, 2008), however, it is not used here. In DDA and Mie theory, it is assumed that an EM plane wave is scattered by a particle, and the incident wave is represented by

\[ E_0 = \begin{bmatrix} E_{0r}e^{i\phi_l} \\ E_{0l}e^{i\phi_r} \end{bmatrix} e^{i(kr - \omega t)}, \] (2.23)

where the \( l \) and \( r \) subscripts are used to represent the parallel and perpendicular components (relative to the scattering plane) of the electric field \( E_0 \) with corresponding phases \( \phi_l \) and \( \phi_r \), respectively. The vector \( k = k_r + ik_l \) is the complex wave number defined by

\[ k \cdot k = \omega^2 \epsilon \mu, \] (2.24)

where \( \omega \) is the angular frequency, \( \epsilon \) is the electric permittivity, and \( \mu \) is the permeability.

The aim of most particle optics calculations is to find a solution to the far-field scattering equation given by

\[ E_{sca} = \frac{1}{kr} \begin{bmatrix} s_1 & s_2 \\ s_3 & s_4 \end{bmatrix} E_0, \] (2.25)
where \( r \) is the distance from the center of the particle to the detector, and \( s_1 \) through \( s_4 \) are the components of the scattering matrix.

### 2.3.1 Mie Theory

Mie theory (Mie, 1908) has been used widely for determining the optical properties of homogeneous, spherical particles. However, even for non-spherical particles, Mie theory can be used as a first order approximation (Bohren and Huffman, 2008). Mie theory provides a solution to the Helmholtz wave equations. The solution of this system of complex vector differential equations is non-trivial (van de Hulst, 1981), requiring a fair amount of mathematical sophistication. Even when solved, the solution is an infinite series and a computer is generally used to reach a solution within a reasonable time. Nonetheless, Mie theory effectively solves Equation (2.25) for homogeneous, spherical particles and yields

\[
E_{\text{scat}}(x, m, \theta) = \frac{1}{kr} \begin{bmatrix}
    s_l(x, m, \theta) & 0 \\
    0 & s_r(x, m, \theta)
\end{bmatrix} E_0, \tag{2.26}
\]

where \( s_2 = s_3 = 0 \), due to the spherical symmetry of the particles. The dependency of the scattered electric field \( E_{\text{scat}} \) on the size parameter \( x \), the index of refraction \( m \), and the scattering angle \( \theta \) has been explicitly stated to highlight the intensive parameters determining the scattered field. The quantities \( s_l \) and \( s_r \) are the parallel and perpendicular phase functions, respectively.
2.3.2 Discrete Dipole Approximation

The discrete dipole approximation (DDA) is a relatively new method for particle optics calculations that uses numerical computation to estimate a solution for the scattering equation (2.25). DDA was first envisioned by numerical pioneers seeking to take advantage of ever improving computational capabilities. Draine and Flatau (1994) published an open-access FORTRAN code that made DDA widely available. DDA has since been traduced, improved, parallelized, and used in numerous light scattering studies ranging from optics of blood cells (Maltsev et al., 2011) to analysis of sea-salt aerosols (Chamaillard et al., 2003). DDA is a flexible scattering calculation that discretizes a particle as a collection of point dipoles in space. Considering the interactions of each dipole with one another, DDA inverts an interaction matrix to find a vector solution for the polarizability of each and every point dipole. The final electric field is given by the sum of individual dipole fields (Schmehl, 1994). Here, we used an open access DDA code written in C and developed by Yurkin and Hoekstra (2011) that allows parallel computation on multiprocessor supercomputers.

2.4 Analysis

We are quantifying the role of index of refraction and particle size on PV cells degradation using the single scattering approximation (i.e., $\tau_{ext} << 1$) and assuming a non-reflective semiconductor surface. Light that interacts with a particle on a PV cell can be absorbed or scattered. The sum of these effects is known as extinc-
tion. Expressing equation (2.2) in terms of cross sections yields

\[ \sigma_{\text{ext}} = \sigma_{\text{abs}} + \sigma_{\text{sca}}, \quad (2.27) \]

where the subscripts “ext”, “abs” and “sca” stand for extinction, absorption, and scattering, respectively. The first term, the absorption cross section \( \sigma_{\text{abs}} \), is a result of the transformation of EM energy into thermal energy. Absorption is associated with the imaginary part of the particle’s index of refraction \( m = m_r + im_i \), where \( m_r \) is the real part and \( m_i \) is the imaginary part. For example, the bulk absorption coefficient \( \alpha \) is related to \( m_i \) as

\[ \alpha = \frac{4\pi}{\lambda} m_i(\lambda). \quad (2.28) \]

Notice that the absorption coefficient depends on the wavelength through the \( \frac{1}{\lambda} \) factor and through a possible wavelength dependence of \( m_i \). For many compounds, \( m_i(\lambda) \) has been spectroscopically tabulated, for instance by Polyansky (2016). Typical values of \( m_i \) in the solar spectrum for aerosols in Earth’s atmosphere span many orders of magnitude, ranging from \( \sim 0 \) to \( \sim 1 \) (Levoni et al., 1997). Through the absorption coefficient, it is possible to define a skin depth \( \delta \), that is the distance within the particle necessary to reduce EM incoming power density by \( \frac{1}{e} \), as

\[ \delta = \frac{2}{\alpha} = \frac{\lambda}{2\pi m_i}. \quad (2.29) \]

In Section 2.2, we defined the power fraction loss \( FL \) by equations (2.5) and (2.12) and the hemispherical backward scattering and absorption efficiency \( BSAE \) by equation (2.19). In Section 2.3, we described the use of scattering theory to calculate the phase functions needed to obtain \( FL \) and \( BSAE \). The hemispherical backward scattering cross section \( \sigma_{bs} \) is obtained by integrating \( |E|^2 \) over the backward scattering hemisphere of the particle.

In order to better explain our results, we introduce the particle radius to skin
depth fraction \( m_{ix} \), where

\[
m_{ix} = \frac{D/2}{\delta}
\]  

(2.30)

is the ratio of particle radius \( D/2 \) to the skin depth \( \delta \). Thus, two spherical particles with equal \( m_{ix} \) share the same ratio of particle radius to skin depth despite different \( x \) or \( m_i \). We shall henceforth refer to \( m_{ix} \) as the radius to skin depth fraction. Wang et al. (2015) have demonstrated that results of EM scattering calculations can be unified if \( m_{ix} \) is used as variable instead of using \( x \) and \( m_i \) independently.

Seinfeld and Pandis (2012) report that aerosol particle size distributions in the atmosphere strongly depend on the ambient conditions with urban aerosol particle numbers peaking in the range \( 0.1 \, \mu m \lesssim D \lesssim 0.5 \, \mu m \); rural continental aerosol number distributions are usually bi-modal with peaks at \( \sim 0.02 \, \mu m \) and \( \sim 0.08 \, \mu m \). Desert aerosols number distributions are often tri-modal with number peaks at \( D \lesssim 0.01 \, \mu m \), \( \sim 0.05 \, \mu m \), and \( \sim 10 \, \mu m \). In addition, PV cell conversion efficiency peaks around \( \lambda \sim 0.6 \, \mu m \), close to the peak of the solar spectrum. The largest particle size at which the number size distribution peaks is for desert aerosol at \( D \sim 10 \, \mu m \), with a corresponding size parameter \( x \), equation (2.9), of

\[
x = \frac{\pi}{0.6 \, \mu m} \sim 50
\]

Hence, particles with \( x \lesssim 50 \) include the majority of aerosols that are deposited on PV cells. Nonetheless, near dust sources, particles as large as \( \sim 100 \, \mu m \) (\( x \sim 524 \)) can be found. It is noteworthy that airborne particle number size distributions may differ strongly from deposited ones due to deposition mechanisms and accumulation of particles (e.g., Li et al. (2009); Tan et al. (2014)). Our study is limited to low, homogeneous deposition loadings (Table 2.1). DDA-substrate calculations for particles with \( x \gtrsim 50 \) are computationally very demanding due to the large number of required dipoles. For very large particles, other methods of scattering calculation
Figure 2.1: The power fraction lost $FL$ as a function of radius to skin depth fraction $m_i x$ for spherical aerosols with index of refraction $m = 1.5 + im_i$ is shown, where $10^{-4} \leq m_i \leq 2.5$. The size parameter is $x = 10$ and the corresponding results from Mie calculation are shown as a solid line. The DDA-substrate calculation includes a substrate with refractive index $n_r = 1.5$ or a negligible substrate with $n_r \approx 1$.

such as the T-matrix technique [Wriedt and Doicu, 1998] can be used.
Figure 2.2: The power fraction lost $FL$ plotted as a function of $m_i x$ in lin-log scale for spherical aerosols with refractive index $m = 1.5 + i m_i$ using both Mie theory and the DDA-substrate method. The refractive index of the substrate is $n = 1.5 + i 0$, similar to that of glass and fused silica. Each curve is for one size parameter. Mie calculations are shown as solid colored lines while DDA calculations are shown as markers on dashed lines. The ovals represent an estimation of $m_i$ for Saharan dust and carbonaceous particles.

### 2.4.1 Power Fraction Lost $FL$

Figure 2.1 shows the power fraction lost $FL$ for spherical aerosol particles with size parameter $x = 10$ (corresponding for $\lambda = 0.6 \, \mu m$ to a particle with diameter $D \approx 2 \, \mu m$) and a refractive index $m = 1.5 + i m_i$ as a function of radius to skin depth fraction $m_i x$. The refractive index of the substrate is given by $n = n_r + i n_i$, where $n_r$ is the real part, and $n_i$ is is the imaginary part. We calculated particle-substrate scattering with DDA using two different refractive indices for the substrate, the first one is $n_r = 1.0$, identical to that of free space (i.e., without substrate), and the second one is $n_r = 1.5$, typical for a glass or fused silica substrate. In both cases, the
substrate was assumed to be non-absorbing with an imaginary refractive index $n_i = 0$. As expected, the free-space Mie scattering and DDA particle-substrate results agree when the DDA substrate is removed by assuming its refractive index as $n_r = 1$. Our results (see Fig. 2.1) indicate that $FL$ is nearly constant with $FL \lesssim 10\%$ for $10^{-4} < m_i x < 10^{-2}$. This small and nearly constant power fraction lost is a result of weak absorption for very small $m_i$, which makes the skin depth much larger than the particle radius. In addition, losses by scattering remain small since most scattering is into the forward hemisphere. For $m_i x$ larger than $10^{-1}$, we observe rapid increase in $FL$ as function of $m_i x$ due to increased absorption. $FL$ peaks at $\sim 0.5$ for $m_i x \sim 2$ corresponding to the skin depth equal to the particle diameter. This indicates that about half of the interacting power can be lost for particles with $x = 10$ and $m_i \sim 0.2$. When the skin depth is comparable to the diameter of the particle, the absorption efficiency $Q_{abs}$ (i.e., ratio of absorption cross section to geometric cross section) peaks at a maximum value of $\sim 1$, while the hemispherical backward scattering efficiency remains small. The net effect is that the power fraction lost is dominated by absorption, thus extinguishing about half the interacting power so that $FL \sim \frac{1}{2}$ (see extinction paradox, Bohren and Huffman (2008)). As $m_i x$ becomes even larger, $FL$ starts to decrease. Particles with $m_i \gtrsim 0.2$ start to acquire metallic, more reflective properties, and as the skin depth becomes much smaller than the radius of the particle, penetration of light into the particle is reduced. This results in more scattered light and less absorption, thus we observe $FL$ starting to decline for increasing $m_i x > 2$. A discussion of the effect of the substrate is given later in Section 2.4.4 “Particle Scattering without and with Substrate”.

In Figure 2.2, we plot $FL$ as function of $m_i x$ using Mie theory as well as DDA particle-substrate calculations for various size parameters. Similarly to Figure 2.1, the particle real refractive index is $m_r = 1.5$, while the substrate real refractive in-
Figure 2.3: We show $Q_{ext}FL$ as function of $m_i x$ for spherical aerosols with refractive index $m = 1.5 + im_i$ calculated with Mie theory and DDA-substrate method. The substrate refractive index is $n = 1.5 + i0$, similar to that of glass and fused silica. Mie theory results are displayed as solid colored lines while the corresponding DDA results are shown as markers on dashed lines.

dex is $n_r = 1.5$. The plot displays the corresponding curves for size parameters $x = 0.01, 0.1, 0.5, 1, 2, 5, 10,$ and $20$. If we use $\lambda = 0.6 \mu m$ as our reference wavelength, the corresponding particle diameters are $D \sim 0.002, 0.02, 0.1, 0.2, 0.4, 1, 2,$ and $4 \mu m$, respectively. We observe that Mie calculations (no substrate) for small particles in the Rayleigh regime (Moosmüller et al., 2009) such as $x = 0.1$, yield $FL \sim 0.5$ when the radius to skin depth fraction is small ($m_i x \ll 10^{-10}$) because small ($x \ll 1$) particles scatter nearly symmetrically in the forward and backward direction, thereby reducing the transmitted power by about half when absorption is negligible (van de Hulst, 1981, Ch. 6). For these small particles, $FL$ increases rapidly as function of $m_i$, reaching $FL \sim 1$ at $m_i x \geq 10^{-9}$ for $x = 0.01$ and at $m_i x = 10^{-4}$ for $x = 0.1$. This is because absorption totally dominates over scattering
Figure 2.4: $BSAE = Q_{ext}FL$ as function of $m_i x$ is shown for spherical particles with refractive index $m = 1.5 + im_i$ in log-log scale by Mie theory and by DDA-substrate method. The refractive index of the substrate is $n = 1.5 + i0$. Curves calculated by Mie theory are shown as a solid lines while DDA-substrate calculations are shown as markers on dashed lines.

For small ($x < 0.5$) particles in this regime. In addition, as the particle becomes absorbing, the skin depth rapidly decreases to become comparable to the diameter of the particle so that absorption is maximized. For larger particles with $x > 0.5$, the scattering direction is preferentially into the forward hemisphere. Hence, we observe that $FL$ decreases for increasing $x$. Particles with $0.5 < x < 1$, reach a $FL$ peak at $m_i x \sim 0.5$, that is, when radius to skin depth fraction is approximately a half. This is because losses caused by backward hemispheric scattering are still significant. Larger particles ($x \gtrsim 1$) reach a peak $FL \sim 0.5$ at $m_i x \approx 2$, that is, when the skin depth is approximately the same as the diameter. It is interesting to compare these curves with common measurements of size and imaginary index of refraction of dust and carbonaceous particles. Suspended mineral dust has a complex chemical
Figure 2.5: $BSAE = Q_{ext}FL$ as function of $x$ is shown for $m_i$ in $10^{-8} < m_i < 2$. The upper horizontal axis shows the particle diameter for $\lambda = 0.6 \mu m$.

and mineralogical composition affecting its optical properties [Engelbrecht et al., 2016; Moosmüller et al., 2012]. Formenti et al. (2011) report Saharan dust particles size number distributions, the maximum count median diameter for airborne collected samples is $\approx 6.6 \mu m$ corresponding for $\lambda = 0.55 \mu m$ to $x \approx 38$. In addition, Ryder et al. (2013) measured Saharan dust’s $m_i$ at $\lambda = 0.55 \mu m$, finding results in the range $10^{-2} \lesssim m_i \lesssim 10^{-3}$ as indicated in Figure 2.2. Similarly, black carbon particle refractive indices are reported by Bond and Bergstrom (2006) at $\lambda = 0.55 \mu m$ with results in the range $10^{-1} \lesssim m_i \lesssim 10^{0}$. Black carbon number size distribution over Europe have been studied by Reddington et al. (2013), finding that black carbon number size distributions peak near $D \approx 200$ nm (corresponding to $x \sim 1$ for $\lambda = 0.55 \mu m$) with standard deviations ranging from $D \sim 50$ nm ($x \sim 0.3$) to $D \sim 400$ nm ($x \sim 2$). These ranges are estimated in Figure 2.2 as ovals. The high $FL$ of black carbon explains why experiments of PV cells deposited with carbon particles yield higher losses per optical depth than other types of particles (Darwish et al., 2015).
2.4.2 Hemispherical Backward Scattering and Absorption Efficiency

$BSAE$

Figure 2.3 plots $BSAE = Q_{ext}FL$ as function of $m_i x$ for different particle sizes. For all sizes, $BSAE$ is nearly constant between $10^{-5} \leq m_i x \leq 10^{-2}$ with the size parameter $x = 5$ having the highest $BSAE \sim 0.4$. $BSAE$s for particles with size $x \geq 1$ peak at $m_i x \approx 2$ (where the skin depth is comparable to the radius of the particle). The peak $BSAE$ for these particles decreases as function of size from $BSAE \sim 2.5$ to $BSAE \sim 1$. Figure 2.4 gives the same data of Figure 2.3 and shows $BSAE$ as function of $m_i x$ for the same size parameters as Figures 2.2 and 2.3, however emphasizing small $BSAE$ through the use of a logarithmic y-axis. Note that $BSAE$ curves for small particles with size $x \leq 1$ are largely different from curves for larger particles with $x > 1$. $BSAE$s for small particles ($x \leq 0.5$) have a positive slope as function of $m_i x$, and the starting point of the positive slope shifts substantially right as $x$ increases. For instance, notice the positive slope of the $x = 0.5$ curve which starts at $m_i x \sim 10^{-2}$ and the slope of $x = 1$ which starts at $m_i x \sim 10^{-1}$. In contrast, the positive slopes for larger particles with $x > 1$ start at $m_i x \sim 10^{-1}$ and are not as large as those for smaller particles with $x < 1$. For this reason, $BSAE$ of $x = 1$ is actually larger at the peak occurring at $m_i x \approx 2$ than $BSAE$s of particles with $x > 1$. Finally, figure 2.5 shows $BSAE$ as function of $x$ (instead of $m_i x$) in log-log space for different $m_i$. A distinct positive slope is noticed in all curves indicating that $BSAE$ generally increases with size, reaching a peak at $x \sim 1$ at which point $BSAE$ starts to decrease. The largest $BSAE$s are observed for $m_i = 1$ with a peak of $BSAE \sim 3$. At larger $m_i$ the overall $BSAE$ values decrease for all size parameters as can be seen for $m_i = 2$. 
2.4.3 Dominance of Absorption or Hemispherical Backward Scattering as Loss Mechanism

The power fraction lost $FL$ is the sum of absorption and hemispherical backward scattering. Either mechanism can dominate $FL$ depending on particle size and refractive index. The dominance of either scattering or absorption as mechanism for light extinction is conventionally quantified using the single scattering albedo ($SSA$) defined as

$$SSA = \frac{\sigma_{sca}}{\sigma_{abs} + \sigma_{sca}} = \frac{\sigma_{sca}}{\sigma_{ext}},$$  \hspace{1cm} (2.31)

where $SSA$ is the fraction of light extinction that is due to scattering. For our application, we use the co-albedo $COSSA$ defined as

$$COSSA = 1 - SSA = \frac{\sigma_{abs}}{\sigma_{ext}},$$  \hspace{1cm} (2.32)

where $COSSA$ is the fraction of light extinction that is due to absorption. The $FL$ parameter defined in equation (2.5) can now be written as

$$FL = \frac{\sigma_{bs}}{\sigma_{ext}} + \frac{\sigma_{abs}}{\sigma_{ext}} = BL + COSSA,$$  \hspace{1cm} (2.33)

where $BL$ is the fraction of extinction that is due to scattering into the backward hemisphere, defined as

$$BL \equiv \frac{\sigma_{bs}}{\sigma_{ext}}.$$  \hspace{1cm} (2.34)

$FL$ and its components $COSSA$ and $BL$ are plotted in Figure 2.6 as a function of the size parameter $x$ for different imaginary parts of the particle’s refractive index. $COSSA$ indicates fractional power loss due absorption while $BL$ indicates fractional power loss due to hemispheric backward scattering. The change in dominance between these processes is marked by the intercepts between $COSSA$ and $BL$ curves. It is noticeable that absorption dominates for small sizes and
**Figure 2.6**: COSSA, BL, and FL are displayed as function of size parameter for spherical particles on a substrate. The refractive index of the particles is \( m = 1.5 + im_i \) while the substrate refractive index is \( n = 1.5 + i0 \). For reference, the upper horizontal axis shows the particle diameter for \( \lambda = 0.6 \mu m \). Horizontally dashed lines represent COSSA; vertically dashed lines are BL, and the solid lines are FL. For each given \( m_i \), the curves COSSA, BL, and FL are plotted in the same color.

Larger imaginary parts of the refractive index. The region of absorption dominance shifts toward larger size parameters for increasing \( m_i \); notice the intercepts between \( \sim 5 \times 10^{-2} \leq x \leq 2 \) shifting right as \( m_i \) becomes larger. This indicates that as the diameter of small particles grows to \( \geq \frac{1}{3} \) of the wavelength (i.e., \( x = 1 \), or \( D = \lambda/\pi \)), for small imaginary parts of the refractive index (i.e. \( m_i \leq 3 \times 10^{-2} \)), the loss of power through hemispherical backward scattering becomes more significant than the loss caused by absorption. Interestingly, there is a limiting value of \( m_i \) above which there are no intercepts between BL and COSSA (i.e., absorption losses are always dominant). This limiting value was calculated numerically and is \( m_i = 0.025 \pm 0.001 \) using the DDA-substrate method; however, Mie theory, neglect-
Figure 2.7: The intercepts between BL and COSSA for the range $10^{-3} \leq x \leq 10^0$ are visible in Figure 2.6. The imaginary part of the particle refractive index of these intercepts is plotted as a function of their size parameter in log-log space. For clarity, the upper horizontal axis shows the particle diameter for $\lambda = 0.6 \ \mu m$ instead of the size parameter. The linear regression of these intercepts parameterizes this division and is shown as a solid line.

The intercepts between $BL$ and $COSSA$ in the region $10^{-2} \leq x \leq 10^0$ can be seen in Figure 2.6. These intercepts and their values of imaginary index of refraction $m_i$ and size parameter $x$ divide the parameter space between dominance of either absorption or hemispherical backward scattering as the main mechanism of power loss for particles deposited on a PV cell. We have plotted these intercepts in Fig-
ure 2.7, and have performed a linear regression in log-log space to describe this dividing line, yielding

\[ \log_{10} m_i = 3.180 \log_{10} x - 1.295 \quad \text{for} \quad x < 1. \]  

(2.35)

This regression subdivides the \( x \) vs \( m_i \) space domain into two regions. For any particle whose \( x \) and \( m_i \) values are in the upper left of the regression line, the main loss mechanism is absorption, while for \( x \) and \( m_i \) values in the lower right, the main loss mechanism is hemispherical backward scattering.

2.4.4 Particle Scattering without and with Substrate

Using DDA code is substantially more time consuming than using Mie code. Therefore, we explore the differences in results between these two approaches, investigating if the use of Mie code can be sufficient for scattering calculations involving spherical particles, in part of the parameter space. In Figure 2.2, we notice that \( FL \) values calculated with Mie code are somewhat different from those calculated with DDA-substrate code. Hence, there exist a difference in \( FL \) depending on whether the substrate is included in our calculations or not.

Figure 2.8 displays the difference in \( FL \)

\[ \Delta FL = FL_{DDA-substrate} - FL_{MIE}, \]  

(2.36)

between calculations of \( FL_{DDA-substrate} \) using DDA-substrate and calculation of \( FL_{MIE} \) using Mie code.

Figure 2.9 shows \( \text{COSSA} \) vs. \( x \) for different \( m_i \) values, calculated using Mie theory, which neglects the substrate, and DDA-substrate, which considers the substrate interaction. It is noticeable that there are no large differences between the
Figure 2.8: We show the difference in power fraction lost $FL$ between DDA-substrate and Mie theory calculations as a function of $m_i$ and $x$. The calculations are for spherical aerosols of $m_r = 1.5 + im_i$, and the index of refraction of the substrate is $n = 1.5 + i0$. curves by both methods. This is expected since COSSA quantifies light extinction due to particle absorption, a mechanism which is largely independent of the substrate. However, in Figure 2.10 we show that $BL$ curves calculated without substrate (Mie theory) for small particles (i.e. $x \lesssim 1$) generally overestimate the $BL$ values of DDA-substrate by nearly a factor of 2. This is because Mie theory does not account for frustrated internal reflection, a factor that decreases hemispherical backward scattering losses for small particles.
Figure 2.9: Fractional losses due to absorption are quantified by COSSA. We display COSSA vs. $x$ calculated using Mie theory (w/o substrate) and DDA-substrate (w/ substrate). The calculation is for homogeneous spherical particles of $m_r = 1.5 + m_i$, where $m_i$ is increased between $10^{-8} \leq m_i \leq 2$. The index of refraction of the substrate is $n = 1.5 = i0$. For clarity, each pair of COSSA curves Mie and DDA-substrate calculated at the same $m_i$ is plotted in the same color.
Figure 2.10: $BL$ vs. $x$ curves calculated by Mie theory (w/o substrate) and by DDA-substrate (w/substrate) are shown. The calculation is for homogeneous spherical particles of $m_r = 1.5 + m_i$, where $m_i$ is increased between $10^{-8} \leq m_i \leq 2$. The index of refraction of the substrate is $n = 1.5 + i0$. Each pair of $COSSA$ curves Mie and DDA-substrate calculated at the same $m_i$ is plotted in the same color.
2.5 Conclusions

We studied power loss due to aerosol deposition on PV cells degrading their efficiency as function of particle size and imaginary part of the particle refractive index, that is as function of intrinsic optical characteristics of the deposited particles. This study contrasts with the large majority of publications that report optical losses of PV cells as function of exposure time to environmental conditions. Since these conditions can rapidly vary from day to day and geographical location, we concur with Al-Hasan (1998) who writes: “It is the amount of sand dust accumulated on the panels which should be correlated with light or solar radiation transmittance.” Here, we followed this guidance and furthermore described a theory of particle optical losses that considers only those losses that reduce solar power production (i.e., absorption and scattering into the backward hemisphere) instead of extinction of the direct beam. This effectively modifies Beer-Lambert law to

\[ P = P_0 e^{\tau FL} \]

where \( FL \) is the fraction of the particle optical depth \( \tau \) that results in reduced solar power production. We also described the hemispherical backward scattering and absorption efficiency \( BSAE = Q_{ext} FL \), where all three parameters are intensive and not a function of mass per unit area on the PV cell. Second, we analyzed \( FL \) and \( BSAE \) as functions of radius to skin depth fraction \( m_{i,x} \). We found that \( FL \) of small particles with \( x \lesssim 1 \) peaks at \( FL \sim 1 \) for \( m_{i,x} \approx 0.5 \), while for large particles with \( x \gtrsim 1 \), \( FL \) peaks at \( FL \sim 0.5 \) for \( m_{i,x} \approx 2 \). Similarly, \( BSAE \) for small particles with \( x \lesssim 1 \) has a positive slope as function of \( m_{i,x} \) in log-log space, while for larger particles \( (x \gtrsim 1) BSAE \) remains nearly constant as function of \( m_{i,x} \) up to \( m_{i,x} \sim 10^{-1} \), reaching a peak at \( m_{i,x} \approx 2 \). Third, we described the mechanism causing optical losses with dominance of either hemispherical backward scattering or absorption in different parts of the parameter space. Fractional power losses caused
by hemispherical backward scattering are described by $BL$ while fractional power losses caused by absorption are described by co-albedo $COS S A$. For particles with size parameter $x \lesssim 1$ and $m_i \lesssim 0.025$, we find that the intercept between $BL$ and $COS S A$ shifts towards larger $x$ as $m_i$ becomes larger. For particles with $m_i > 0.025$, absorption is always dominant, and there exists no intercept. Fourth, we described how optical interactions with the substrate modify particle optics compared to free space conditions, and how this affects $FL$. The $COS S A$ is mostly unaltered by the presence of a substrate since absorption is largely independent of the substrate interaction. However, $BL$ is reduced by a factor of $\sim 2$ when the particles are small (i.e. $x \lesssim 1$) due to frustrated internal reflection. If the particle is $x \gtrsim 1$, $BL$ is increased by $\sim 0.1$ due to increased hemispherical backward scattering caused by Fresnel reflection.

Overall, the behavior of power losses due to dust deposition quantified here can serve as an essential part of solar power forecasting if the thickness of the particle layer to be deposited can be estimated from atmospheric particle transport and deposition and if particle properties including size distribution and complex refractive index can be obtained from knowledge about the source region and entrainment and transport processes. However, it must be noted that this initial work assumes simplifications including normal incidence of the radiation, small particle loading, and homogeneous spherical particles (see Table 2.1). Further research is needed to extend our results beyond these simplifications, and we expect substantial new insights during this process.
2.6 Acknowledgments

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CHAPTER 3
OPTICAL LOSSES OF PHOTOVOLTAIC CELLS DUE TO MINERAL DUST DEPOSITION: EXPERIMENTAL MEASUREMENTS AND THEORETICAL MODELING

by
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Abstract

Deposition of particles on photovoltaic (PV) cells have the potential to increase costs of solar energy production and maintenance and to affect grid-connected energy forecasting. Particles deposited on PV cells can degrade the optical transmission to the PV semiconductor significantly (> 50%) due to absorption and scattering. Although there are many previous studies on PV cell efficiency degradation with respect to exposure time, angle tilt of the PV cell, and other environmental factors, there has been little work on PV cell degradation with respect to the optical characteristics of the deposited particles (e.g., refractive index, optical depth). Here, we deposited two types of dust onto glass slides, optically absorbing dust and optically non-absorbing dust. We systematically increased the mass density per unit area deposited onto the glass slides and measured the optical depth and total transmission (i.e., direct plus diffuse light) using a spectrophotometer with an integrating sphere detector system. Our experimental measurements were compared with a two-stream radiative transfer model, and with Monte Carlo radiative transfer calculations, yielding good agreement for both absorbing and non-absorbing dust. Our results indicate that total transmission decreases linearly as
function of dust mass density deposited per unit area, with the slope being highly sensitive to the absorptivity of the dust. The results and models obtained in this study can be used in conjunction with deposition models to predict the degradation of the optical transmission of PV cells with respect to mass per unit area loading.

3.1 Introduction

Photovoltaic (PV) solar cells are exposed to the environment, and aerosol particles, including mineral dust, can deposit on them. Experimental studies have revealed that dust deposition can significantly (> 50%) degrade the power output of PV cells (Sayyah et al., 2014; Sulaiman et al., 2014). Although some experimental work on PV cell degradation as function of environmental factors (e.g., exposure time, wind speed, relative humidity, PV cell tilt angle) has been done (Etyemezian et al., 2017; Maghami et al., 2016; Mani and Pillai, 2010), very few experiments have studied PV cell degradation as function of deposited aerosol optical depth $\tau_0$, the key parameter quantifying optical transmission through a layer of particles. In recent years, there has been growing interest in reducing solar energy costs in order to compete with energy generated by fossil fuels, with some reports indicating that solar energy production can be nearly 50% more expensive than energy generated by fossil fuels (Fu et al., 2017). Similarly, there has been growing interest in energy forecasting given the increasing penetration of grid-connected solar power (Inman et al., 2013). One factor influencing solar energy costs as well as solar energy forecasting is the reduced efficiency of PV cells with particle deposits on their surfaces (Gholami et al., 2017). Deposited aerosol particles extinguish irradiance directed towards the PV semiconductor due to scattering and absorption...
(Moosmüller et al., 2009), but mathematical modeling of these mechanisms is lacking. Among one of the very few models, Al-Hasan (1998) developed a model for reduction of transmission of direct radiation onto a solar panel, with experimental validity of up to 50% transmission reduction. More recently, our group has conducted a theoretical study of the optical losses due to scattering and absorption of radiation by particles deposited onto PV cells. This previous study (Piedra and Moosmüller, 2017) considered that optical losses are fundamentally due to scattering into the backward hemisphere direction and due to absorption, but that forward hemisphere scattering still reaches the PV semiconductor. This work was limited to small ($\tau_0 << 1$) optical depths of deposited aerosol and did not include any comparison with experimental results. In addition, we do not know of any models of PV cell degradation as function of optical depth that take into account both direct and diffuse radiation.

Here, we develop an optical model based on the two-stream approximation (Bohren, 1987) to calculate the optical losses due to deposition of aerosols onto PV cells that includes direct and diffuse radiation. In addition, we present calculations of optical losses using Monte Carlo techniques (e.g., Wang et al., 1995). The validity of our models is examined by experimentally depositing suspended dust onto glass slides acting as surrogates for PV solar cells. The models presented here assume normally-incident, monochromatic light. They can be expanded to different incidence angles by discretization of directionality, for instance by the discrete-coordinate method (Liou, 2002) and to the spectrum of incident solar radiation by integration over the relevant wavelength region with a spectral sensitivity function for the PV cell of interest. These optical models can be used in conjunction with deposition models relevant to the location intended to study (e.g., Hammad et al., 2017) to predict optical efficiency losses of PV cells due to aerosol deposition.
3.2 Experimental Measurements

In the following section, we describe a suspension-deposition experiment that was conducted to first suspend mineral dust and subsequently allowing it to settle gravitationally onto glass slides that are used as surrogate for PV cell surfaces.

3.2.1 Mineral Dust Suspension and Deposition

We suspended absorbing and non-absorbing mineral dust samples with a mass of ∼20 g sample placed into a sample flask. The absorbing dust consisted of pure hematite (Fe$_2$O$_3$) particles (Powder Technology Inc., Arden Hills, MN). The non-absorbing dust was an off-white lakebed deposit, diatomaceous shale, consisting of plagioclase, quartz, and lesser amounts of clay, collected as part of a recent study on the characterization of mineral dust (Engelbrecht et al., 2016). Pressurized air was injected into the sample flask, entraining the sample and transporting it through a tube into the deposition chamber where it consequently gravitationally settles and deposits onto glass slides placed horizontally at the bottom of the deposition chamber (see Figure 3.1). We obtained size distributions for the deposited mineral dust particles from digital image analysis of scanning electron microscope (SEM) images of the deposits. For this analysis, we used dust depositions with nearly equal, low area mass density (i.e., 0.43 g/m$^2$ for non-absorbing dust and 0.44 g/m$^2$ for absorbing dust). The particles’ longest dimensional lengths (the diameter) yielded a histogram that was fitted with a log-normal number size distribution $n(D)$ given by

$$n(D) = \frac{1}{C \sigma D \sqrt{2\pi}} \exp \left[ -0.5 \left( \frac{\ln D - \mu}{C \sigma} \right)^2 \right],$$

(3.1)
Figure 3.1: Schematic diagram of mineral dust suspension and deposition experiment. Pressurized air is injected into the sample flask entraining the dust sample and transporting it into the deposition chamber where it gravitationally settles and deposits onto glass slides.

where \( D \) is a free variable used to represent the longest length of the particles as a continuous probability distribution function, \( \sigma \) is the standard deviation of \( \ln D \), \( \mu \) is the mean of \( \ln D \), and \( C \) is a scaling constant used to normalize the probability distribution such that the integral of \( n(D) \) over the \( D \) domain is one. The normalized histograms and curve-fits can be seen in Figure 3.2, including its fitting parameters. The peak or mode of the log-normal distribution for the absorbing samples was located at \( \sim 1.3 \ \mu m \), while the peak of the non-absorbing sample was located at \( \sim 0.8 \ \mu m \).
3.2.2 Optical Characterization of Deposited Dust

The optical properties of mineral dust samples deposited on glass slides were characterized with a Perkin Elmer 1050 UV/Vis/NIR spherical integrating spectrophotometer (SIS) equipped with a detector system consisting of a 150-mm diameter integrating sphere with InGaAs/PMT detectors covering the 250 to 2500-nm spectral range (Padera, 2013). This SIS system has two measurement ports: a transmission port located in front of the sphere, and a reflection port located at the back of the sphere (Figure 3.3, Figure 3.4). It allows for measuring either the scattering into the forward hemisphere (Figure 3.3) or the total transmission into the forward hemisphere, which is the sum of direct beam transmission and scattering into the forward hemisphere (Figure 3.4).
We have normalized our measurements of dust-deposited (dirty) glass slides transmission \( T \) so that the non-deposited (clean) glass slide transmission \( T_{\text{clean raw}} \) is normalized to \( T_{\text{clean}} = 1 \). The normalized transmission \( T \) of the particles-glass slide system is obtained from a raw measurement \( T_{\text{raw}} \) normalized with respect to the raw measurement of a clean glass slide transmission \( T_{\text{clean raw}} \) as

\[
T = \frac{T_{\text{raw}}(\lambda)}{T_{\text{clean raw}}(\lambda)} \tag{3.2}
\]

This normalization isolates the effect of deposited dust on optical transmission. In our experiments, \( T_{\text{clean raw}} \) ranged from \( \sim 0.91 \) to \( \sim 0.93 \), comparable to the normal incidence \( \sim 0.92 \) transmission through a air-glass-air system with glass refractive index of 1.5, where losses are caused by Fresnel reflections from two surfaces. All transmission measurements discussed in the following discussion have been normalized with equation (3.2).

**Forward-Hemisphere Scattering Measurement**

The SIS spectrometer can be used to selectively measure the transmission of light scattered into the forward hemisphere \( T_{\text{fwd}} \) by locating the sample in the transmittance port in front of the SIS and eliminating the direct beam power through absorption by a non-reflecting (black) surface (Figure 3.3).

**Total Transmission and Direct Beam Measurement**

The direct beam is the part of the incident beam that is neither scattered nor absorbed by the sample, but transmitted. By removing the non-reflective surface
Figure 3.3: Spherical Integrating Spectrophotometer (SIS) set up for measuring transmission $T_{fwd}$ due to scattering into the forward hemisphere.

From the SIS configuration shown in Figure 3.3, the SIS sensor can measure the forward-hemisphere transmission due to forward-hemisphere scattering plus direct beam transmission (i.e., $T_{fwd} + T_{dir}$) as shown in Figure 3.4. This measurement of direct plus diffuse (i.e., forward-hemisphere scattering) transmission is henceforth simply referred to as the total transmission given by

$$\text{T}_{measured} = T_{fwd} + T_{dir}$$  \(3.3\)

From the total transmission measurement, we obtained $T_{dir}$ by subtracting the forward-hemisphere scattering transmission, yielding
Figure 3.4: Spherical Integrating Spectrophotometer (SIS) set up for measuring direct beam plus forward scattering transmission.

\[ T_{dir} = (T_{fwd} + T_{dir}) - T_{fwd} \] (3.4)

Aerosol Optical Depth Retrieval

For the direct beam, light is extinguished due to scattering and absorption by particles deposited onto the glass slide (e.g., Moosmüller et al. 2009). The direct beam transmission \( T_{dir} \), with losses due to particle scattering and absorption, is described by the Beer-Lambert law as

\[ T_{dir} = \frac{P}{P_0} = e^{-\tau'_0}, \] (3.5)

where \( \tau'_0 \) is the measured aerosol optical depth (AOD) of the deposited particle layer. Measurement of the direct beam transmission allow us to retrieve the optical
depth AOD $\tau'_0$ as

$$\tau'_0 = -\ln (T_{\text{dir}}).$$

(3.6)

However, SIS measurements are susceptible to angular truncation errors due to strongly forward scattering peaks of diffracted light (i.e., a fraction of forward scattering light is eliminated incorrectly, yielding higher measurement of $T_{fwd}$. This has the effect of underestimating the actual AOD $\tau_0$. To correct for this, we applied a scaling factor applying the delta-Eddington approximation (Liou [2002]).

$$\tau_0 = \frac{\tau'_0}{1 - f \omega},$$

(3.7)

where $\omega$ is the single scattering albedo (SSA) of the dust, and $f$ is the fraction of near-forward scattered and/or diffracted light. This correction factor is explained in more detail in the next section.

### 3.2.3 SIS Truncation Errors

One consideration of great importance for the correct distinction between direct and diffuse light is the angular truncation of the SIS detector system. Given that the SIS detector in Figure 3.3 uses a non-reflective surface with a finite area to eliminate the power of the direct beam, some near-forward scattered light (mostly diffraction) will inevitably be eliminated incorrectly leading to a lower optical depth retrieval. This is the scaled optical depth detected by the SIS in equation (3.6). Truncation errors are accentuated for absorbing particles because diffraction constitutes a larger fraction of the total scattered light (Moosmuller and Arnott [2003]). Cor-
recting this truncation error from the theoretical standpoint is not trivial because it requires very accurate determination of the fraction of diffracted power as function of optical depth. However, for multiple-scattering, the fraction of diffracted power depends on the optical depth itself, and in general, it is not possible to solve this problem analytically (Liou, 2002). The delta-Eddington approximation (Meador and Weaver, 1980) and its cousin, the delta-M approximation (Wiscombe, 1977) tackle this problem by parameterizing the phase function as a sum of a fractional $f$ Dirac-delta function in the forward direction plus a smooth phase function in all other directions. The phase function of the dust layer medium is expanded as a Legendre polynomial summation (Sobolev, 1975), and this expansion allow us to estimate truncation errors since they are caused by the higher moments of the Legendre expansion. Joseph et al. (1976) showed that the delta-Eddington approximation is a second order Legendre expansion of the phase function in the angular direction. Given that the phase function is not known, we can model a forward peaking phase function using a Henyey-Greenstein phase function (Henyey and Greenstein, 1941). Ultimately, modeling our phase function in this manner, estimates to second order the Legendre expansion moment $f \approx g^2$ (e.g., Joseph et al., 1976; Liou, 2002). This factor reveals that our SIS device can distinguish scattered from direct light up to the first moment of the Legendre expansion. However, from the second moment and beyond, some forward scattering peaks are erroneously truncated by the non-reflective surface. With this estimation of $f$, the scaled $\tau'_0$ detected by our SIS can be approximated to the actual optical depth $\tau_0$ by substituting $f$ into equation 3.7, yielding

$$\tau_0 = \frac{\tau'_0}{1 - g^2 \omega},$$

(3.8)
Empirically, we found that our theory fits our measurements somewhat better using a correction $f \approx g^{2.3}$ which implies that our detector may be somewhat sensitive to the second moment, and that the truncated near-forward fraction is somewhere between the second and the third moment of the Legendre expansion. However, we do not have any theoretical basis to apply this correction since Legendre polynomial expansions are discreet.

### 3.3 Theoretical Modeling

#### 3.3.1 Multiple Scattering: The Two-Stream Approximation

For high particle loading, the assumption of single scattering of light is not applicable since the required single scattering condition of AOD $\tau \ll 1$ is not valid. In this scenario, light interacting with aerosol particles deposited on glass slides or PV cells is likely to undergo multiple scattering events along its optical path through the deposition layer. However, radiative transfer equations are complicated and cannot be solved analytically unless invoking restrictive and unrealistic simplifications. For this reason, there exist a number of radiative transfer models with varying degrees of simplifications and ad hoc applications. The two-stream approximation is a simple model of radiative transfer for parallel layers of a multiple-scattering propagation medium and assumes bi-directionality of light fluxes. The two-stream approximation is derived from assuming homogeneity of the medium as well as azimuthally symmetric phase functions. These simplifications are appropriate for our experiment because a very large number of dust particles are deposited onto a glass slide, constituting a fairly homogeneous medium
and because the phase function for these azimuthally randomly oriented particles is expected to be on average azimuthally symmetric, even if the phase function for individual, non-spherical particles is not. Thus, we compare results obtained with the two-stream approximation with our experimental measurements.

To describe the two-stream approximation, let us consider a simplified 1-dimensional system where optical power can only move normal to the plane of the PV cell, this simplification that can be overcome by extending this method to N-stream theory (Bohren and Clothiaux, 2006). Power moving down (towards the PV cell semiconductor) is denoted by $P_d$, while power moving up by $P_u$. Neglecting thermal emission (a realistic simplification for dust on solar cells since temperatures are too low for emission within the PV cell spectral response), the two-stream equations of radiative transfer are given by (e.g., Petty, 2006)

\[
\frac{d}{d\tau}(P_d - P_u) = -(1 - \omega)(P_d + P_u),
\]

\[
\frac{d}{d\tau}(P_d + P_u) = -(1 - \omega g)(P_d - P_u),
\]

where $\omega$ is the SSA defined as the ratio of single-scattering and extinction cross-section ($\sigma_{sca}/\sigma_{ext}$) and $g$ is the asymmetry parameter (Andrews et al., 2006); these are also the key aerosol optics intensive parameters used for atmospheric aerosol radiative forcing calculations (Chylek and Wong, 1995; Moosmüller and Ogren, 2017; Hassan et al., 2015). The boundary conditions for our two-stream model at $\tau = 0$ and at $\tau = \tau_0$ (where $\tau_0$ is the AOD of the dust layer) are given in Figure 3.5 with $R$ being the total reflectance (i.e., backward hemispheric reflection), while $T$ is the total transmittance thorough the dust layer accounting for both directly (i.e.,
Figure 3.5: Two-Stream approximation reference system and boundary conditions. $P_0$ is the incident power, $R$ is the total reflectance, $T$ is the total transmittance.

unaffected) and diffusely (i.e., single or multiple scattered) transmitted radiation.

When the system of coupled differential equations (3.9) and (3.10) is solved using the boundary conditions specified in Figure 3.5, the total transmission $T$ at optical depth $\tau_0$ can be expressed as (Liou, 2002)

$$T(\tau_0, \omega, g) = \frac{2}{2 \cosh(K\tau_0) + \frac{\sinh(K\tau_0)}{K}[2 - \omega(1 + g)]}, \quad (3.11)$$

where $K = \sqrt{(1 - \omega)(1 - \omega g)}$.

This equation is a very simple analytical solution for the total transmission $T$ into the forward direction thorough a layer of scattering and absorbing medium.

The transmission equations give the total diffuse and direct transmission $T$ as function of two intensive particle properties, SSA $\omega$ and asymmetry parameter $g$, as well as one extensive property of the particle layer, its optical depth $\tau_0$. Typical values of $\omega$ for dust commonly range from $\sim 0.4$ to $\sim 1$ (Engelbrecht et al., 2016),
while $g$ commonly ranges from $\sim 0.45$ to $\sim 0.65$ (Fiebig and Ogren, 2006).

### 3.3.2 Intensive Parameter of Optical Degradation: Asymmetry Parameter $g$

The asymmetry parameter for single scattering by particles is given by (e.g., Andrews et al., 2006; Videen et al., 1998)

$$g = \frac{\int_{4\pi} \frac{d\sigma_{\text{sc}}}{d\Omega} \cos \theta d\Omega}{\int_{4\pi} \frac{d\sigma_{\text{sc}}}{d\Omega} d\Omega} \quad (3.12)$$

where $\frac{d\sigma_{\text{sc}}}{d\Omega}$ is the angular distribution of scattered power. In spherical coordinates, $\theta$ is the polar angle, $\phi$ is the azimuthal angle, and $d\Omega = \sin \theta d\theta d\phi$ is the differential solid angle. From equation (3.12), it follows that $g$ is the mean cosine of the angular scattering power distribution. One-dimensionally, $(1 - g)/2$ can be interpreted as the probability that scattered light will change its direction from up to down or vice versa, while $(1 + g)/2$ is the probability that scattered photon will continue in its original direction after scattering (Bohren, 1987). If the size distribution of particles is not monodisperse, the angular distribution $\frac{d\sigma_{\text{sc}}}{d\Omega}$ must be integrated with respect to the particle size number distribution $n(D)$ (i.e., the number of particles with diameter $D$). In either case, $\frac{d\sigma_{\text{sc}}}{d\Omega}$ can be calculated using light scattering theory such as Mie theory (Mie, 1908), T-matrix (e.g., Mishchenko et al., 2007; Liu et al., 2008), or discrete dipole approximation (Yurkin and Hoekstra, 2011). A simple model is Mie theory, an exact solution for homogeneous, spherical particles where $\frac{d\sigma_{\text{sc}}}{d\Omega}$ is only dependent on the particles refractive index $m$, diameter $D$, and wavelength $\lambda$ of the incident radiation. In this case, the angular distribution of
scattered power, integrated over a polydisperse size distribution can be written as

\[
\frac{d\sigma_{\text{sca}}(m, \lambda)}{d\Omega} = \int_{D_1=0}^{D_2=\infty} \frac{d\sigma_{\text{sca}}(D, m, \lambda)}{d\Omega} n(D) dD
\]  

(3.13)

where we integrate over the size dependence of the differential scattering cross section weighed by the number size distribution \(n(D)\). In practice, the integration of equation (3.13) is done numerically, and the limit \(D_2\) is chosen such that the scattering from particles with \(D > D_2\) approaches zero. It is necessary to use a nearly continuous function \(n(D)\) so that accumulation of errors by numerical integration is minimal. Hence, prior to integration, \(n(D)\) should be fitted by a continuous function, typically a log-normal size distribution function (e.g., Piedra, 2014) such as that of equation (3.1).

### 3.3.3 Intensive Parameter of Optical Degradation: Single Scattering Albedo (SSA) \(\omega\)

For a single particle, the optical power removed from the direct beam by scattering from a particle is proportional to \(\sigma_{\text{sca}}\), while the optical power absorbed and converted into heat is proportional to the absorption cross section \(\sigma_{\text{abs}}\). The extinction cross section \(\sigma_{\text{ext}} = \sigma_{\text{abs}} + \sigma_{\text{sca}}\) is the sum of absorption and scattering cross section. The SSA is an intensive optical property of a particle that indicates the fraction of light extinction due to scattering. SSA is defined as

\[
\omega = \frac{\sigma_{\text{sca}}}{\sigma_{\text{ext}}} 
\]  

(3.14)

Just like the asymmetry parameter \(g\), the SSA \(\omega\) is an intensive particle property, independent of the number of particles involved. For homogeneous, spherical par-
articles, scattering, absorption, and extinction cross sections and consequently SSA $\omega$ can be calculated with Mie theory and depend exclusively on the particle refractive index $m(\lambda)$ and size $D$, and the wavelength $\lambda$ of the incident radiation. If the size distribution of particles is not monodisperse, an integration over the size distribution (similar to eq. (3.13)) is needed. Here, we have used a Mie calculation routine initially developed in Fortran by (Bohren and Huffman, 2008) and translated into Python by Kaiser (2014).

3.3.4 Monte Carlo Method

Monte Carlo methods (Metropolis and Ulam, 1949) are appealing given the relative simplicity of their implementation and the increasing power of modern computers. For optical propagation calculations, these methods model the optical path of a large number of photons, and keep track of each and every photons fate. The implementation used here is included in Appendix A and closely follows the logical flow of Prahl et al. (1989) with the difference that our implementation is one-dimensional (1-D) and uses a dimensionless optical depth (i.e., it does not require the actual physical thickness of the dust layer).

The logical flow of our code can be seen in Figure 3.6. We start by generating a photon in the down direction, which has a probability $\delta$ of propagating directly through the deposited dust layer

$$\tau = \ln \delta$$

(3.15)

where $\delta$ is a number randomly generated with equal probability to be between 0
Figure 3.6: Logical flow of the Monte Carlo method used here.

and 1. If the generated photon propagates beyond $\tau > \tau_0$, it is counted as transmitted. Otherwise, the photon is inside the dust layer medium and is either scattered or absorbed. To decide if the photon is absorbed or scattered, we generate another $\delta$ and allow the photon to be absorbed if $\delta > \omega$ or scattered if $\delta < \omega$. If the photon is scattered, it will change the photons direction. To model this directional variation consistently with two-stream theory, we generate another $\delta$ at random, and turn the photon into the opposite direction if $\delta > (1 + g)/2$ (Ch.5, Bohren and Clothiaux, 2006), or else keep its original direction if $\delta < (1 + g)/2$. It is noteworthy that expansion of this method to 3-D geometry is straightforward as it requires simple vector rotations of the propagating photon direction along appropriate planes of scattering. These rotations can be implemented with quaternions, Euler angles, or the Rodriguez formula.
3.4 Results and Discussion

Our objective is to understand optical losses on PV cells due to deposition of particles and to develop simple models that can be used to estimate such optical losses. The models used here are directly applicable only for direct sunlight (i.e., black sky) and for normal incidence, and assume that no diffuse radiation exists above the deposited dust layer. However, diffuse radiation (incoming radiation scattered by atmospheric gases and particles, including clouds) contributes to the total solar radiation received by PV cells. Depending on the solar zenith angle, wavelength, and atmospheric conditions, the fraction of diffuse radiation in total solar radiation can range from ~0% for clear days and near-infrared radiation to ~100% on cloudy days (Kaskaoutis and Kambezidis, 2009); future work should expand directionality simplifications and incorporate the attenuation of diffuse radiation for instance by using ray-tracing techniques (Zorrilla-Casanova et al., 2013), or by expanding incident directions using the Monte Carlo method shown here.

3.4.1 Experimental Results

Figure 3.7 and Figure 3.8 show a summary overview of our experimental measurements of total transmission as function of dust mass deposited density per unit area for the spectral range of 400 nm to 1400 nm and for absorbing and non-absorbing dust, respectively. The 3-D surface plots show a clear distinction between transmissions of the absorbing and the non-absorbing dust. For instance, notice that for the absorbing dust sample at a deposition mass density of 10 g/m², the minimum transmission occurs near a wavelength of 550 nm with a forward hemispheric transmission of ~0.3 In contrast, for the non-absorbing dust sample,
Figure 3.7: Absorbing dust sample total transmission $T$ as function of mass density per unit area and wavelength. For clarity, $T$ is plotted both as a surface and as color-map.

Figure 3.8: Same as Figure 3.7 but for non-absorbing dust sample.
at 10 g/m², the minimum forward hemispheric transmission is ∼0.6. In this simple example, assuming PV cell efficiency is proportional to optical transmission, the efficiency of the PV cell at 550 nm covered by 10 g/m² of non-absorbing dust would be about twice that of a PV cell covered by 10 g/m² of absorbing dust. This comparison highlights the importance of optical characterization of dust for PV cell power forecasting and location selection. While deposition of absorbing dust could be highly detrimental for PV cell efficiency, transmission losses caused by non-absorbing particles would be significantly smaller for the same deposition mass density. Another important observation is that transmission losses are not limited to the spectral region of very high imaginary refractive index of the dust type. Indeed, SSA is the lowest for intermediate values of imaginary refractive index, but higher for both very low and very high values (Moosmüller and Sorensen, 2018). We also observe that our measurements of total transmission vary strongly as function of mass per unit area but not as much as function of wavelength. Such near constancy of total transmission thorough the spectrum highlights the dependency of optical transmission on the different particle sizes that a sample of dust could have. Even though a single particles SSA can change substantially as function of wavelength depending on its size and imaginary refractive index, the overall SSA for the whole dust sample remains fairly constant through the spectrum. This result is reasonable since losses into the forward hemisphere due to absorption and scattering are governed by the ratio of particle diameter to particle skin depth as opposed to the imaginary refractive index alone (Wang et al., 2015; Piedra and Moosmüller, 2017).
Figure 3.9: Total transmission $T$ as function of AOD $\tau_0$ at wavelengths $\lambda = 410, 600,$ and 780 nm from measurements ($T_{\text{measured}}$, round dots), against two-stream theory ($T_{\text{two stream}}$, solid lines) and Monte Carlo techniques ($T_{\text{Monte Carlo}}$, dotted lines) for absorbing (left column) and non-absorbing (right column) dust deposited onto glass slides. Input parameters for two-stream and Monte Carlo calculations are shown in Table 3.1.

3.4.2 Theoretical Results and Their Comparison with Experimental Results

For our absorbing hematite powder sample and non-absorbing dust sample, Figure 3.10 displays a comparison of measurements and calculations of total transmission $T$ as function of deposited particle AOD $\tau_0$ at wavelength $\lambda = 400, 600,$ and 780 nm. The left and right columns contain measurements and calculations for the
Table 3.1: Summary of input values for curves displayed in Figure 3.9

<table>
<thead>
<tr>
<th>λ (nm)</th>
<th>( \omega )</th>
<th>( g )</th>
<th>( m )</th>
<th>( \omega )</th>
<th>( g )</th>
<th>( m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>410</td>
<td>0.630</td>
<td>0.778</td>
<td>2.72 + i1.2</td>
<td>0.983</td>
<td>0.802</td>
<td>1.5 + i3.3 \times 10^{-4}</td>
</tr>
<tr>
<td>600</td>
<td>0.612</td>
<td>0.784</td>
<td>3.14 + i0.16</td>
<td>0.997</td>
<td>0.780</td>
<td>1.5 + i8.5 \times 10^{-5}</td>
</tr>
<tr>
<td>780</td>
<td>0.649</td>
<td>0.743</td>
<td>2.78 + i0.032</td>
<td>0.999</td>
<td>0.768</td>
<td>15 + i3.7 \times 10^{-5}</td>
</tr>
</tbody>
</table>

absorbing and the non-absorbing dust sample, respectively. We use the notation \( T_{\text{measured}} \) to denote SIS measurements of total transmission, \( T_{\text{two stream}} \) to denote total transmission \( T \) calculated by equation (3.11), and \( T_{\text{Monte Carlo}} \) for \( T \) calculated by the Monte Carlo method. The particle number size distribution \( n(D) \) used was from the log-normal fit to an experimental particle number size distribution obtained from microscopy of the deposited sample (see Section 3.2.1). The quantities \( \omega \) and \( g \) were calculated using Mie theory as discussed in Section 3.3.2 and Section 3.3.3, respectively. The refractive indices for the absorbing sample were obtained from Querry (1985). The non-absorbing sample had not been characterized by refractive index but by SSA \( \omega \) by Engelbrecht et al. (2016). As with the absorbing sample, we have measured \( n(D) \) by microscope image analysis and estimated its real part of the refractive index to be \( m_r \sim 1.5 \). The measured \( \omega \) and the assumed \( m_r \) allowed us to retrieve the imaginary part of the refractive index \( m_i \), which yields the asymmetry parameter by applying equation (3.12) with Mie theory, under the assumption of homogeneous spherical particles. In Table 3.1, we give a summary of values of SSA \( \omega \) asymmetry parameter \( g \), and refractive index \( m \) used to obtain the curves shown in Figure 3.9.
Table 3.2: Slopes $m$, $y$-intercepts $b$, and correlation coefficients $R^2$ obtained from linear regressions in Figure 3.10 for the absorbing sample.

<table>
<thead>
<tr>
<th>$\lambda$ (nm)</th>
<th>Two-Stream Theory</th>
<th>Monte Carlo Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$m$</td>
<td>$b$</td>
</tr>
<tr>
<td>410</td>
<td>0.95 ± 0.060</td>
<td>0.02 ± 0.049</td>
</tr>
<tr>
<td>600</td>
<td>1.08 ± 0.066</td>
<td>−0.1 ± 0.056</td>
</tr>
<tr>
<td>780</td>
<td>1.13 ± 0.066</td>
<td>−0.15 ± 0.056</td>
</tr>
</tbody>
</table>

3.4.3 Evaluation of Methods

We now move our attention to quantitatively characterizing the goodness of fit of our theoretical calculations to our experimental measurements results as shown in Figure 3.7. We evaluate our models by plotting our calculated values as function of our measured ones. For both pairs of datasets, that is $(T_{\text{measured}}, T_{\text{two stream}})$ and $(T_{\text{measured}}, T_{\text{Monte Carlo}})$, a linear regression was performed, yielding slope $m$, intercept $b$, and correlation coefficient $R^2$. Perfect agreement would mean that $m = 1$, $b = 0$, and $R^2 = 1$. Figure 3.10 displays a comparison of total transmission obtained by measurement plotted against total transmission obtained by models for the same wavelengths used to calculate Figure 3.9 ($\lambda = 400, 600,$ and 780 nm). In the left column, we present the absorbing sample, while in the right column, we present the non-absorbing sample. Table 3.2 summarizes obtained slopes, intercepts and correlation coefficients obtained from linear regression using the absorbing sample, while Table 3.3 does the same for the non-absorbing sample.

In general, we see that both methods, two-stream and Monte Carlo, yield very similar transmissions, including nearly identical slopes, intercepts, and correlation
Table 3.3: Same as Table 3.2 for the non-absorbing sample.

<table>
<thead>
<tr>
<th>λ (nm)</th>
<th>Two-Stream Theory</th>
<th>Monte Carlo Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$m$</td>
<td>$b$</td>
</tr>
<tr>
<td>410</td>
<td>0.96 ± 0.004</td>
<td>0.03 ± 0.003</td>
</tr>
<tr>
<td>600</td>
<td>1.01 ± 0.009</td>
<td>−0.02 ± 0.007</td>
</tr>
<tr>
<td>780</td>
<td>1.04 ± 0.016</td>
<td>−0.06 ± 0.013</td>
</tr>
</tbody>
</table>

Figure 3.10: Total transmission $T$ as function of AOD $\tau_0$ at wavelengths $\lambda = 410, 600, \text{ and } 780 \text{ nm}$ from measurements ($T_{\text{measured}}$, blue diamonds, red X’s against two-stream theory ($T_{\text{two stream}}$, blue solid lines) and Monte Carlo techniques ($T_{\text{Monte Carlo}}$, red dotted lines) for absorbing (left column) and non-absorbing (right column) dust deposited onto glass slides. Input parameters for two-stream and Monte Carlo calculations are shown in Table 3.1.
Figure 3.11: Difference between measurement and two-stream calculation of transmission for absorbing dust as function of wavelength and deposition mass density.

coefficients when compared by linear regression with our experimental results. The linear regression for absorbing sample has an intercept closer to zero than for the non-absorbing sample. The linear regression intercepts for both absorbing and non-absorbing samples become negative as wavelength increases. Overall, linear regressions between two-stream and Monte Carlo transmissions and experimental transmissions have slopes close to one, and intercepts close to 0 which indicates good agreement between theory and experiment. In addition, the correlation coefficients are very close to one, indicating that these methods are very good at predicting the total transmission as function of optical depth for absorbing and non-absorbing mineral dust deposits.

Figure 3.11 and Figure 3.12 illustrate the absolute difference between our ex-
Figure 3.12: Difference between measurement and two-stream calculation of transmission for non-absorbing dust as function of wavelength and deposition mass density.

Experimental measurements and theoretical calculations of total transmission $T$ for the absorbing and non-absorbing samples, respectively. This difference is defined as

$$\text{Difference} = |T_{\text{measured}} - T_{\text{two stream}}|$$  \hspace{1cm} (3.16)

and is plotted as a color-map contour. Comparisons with Monte Carlo methods are obviated since they Monte Carlo transmission results differ from those of two-stream theory by less than 1%. In the case of absorbing dust (Figure 3.11), the two-stream method transmission results remains within $\lessapprox 0.1$ of the experimental results for almost the entirety of the $\rho_m - \lambda$ domain, reaching $0.1 \lessapprox \text{Difference} \lessapprox 0.16$.
at large wavelengths $\lambda \gtrsim 1100$ nm and high mass density $\rho_m \gtrsim 6$ g/m$^2$.

A comparison of two-stream model calculations and measurements of transmission for non-absorbing dust (Figure 3.12) shows good agreement for the spectral range of 410 nm to 780 nm (this sample had not been characterized beyond this spectral range), with differences in transmission less than 0.08. These results suggest that two-stream theory and Monte Carlo methods can estimate solar cell transmission degradation for most practical purposes for absorbing dust and non-absorbing dust.

### 3.5 Conclusions

This paper examines the spectral transmission of radiation through dust covered glass slides as surrogate for dust covered PV cells. A major conclusion is the strong variation of total transmission as function of the single scattering albedo (SSA) of the dust. Our experimental results indicate that forward hemispheric transmission decreases approximately linearly with deposited mass per unit area. However, the slope of this decrease is highly sensitive to the absorptivity of the dust. Furthermore, our experimental and theoretical results for the total transmission in the spectral range between 400 and 1400 nm show very low variation as function of wavelength compared to variations as function of mass density per unit area. Therefore, we conclude that transmission losses due the deposited dust are largely independent of wavelength and not limited to the spectral region of very high imaginary part of refractive index of the absorbing dust. This is explained by the fact that strong light absorption by large particles occurs for intermediate values of imaginary refractive index, with less absorption for both very low and
very high values. In terms of theoretical modeling, we show that both two-stream and Monte Carlo methods can model solar cell optical degradation for absorbing and non-absorbing dust in good agreement with our experimental results.

3.6 Acknowledgments

This work has been supported in part by the National Science Foundation Solar Energy-Water-Environment Nexus program under the cooperative agreement No. EPS-IIA-1301726. Patricio Piedra acknowledges a Graduate Student Fellowship from NASA-EPSCOR. Very helpful discussions with Drs. W. Patrick Arnott and Christopher M. Sorensen have greatly contributed to the radiative transfer discussion and the comparison with experiments. Dr. Johann P. Engelbrecht has made samples of non-absorbing mineral dust available and Dr. Vicken R. Etyemezian has been essential in motivating and organizing this project. It is also a pleasure to acknowledge helpful discussions and training by Dr. David E. Rhode on the use of microscopic instruments. Patricio Piedra and Laura Llanza kindly acknowledge the contribution of Mr. Nicholas D. Beres who has helped with the development of the experimental apparatus and with helpful discussions on using our laboratory's spectrophotometer.
CHAPTER 4
CONCLUSIONS AND RECOMMENDATIONS

This dissertation explores the optical effects of particles deposited onto PV cells, and how these particles deteriorate radiative transfer towards the PV cell semiconductor. In Chapter 2, we explored optical losses due to deposition of a sample with low mass per unit area (i.e., $\tau_0 \ll 1$). Fundamentally, we described that losses into the forward hemisphere direction are due to absorption and backward hemispheric scattering. We defined the power fraction lost $FL = \frac{\sigma_{bs} + \sigma_{abs}}{\sigma_{ext}}$ as the ratio of backward hemispheric scattering and absorption to total extinction. Similarly, we defined the backward hemispheric scattering and absorption efficiency $BSAE = Q_{ext}FL$ which is an intensive parameter, independent of the number of particles on the PV cell, and describes optical losses in the forward direction as function of particle type. With these two parameters, we studied the role of imaginary refractive index $m_i$ and size parameter $x$ on $FL$ and $BSAE$. The resulting analysis demonstrates that per optical depth, fine particles yield higher losses in forward direction than coarser ones. This is because for fine particles, backward hemispheric scattering plays a more significant role than for coarser ones. Another important result shown in this study is that neither parameter $m_i$ or $x$ on its own is a good indicator of optical losses in the forward direction. Indeed, it is the combination $m_i x$ (i.e., the ratio of particle radius to skin depth) that determines losses in the forward direction. We found that particles produce the highest losses in the forward direction when skin depth is similar to particle diameter. Finally, we demonstrated that particles with $m_i > 0.025$ will always have absorption as dominant mechanism of losses in the forward direction. From these findings in Chapter 2, we conclude that light-absorbing carbonaceous particles such as smog emitted by cars or factories and light absorbing mineral dust can greatly deteriorate the
efficiency of PV cells. Hence, manufacturers of PV cells deployed in urban areas in the proximity of smog are advised to attempt to coat their PV cells to prevent adhesion of these types of particles to the PV cell. On the other hand, large, non-absorbing particles such as non-absorbing desert dust, are not as deteriorating to PV cell efficiency. If there are frequently occurring natural mechanisms of dust removal such as wind and rain, solar efficiency may not be impacted heavily since most of the optical scattering is in the forward direction and therefore does not reduce PV efficiency. In this case, solar operations are advised to ignore minor dust deposition, thereby saving labor costs and water.

Finally, in Chapter 3, we explore radiative transfer deterioration due to larger, often more realistic loading of dust on PV cells (i.e., $0 < \tau_0 \lesssim 7$). We experimentally suspended and deposited two types of dust (i.e., optically absorbing and nonabsorbing) onto glass slides that served as surrogates for PV cells. The total transmission in the forward hemisphere direction was measured using a spherical integrating spectrophotometer (SIS). We found that total transmission in the forward hemisphere $T$ is nearly linearly proportional to the amount of dust per unit area on the PV cell, and the slope of this proportionality is highly sensitive to the single scattering albedo (SSA) of the dust. Optically absorbing dust reduces total transmission by approximately twice the amount of non-absorbing dust. Similarly, we found that optical losses are relatively independent of the optical wavelength and thus are not limited to spectral regions where SSA is low. Indeed, the effect of wavelength averaging with respect to broad spectrum is equivalent to size-averaging with respect to particle size distribution. Evidently, this near constancy of the optical transmission though the spectrum is the effect of optical transmission in the forward direction being a function of both $m_i$ and $x$ as shown in Chapter 2. Hence, we experimentally observed that optical transmission is nearly constant as
function of wavelength. We also demonstrated that two-stream theory and Monte Carlo methods can model radiative transfer well for our dust samples. These models simulate dust as a continuous homogeneous medium and obviate many of the problems that arise from treating dust as a collective of many individual light scattering particles, a problem that is very difficult to simulate. From these findings, we conclude that PV cell optical losses due to non-absorbing dust can potentially be tolerated while losses due to absorbing dust are highly detrimental to the solar transmission onto the PV cell semiconductor. Solar operations are advised to conduct optical analysis of dust deposits in the location where PV cells are to be placed. It is important to notice that dust can also be transported from far-away locations, hence, it is important to not only analyze the optical characteristics of dust sources in the vicinity of the PV cell installations. Careful selection of locations where dust deposition is dominated by non-absorbing particles has the potential to save costs of solar energy production due to reduced maintenance, labor, and water needed for cleaning.

4.1 Additional Work Needed

For practicality, let us consider a PV cell with dust deposited on it, and our aim is to forecast its efficiency. There are many different aspects to this problem space, from forecasting the number of particles depositing on the PV cell to determine different combinations of dust minerals for optical calculations. The flow chart in Figure 4.1 shows a general representation of how deposition models can be combined with optical ones to forecast PV cell efficiency. As can be seen in the oval, this dissertation addressed part of the whole problem space by determining an appropriate radiative model. Future work should address the determination of optical depth
from deposition models in combination with optical ones. This will require that a deposition model can correctly estimate the mass per unit area $\rho_M$ deposited in the PV cell. If the volume density $\rho$ of the dust is also known, one can estimate the average thickness $L$ of the deposition by $L \approx \frac{\rho_M}{\rho}$. Additionally, optical characterization of dust will be required to yield the extinction coefficient $\beta_{\text{ext}}$ as well as the scattering coefficient $\beta_{\text{sca}}$ (or the absorption coefficient $\beta_{\text{abs}}$) of the dust sample. These measurements can yield the optical depth $\tau_0 = \beta_{\text{ext}}L$ as well as $\omega = \beta_{\text{sca}}/\beta_{\text{ext}}$. The radiative model shown in Chapter 3 also depends on the asymmetry parameter $g$. However, dust particles are highly scattering in the forward direction and equation (3.11) is largely dominated by $\omega$ rather than $g$. Hence, a typical value (e.g., $g \sim 0.75$) can be assumed. The radiative models developed in Chapter 3 need to include different incident angles of solar irradiance. This can be done by simply modifying the optical path along the dust sample with respect to the incidence angle. In the same manner, a diffuse, nearly constant, irradiance component should be integrated with respect to all incident angles. Combinations of different mixes of dust should also be addressed; this can be done using the models described here by expanding them for multiple layers of different types of dust with various $\omega$ and $\tau_0$. The final step will be to weight the transmission response with respect to the solar spectrum and the spectral response of the PV cell semiconductor. This will ultimately yield the efficiency loss of the PV cell.
Figure 4.1: Flow diagram of problem space on forecasting effects of dust on PV cells. The section in the oval is the part of the problem that has been addressed in this dissertation.
BIBLIOGRAPHY


Hammad, B., M. AlAbed, A. AlGhandoor, A. AlSardeah, and A. AlBashir (2017). Modeling and analysis of dust and temperature effects on photovoltaic systems


Moosmüller, H. and J. A. Ogren (2017). Parameterization of the aerosol upscatter fraction as function of the backscatter fraction and their relationships to the asymmetry parameter for radiative transfer calculations. *Atmosphere* 8(8), 133. pages 50


Padera, F. (2013). Measuring absorptance (k) and refractive index (n) of thin films with the perkinelmer lambda 950/1050 high performance uv-vis/nir spectrometers. *PerkinElmer Inc.: Application note: UV/Vis Spectroscopy*. pages 43


Stocker, T. (2014). *Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. pages 1


This section describes a Monte Carlo subroutine used to model 1-D radiative transfer calculations as function of optical depth without explicitly imposing physical dimensions on the dust layer. The total dust layer optical thickness $\tau_0$ along the direction of propagation $z$ (i.e., downwards toward the PV semiconductor) in a Cartesian frame of reference $x, y, z$ is used instead as metric of light propagation. This subroutine is a Python unitless adaptation and closely follows Prahl (1988). Light is propagated in the $\tau$ or $-\tau$ direction (for a 1-D model). However, this code can be expanded to three dimensions where light would propagate in a $\vec{\tau}$ vector direction composed of $[x \cdot \vec{\tau}, y \cdot \vec{\tau}, z \cdot \vec{\tau}]^T$. If used in this manner, polar rotations for propagation of scattered light along $\theta$ (i.e., the scattering angle for azimuthally symmetric particles) can be performed by using quaternion vector rotation along the axis $z \times \vec{\tau}$. Similarly, rotations for the propagation of scattered light along the azimuthal angle $\phi$ are performed along the axis $\vec{\tau} / |\vec{\tau}|$. The main Monte Carlo subroutine “MC-1D” is shown as well as two functions: (1) “in-medium” is used to check if photon is still inside the boundaries $0 < \tau < \tau_0$, and (2) “scat-direction” is used to switch the direction of a scattered photon according to two stream theory.

## inputs:

- $\tau$ range is an array of levels of optical depth
- $w$ is the single scattering albedo of the dust
- $g$ is the asymmetry parameter of the dust
- $N_{\text{photons}}$ is the number of photons used in the Monte Carlo simulation

## outputs:

- $T_{\text{monte}}$ is the total transmission for the optical depth
from pylab import *
import numpy as np
from scipy.interpolate import interp1d

def MC_1D(tau_range, w, g, N_photons):
    # initiate transmission, absorption and reflection photon count
    T_count = 0
    A_count = 0
    R_count = 0

    z = np.array([0, 0, 1])  # direction down
    T_list = []

    # reducing the number of taus in the array to 5 elements
    # this is done to save computation time
    tau_range_MC = linspace(tau_range[0], tau_range[-1], 5)

    for tau_max in tau_range_MC:
        for i in range(N_photons):

            # always start with photon going down towards z, with tau=0
            tau_z = 0.0
            direction = np.array([0, 0, 1])

            t = rm.random()
$$\text{dtau} = -\log(t)$$

*important direction is only z for our purposes*

$$\text{tau}_z += \textbf{float}(\text{np.dot(direction, } z)) \ast \text{dtau}$$

```python
if in_medium(\text{tau}_z, \text{tau}_\text{max}) == False:
    \text{T}_\text{count} += 1

else:
    # while photon is still in medium, it can scatter or be absorbed
    \text{while in_medium(\text{tau}_z, \text{tau}_\text{max}) == True:}
        \text{scat_or_abs} = \text{random()}

    # if photon is absorbed, count it and go back to next photon
    if \text{scat_or_abs} > \text{w:}
        \text{A}_\text{count} += 1
        break

    # if is scattered, it can scatter in different direction
    # run monte-carlo for direction

else:
    \text{direction} = \text{scat_direction}(g, \text{direction})

# photon is thrown into medium an optical depth tau
    # at an angle from the z axis
t = rm.random()
dtau = -log(t)

# along the medium in direction z, photon advances tau_z
tau_z = float(np.dot(direction, z)) * dtau

# check if scattered photon is still in medium and if it
# was transmitted in the down direction tau_z > 0, count as transmitted
# otherwise, re-iterate

if in_medium(tau_z, tau_max) == False:
    if float(np.dot(direction, z)) > 0:
        T_count += 1

# if direction was up, you can count as reflected
else:
    R_count += 1
    pass
    break
else:
    pass

T_list.append(float(T_count)/N_photons)

T_count = 0
A_count = 0
R_count=0

# re-interpolate to originally given tau_range array
tau_interp = interp1d(tau_range_MC, T_list, kind='cubic')
T_monte=tau_interp(tau_range)
return T_monte

# function used to check if photon is still in the medium
def in_medium(tau_current, tau_max):
    if tau_current>tau_max or tau_current<0:
        return False
    else:
        return True

# function used to change current direction and change photon direction according to two stream probability
def scat_direction(g, curr_direction):
    p_turn=(1.0+g)/2.0
    t=random() / 2.0
    if t>p_turn:
        return -1*curr_direction
    else:
        return curr_direction