1
Introduction

1.1
Brief History

The idea or notion that *light attenuation* is proportional to the inverse square of the distance traveled can be traced to Kepler [1]. Its experimental verification was provided by Bouguer [2], who used the inverse square dependence to establish the exponential *extinction law* by studying the attenuation of light passing through *translucent media*. A mathematical foundation of *radiometry* was provided by Lambert [3], who used calculus to interpret experimental results and thereby develop appropriate mathematical models and physical theories. As pointed out by Mishchenko [4], although the first introduction of the *radiative transfer equation (RTE)* has traditionally been attributed to Schuster [5], the credit should go instead to Lommel [6], who derived an integral form of the RTE by considering the directional flow of radiant energy crossing a surface element; almost identical results were obtained independently by Chwolson [7].

The *specific intensity* (or *radiance*) $I(\mathbf{r}, \hat{\mathbf{\Omega}})$ is the most important quantity of classical *radiative transfer theory (RTT)*. Planck [8] defined it by stating that the amount of radiant energy dE transported through a surface element dA in directions confined to a *solid angle* $d\omega$ around the direction of propagation $\hat{\mathbf{\Omega}}$ in a time interval dt is given by $dE = I(\mathbf{r}, \hat{\mathbf{\Omega}}) \cos\theta dAdtd\omega$, where $\mathbf{r}$ is the position vector of the surface element dA, and θ is the angle between $\hat{\mathbf{\Omega}}$ and the normal to dA. This definition was adopted in the works of Milne [9], Hopf [10], and Chandrasekhar [11], and has since been used in many monographs [12–16] and textbooks [17–21] on RTT. To treat the polarization properties of radiation Stokes [22] introduced four parameters to describe the state of polarization. These so-called *Stokes parameters* were used by Chandrasekhar [11, 23] to replace the specific intensity with the four-element column vector $\mathbf{I}(\mathbf{r}, \hat{\mathbf{\Omega}})$ to describe polarized radiation.

The heuristic derivation of the RTE adopted in Chapter 3 of this book for *unpolarized* as well as *polarized radiation* is based on classical RTT invoking the specific intensity and simple energy conservation arguments. Such a derivation is easy to understand and sufficient for our purpose. Mandel and Wolf [24] noted that a more fundamental derivation that can be traced to the *Maxwell equations* was

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desirable, and stated "In spite of the extensive use of the theory of radiative energy transfer, no satisfactory derivation of its basic equation... from electromagnetic theory... has been obtained up to now." Recently, however, much progress toward such a derivation has been made, as reported by Mishchenko [25].

1.2 What is Meant by a Coupled System?

In many applications, an accurate description is required of light propagation in two adjacent slabs of *turbid media* that are separated by an interface, across which the refractive index changes. Such a two-slab configuration will be referred to as a *coupled system*. Three important examples are atmosphere–water systems [26, 27], atmosphere–sea ice systems [28, 29], and air–tissue systems [30]. In each of these three examples, the change in the refractive index across the interface between the two media must be accounted for in order to model the transport of light throughout the respective coupled system correctly. In the second example, the refractive-index change, together with *multiple scattering*, leads to a significant trapping of light inside the strongly scattering, optically thick sea-ice medium [28, 29]. For *imaging* of biological tissues or satellite remote sensing of water bodies, an accurate radiative transfer (RT) model for a coupled system is an indispensable tool [31, 32]. In both cases, an accurate RT tool is essential for obtaining satisfactory solutions of retrieval problems through iterative forward/inverse modeling [33, 34].

In *remote sensing* of the Earth from space, one goal is to retrieve atmospheric and surface parameters from measurements of the radiation emerging at the top of the atmosphere (TOA) at a number of wavelengths [35, 36]. These *retrieval parameters* (RPs), such as aerosol type and loading and concentrations of aquatic constituents in an open ocean or coastal water area, depend on the *inherent optical properties* (IOPs) of the atmosphere and the water. If there is a model providing a link between the RPs and the IOPs, a forward RT model can be used to compute how the measured TOA radiation field should respond to changes in the RPs, and an inverse RT problem can be formulated and solved to derive information about the RPs [37, 38]. A *forward RT model*, employing IOPs that describe how atmospheric and aquatic constituents absorb and scatter light can be used to compute the *multiply scattered light field* in any particular direction (with specified polar and azimuth angles) at any particular depth level (including the TOA) in a vertically *stratified medium*, such as a coupled atmosphere–water system [34, 39]. In order to solve the *inverse RT problem*, it is important to have an accurate and efficient forward RT model. Accuracy is important in order to obtain reliable and robust retrievals, and efficiency is an issue because standard iterative solutions of the *nonlinear inverse RT problem* require executing the forward RT model repeatedly to compute the radiation field and its partial derivatives with respect to the RPs (the *Jacobians*) [37, 38].

1.3 Scope

While solutions to the *scalar RTE*, which involve only the first component of the *Stokes vector* (the radiance or intensity), are well developed, modern RT models that solve the *vector RTE* are capable of also accounting for polarization effects described by the second, third, and fourth components of the Stokes vector. Even if one's interest lies primarily in the radiance, it is important to realize that solutions of the *scalar RTE*, which ignores *polarization effects*, introduce errors in the computed radiances [40–42].

In this book, we will consider the theory and applications based on both scalar and vector RT models, which include polarization effects. There are numerous RT models available that include polarization effects (see Zhai *et al.* [43] and references therein for a list of papers), and the interest in applications based on *polarized radiation* is growing. There is also a growing interest in applications based on vector RT models that apply to coupled systems. Examples of vector RT modeling pertinent to a coupled atmosphere–water system include applications based on the *doubling-adding method* (e.g., Chowdhary [44], Chowdhary *et al.*, [45–47]), the *successive order of scattering method* (e.g., Chami *et al.*, [48], Min and Duan [49], Zhai *et al.*, [43]), the *matrix operator method* (e.g., Fisher and Grassl, [50], Ota *et al.*, [51]), and *Monte Carlo methods* (e.g., Kattawar and Adams [40], Lotsberg and Stamnes [52]).

Chapter 2 provides definitions of IOPs including *absorption* and *scattering coefficients* as well as the *normalized angular scattering cross section*, commonly referred to as the *scattering phase function*, and the corresponding *scattering phase matrix* needed for vector RT modeling and applications. In several subsections basic scattering theory with emphasis on spherical particles (*Mie–Lorenz theory*) is reviewed, and IOPs for atmospheric gases and aerosols as well those for surface materials including snow/ice, liquid water, and land surfaces are discussed. The impact of a rough interface between the two adjacent slabs is also discussed.

In Chapter 3, an overview is given of the *scalar RTE* as well as the *vector RTE* applicable to a coupled system consisting of two adjacent slabs with different refractive indices. Several methods of solution are discussed: the *successive order of scattering method*, the *discrete-ordinate method*, the *doubling-adding method*, and the *Monte Carlo method*. In Chapter 4, we discuss forward RT modeling in coupled environmental systems based on the discrete-ordinate method, while Chapter 5 is devoted to a discussion of the inverse problem. Finally, in Chapter 6, a few typical applications are discussed including (i) how spectral redundancy can be exploited to reduce the computational burden in atmospheric RT problems, (ii) simultaneous retrieval of total ozone column amount and cloud effects from ground-based irradiance measurements, (iii) retrieval of aerosol and snow-ice properties in coupled atmosphere–cryosphere systems from space, (iv) retrieval of aerosol and aquatic parameters in coupled atmosphere–water systems from space, (v) vector RT in coupled systems, and (vi) how polarization measurements can be used to improve retrievals of atmospheric and surface parameters in coupled atmosphere–surface systems.

1.4 Limitations of Scope

We restrict our attention to scattering by molecules and small particles such as aerosols and cloud particles in an atmosphere, hydrosols in water bodies such as oceans, lakes, and rivers, and inclusions (air bubbles and brine pockets) embedded in ice. To explain the meaning of *independent scattering*, let us consider an infinitesimal volume element filled with small particles that are assumed to be randomly distributed within the volume element. Such infinitesimal volume elements are assumed to constitute the elementary scattering agents. *Independent scattering* implies that each particle in each of the infinitesimal volume elements is assumed to scatter radiation independently of all other volume elements.

Although there are many applications that require a three-dimensional (3-D) RT treatment, in this book we limit our discussion to *plane-parallel* systems with an emphasis on the coupling between the atmosphere and the underlying surface consisting of a water body, a snow/ice surface, or a vegetation canopy. For a clear (cloud- and aerosol-free) atmosphere, 3-D effects are related to the impact of the Earth's curvature on the radiation field. To include such effects, a *pseudo-spherical* treatment (see Dahlback and Stamnes [53]) may be sufficient, in which the direct solar beam illumination is treated using spherical geometry, whereas *multiple scattering* is done using a plane-parallel geometry. This pseudo-spherical approach has been implemented in many RT codes [54, 55]. There is a large body of literature on *3-D RT modeling* with applications to broken clouds. Readers interested in RT in cloudy atmospheres may want to consult books like that of Marshak and Davis [12] or visit the Web site http://i3rc.gsfc.nasa.gov/.

3-D RT modeling may also be important for analysis and interpretation of *lidar* data. In this context, the classical "searchlight problem" [56], which considers the propagation of a *laser beam* through a *turbid medium*, is relevant. Long-range propagation of a lidar beam has been studied both theoretically and experimentally [57]. Monte Carlo simulations are well suited for such studies [58], and use of deterministic models such the *discrete-ordinate method*, discussed in Chapters 3 and 4 of this book, have also been reported [59, 60].

Most RT studies in the ocean have been concerned with understanding the propagation of sunlight, as discussed by Mobley *et al.* [26]. For these applications, the transient or *time-dependent* term in the RTE can be ignored, because changes in the incident illumination are much slower than the changes imposed by the propagation of the light field through the medium. While this assumption is satisfied for solar illumination, lidar systems can use pulses that are shorter than the attenuation distance of seawater divided by the speed of light in water. Also, as pointed out by Mitra and Churnside [61], due to multiple light scattering, understanding the lidar signal requires a solution of the *time-dependent RTE*. Although such studies are beyond the scope of this book, the transient RT problem can be reduced to solving a series of *time-independent* RT problems, as discussed by Stamnes *et al.* [62].

We restrict our attention to *elastic scattering*, although *inelastic scattering* processes (Raman and Brillouin) certainly can be very important and indeed essential in some atmospheric [63–65] and aquatic [66, 67] applications. Although most particles encountered in nature have nonspherical shapes – cloud droplets being the notable exception – we will not consider nonspherical particles in this book. Although the general introduction to the scattering problem provided in Chapter 2 is generic in nature and thus applies to particles of arbitrary shape, our more detailed review is limited to spherical particles (Mie–Lorenz theory). The reader is referred to the books by Bohren and Huffman [68] and Zdunkowski *et al.* [20] for a more comprehensive discussion of the Mie-Lorenz theory and to the recent book by Wendisch and Yang [21] for an excellent introduction to scattering by nonspherical particles.