

Light Scattering Reviews 5

Single Light Scattering and Radiative Transfer

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1st Edition. 2010. Buch. xxvii, 549 S. Hardcover

ISBN 978 3 642 10335 3

Format (B x L): 17 x 24 cm

Gewicht: 1249 g

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Preface

Light scattering by densely packed inhomogeneous media is a particularly challenging optics problem. In most cases, only approximate methods are used for the calculations. However, in the case where only a small number of macroscopic scattering particles are in contact (clusters or aggregates) it is possible to obtain exact results solving Maxwell's equations. Simulations are possible, however, only for a relatively small number of particles, especially if their sizes are larger than the wavelength of incident light. The first review chapter in Part I of this volume, prepared by Yasuhiko Okada, presents modern numerical techniques used for the simulation of optical characteristics of densely packed groups of spherical particles. In this case, Mie theory cannot provide accurate results because particles are located in the near field of each other and strongly interact. As a matter of fact, Maxwell's equations must be solved not for each particle separately but for the ensemble as a whole in this case. The author describes techniques for the generation of shapes of aggregates. The orientation averaging is performed by a numerical integration with respect to Euler angles. The numerical aspects of various techniques such as the T-matrix method, discrete dipole approximation, the finite difference time domain method, effective medium theory, and generalized multi-particle Mie solution are presented. Recent advances in numerical techniques such as the grouping and adding method and also numerical orientation averaging using a Monte Carlo method are discussed in great depth.

The second chapter in Part I of this volume, prepared by Sandra Jacquier and Frédéric Gruy, also considers the scattering properties of aggregates. The authors consider particles with radii both much smaller and larger as compared to the wavelength of the incident light. In the least case the methods based on the direct solution of Maxwell's equations cannot be used due to computational problems. Therefore, various approximate techniques are introduced and thoroughly discussed in the chapter. They include the anomalous diffraction approximation developed by van de Hulst, the Berry–Percival–Khlebtsov method, effective medium technique, and a compact sphere method. The performance of these methods (where it is possible) is evaluated against exact computations. As an application of theoretical techniques, the authors consider the process of agglomeration of small primary particles in a homogeneous suspension and its monitoring using measurements of turbidity.

Part II of this book deals with radiative transfer theory. This theory is used to describe reflectance and transmittance of turbid media such as the atmosphere and the ocean. It is based on solution of the vector radiative transfer equation (VRTE). Usually the VRTE is solved using the approximation of horizontally homogeneous

media. However, such an approach cannot be used in many cases (e.g., in the vicinity of cloud edges) and the 3-D VRTE must be formulated and solved. Céline Cornet and co-authors describe one possible way of solving the 3-D VRTE. It is based on the Monte Carlo approach. The technique implemented in the developed software (code 3DMCpol) is described together with validation using the adding-doubling method and also the Spherical Harmonics Discrete Ordinate Method (SHDOM). The code is applied to study the Stokes vector of reflected light for a synthetic heterogeneous cloud field.

The authors of the second chapter in Part II, Holger Walter and Jochen Landgraf, deal with 3-D radiative transfer as well. However, they ignore polarization characteristics of light and concentrate their efforts on the solution of the radiative transfer equation in a spherical geometry, which is of importance for atmospheric remote sensing, including satellite limb measurements. The Picard iteration method is used with validation from reference Monte Carlo calculations. Also, the authors perform the linearization of the radiative transfer problem in the spherical geometry. The forward and adjoint radiative transfer equations (ARTE) are introduced. ARTE differs from the standard radiative transfer equation by the sign of the streaming term d/ds (also the directions in the scattering function are reversed). An important point is that ARTE can be solved using the same radiative transfer solver as applied for the solution of the standard forward radiative transfer equation (by exchanging and reversing the incoming and outgoing directions). The solutions of the forward and adjoint radiative transfer equations are used to estimate the impact of change in the atmospheric state on the light intensity in a given direction, which is of great importance both for sensitivity studies and for the inverse problem solution.

The next chapter (Chapter 5) prepared by Vladimir Budak and co-authors, describes a method for solving the radiative transfer problem with strongly anisotropic scattering (e.g., relevant to light propagation in the ocean, where the asymmetry parameter can reach 0.99). The subject is very important, and the authors offer an original and very effective solution based on a separation of regular (smooth) and highly anisotropic components. Comparison with a well-established discrete ordinate code (DISORT) is given. This confirms a high accuracy of the developed code (and, in addition, it has much higher speed as compared to DISORT in the case of the highly elongated in the forward direction phase functions). To eliminate the anisotropic part of the solution of the radiative transfer equation the authors used the small-angle approximation in Goudsmit–Saunderson form. It results in a boundary-value problem for the regular part of the solution that is similar to the initial problem, but with the modified source function on the right-hand side of equation and the modified boundary conditions. The solution of the obtained equation for the regular part is found by the discrete ordinates method. In the case of plane-parallel geometry this problem has the analytical solution as a matrix exponential. The authors also generalized their approach to account for the vector nature of light and solved VRTE using the same methodology. Moreover, the 3-D radiative transfer has also been considered in the framework of the generalized Goudsmit–Saunderson approximation.

Chapter 6, by Lyapustin and co-authors, provides an overview of the publicly available radiative transfer code SHARM. Among rigorous scalar codes, SHARM

is one of the most numerically efficient and is based on the method of spherical harmonics. Following descriptions of the algorithm and interface of the code, the chapter describes the code SHARM-3D, which is designed for computations with non-homogeneous anisotropic surfaces. SHARM-3D uses a rigorous 3-D Green's function solution for radiance in combination with the linear kernel model of the land surface bi-directional reflectance. In this case, the top-of-the-atmosphere radiance analytically depends on the surface BRDF parameters. This provides superior numerical efficiency, because when the atmosphere can be considered horizontally homogeneous, the atmospheric Green's function and the related functions need to be calculated only once. To handle the 'adjacency' effect, SHARM-3D uses a comprehensive pre-computed look-up table (LUT) of the 3-D optical transfer function (OTF) developed for different atmospheric conditions and geometries. OTF is a Fourier transform of the atmospheric 3-D Green's function. Certain symmetry properties of the OTF allow for a small LUT and a fast OTF-restore algorithm for arbitrary atmospheric conditions, geometry, and spatial resolution (currently ≥ 30 m). Comparisons of SHARM-3D with rigorous 3-D code SHDOM showed an agreement to 0.5–1%. At the same time, SHARM-3D is much faster (a factor of $\sim 10^3$) and, contrary to SHDOM, allows the processing of large scenes (side dimension of 10^3 – 10^4) on a common laptop.

As we see, all the chapters in Part II touch upon 3-D radiative transfer problems, which is a hot topic of modern radiative transfer research. Usually, light propagation in media with arbitrary spatial distributions of optical characteristics is studied using numerical calculations and it is a difficult matter to derive analytical results in this case. One possibility of the simplification of the 3-D solution is based on the principles of invariance. These principles were introduced in the radiative transfer theory by V. A. Ambartsumian, who derived the nonlinear integral radiative transfer equation for a semi-infinite layer using the fact that adding an additional layer at the top with the same properties as the medium itself will not change the reflected light intensity (by definition of a semi-infinite layer). Further, the principles of invariance have been explored by a number of prominent scientists such as S. Chandrasekhar and R. Bellman. In the concluding chapter of Part II, Nikolai Rogovtsov describes the physical and mathematical foundations of the general invariance relations reduction method (GIRRM). GIRRM is one of the most general methods of the solution for both direct and inverse radiative transfer problems. The method can be used as the basis for the development of both effective numerical schemes and analytical solutions of 3-D radiative transfer problems for arbitrary phase functions and spatial distributions in turbid media of various configurations. In addition, using the described approach, the author derived a new approximate representation for the reflection function of a semi-infinite plane-parallel medium. The asymptotic solutions valid if the characteristic dimensions of the disperse medium are much larger as compared to the photon mean path length in the medium are derived for a number of light scattering objects. In particular, disperse media with shapes of sphere, cube, cylinder, and spheroid have been considered. The derived results can be utilized, for example, for testing various numerical methods and Monte Carlo solutions of the 3-D problem.

The book concludes with Part III aimed at applications. Bonnie Light presents a comprehensive summary of sea ice optical properties and their relationships with

the structural properties of sea ice. Here the focus is not on light polarization and 3-D effects but rather on the quantification of the impact of various ice impurities such as brine inclusions, precipitated salt crystals, inclusions of biogenic and lithogenic origin, and bubbles on light scattering and radiative transfer in sea ice. The main problem here is the size and shape of inclusions, and also their refractive index. Inclusions can be several centimeters long and have irregular shapes. The sizes, shapes, and also refractive indices of some inclusions (e.g., brine) in ice strongly depend on temperature. Clearly, ice is a very difficult turbid medium to study in the field. Therefore, the author concentrated her study on the quantification of ice optical and microphysical properties in the cold laboratory, which resulted in the development of a physically based structural-optical model for first-year Arctic sea ice. The results of this comprehensive work are invaluable for the development of new methods of satellite remote sensing of ice, which are needed to quantify the effects of global change in the Arctic.

Ice is often covered by snow and, therefore, understanding snow optical properties in relation to the snow grain size, density, wetness, and level of pollution is also of great importance. This subject is explored by Jouni Peltoniemi and co-authors. Both theoretical methods (ray tracing) and comprehensive measurement field campaigns together with relevant instrumentation and data processing are described. The authors show not only the snow bi-directional reflection function but also the spectral and directional dependencies of the measured degree of polarization, which is low in the visible and increases dramatically in the vicinity of ice absorption bands in the near-infrared. The potential of optical methods for snow melt monitoring is discussed.

The next chapter, Chapter 10, prepared by Per Edström, is aimed at the modeling of light scattering in paper. Paper is close in appearance to snow and this is due to the fact that scattering elements are weakly absorbing and strong multiple scattering takes place. However, there are also some differences due to the size, shape, and refractive index of scattering elements in paper. The author describes various models used currently in the paper industry to understand and optimize paper appearance and spectral reflectance. They include Kubelka–Munk theory, the discrete ordinates method, the Monte Carlo technique, and asymptotic radiative transfer solutions.

The last chapter of this volume is also aimed at studies of reflection but for planetary regoliths. Their brightness is much smaller compared to snow, ice, and paper. As stated by Karri Muinonen and his co-authors, two ubiquitous phenomena are observed for the planetary regoliths near opposition (where the direction of illumination almost coincides with the viewing direction and backscattering effects dominate): negative linear polarization and nonlinear surge of brightness. The phenomena are observed at sun–object–observer angles of less than 30 and 10 degrees, respectively, sometimes showing up at extremely small phase angles within a degree from opposition. Coherent backscattering and shadowing mechanisms have been introduced to explain the phenomena. The authors have studied interference mechanisms in scattering by single particles capable of explaining such intensity and polarization phenomena. The presented modeling constitutes an important advance in the interpretation of the observations of atmosphereless solar-system

objects. As shown by the authors, their observed scattering characteristics can be linked to the physical characteristics of submicrometer-scale scatterers.

In conclusion, I thank all the contributors for the preparation of the excellent papers presented in this volume. I am also indebted to Clive Horwood, Publisher, for advice, patience, and encouragement.

Bremen, Germany
October, 2009

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