Journal of Quantitative Spectroscopy & Radiative Transfer 112 (2011) 671–692

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Review

Electromagnetic scattering by a morphologically complex object: Fundamental concepts and common misconceptions

Michael I. Mishchenko [a,*], Victor P. Tishkovets [b], Larry D. Travis [a], Brian Cairns [a], Janna M. Dlugach [c], Li Liu [a], Vera K. Rosenbush [c], Nikolai N. Kiselev [c]

[a] NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA
[b] Institute of Radio Astronomy of NASU, 4 Chervonopraporna Street, Kharkiv 61002, Ukraine
[c] Main Astronomical Observatory of the National Academy of Sciences of Ukraine, 27 Zabolotny Street, Kyiv 03680, Ukraine

ARTICLE INFO

Article history:
Received 11 January 2010
Received in revised form
2 March 2010
Accepted 29 March 2010
Available online 1 April 2010

Keywords:
Macroscopic Maxwell equations
Electromagnetic scattering
Multiple scattering
Coherent backscattering
Radiative transfer

ABSTRACT

Following Keller (Proc Symp Appl Math 1962;13:227–46), we classify all theoretical treatments of electromagnetic scattering by a morphologically complex object into first-principle (or "honest" in Keller's terminology) and phenomenological (or "dishonest") categories. This helps us identify, analyze, and dispel several profound misconceptions widespread in the discipline of electromagnetic scattering by solitary particles and discrete random media. Our goal is not to call for a complete renunciation of phenomenological approaches but rather to encourage a critical and careful evaluation of their actual origin, virtues, and limitations. In other words, we do not intend to deter creative thinking in terms of phenomenological short-cuts, but we do want to raise awareness when we stray (often for practical reasons) from the fundamentals. The main results and conclusions are illustrated by numerically-exact data based on direct numerical solutions of the macroscopic Maxwell equations.

Published by Elsevier Ltd.

Contents

* Corresponding author. Fax: +1 212 678 5622.
E-mail addresses: crmim2@gmail.com, mmishchenko@giss.nasa.gov (M.I. Mishchenko).

0022-4073/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.jqsrt.2010.03.016

1. Introduction: microphysical and phenomenological approaches to electromagnetic scattering

Scientific, biomedical, and engineering problems involving the scattering of light (or other electromagnetic radiation) by a morphologically complex macroscopic object are quite common. Among typical examples of a complex scattering object are a cloud, a particulate surface, a particle suspension, a tissue sample, or an isolated morphologically complex particle. Quite often electromagnetic scattering by a complex object is addressed without an explicit solution of the macroscopic Maxwell equations (MMEs). In some cases it is acknowledged that the MMEs do control the scattering phenomenon, but then it is claimed that a direct solution of the MMEs is far too difficult to attempt. In many cases the MMEs are not mentioned at all. Instead, an *ad hoc* "approximation" is used and is essentially elevated to the level of an independent basic physical principle, as exemplified by the phenomenological radiative transfer theory (RTT). Usually this is done based on vague "physical grounds", which is a traditional implicit excuse for not being able to derive the desired outcome mathematically from primordial equations such as the MMEs.

Such approximations are often based on "physical concepts" many of which are the consequence of trying to describe a complex physical phenomenon using a simplified analogy. For example, the propagation of electromagnetic waves is often described as being analogous to the propagation of waves on the surface of a pond. Such an analogy may serve to increase the level of mental comfort of students by helping them "visualize" a physical phenomenon that escapes completely human natural senses. However, this analogy can be quite misleading and contains no real physics whatsoever since electromagnetic waves are not mechanical surface waves. Instead, *real physics is contained in the proper selection of mathematical equations intended to adequately describe specific natural phenomena*. Once these primordial equations have been formulated, solving these equations directly without invoking any *ad hoc* "physical concepts" would solve all real needs of the physicist.

Let us imagine, for example, that we have at our disposal a direct computer solver of the MMEs (in the form of a suitable {computer; computer program} combination) applicable to an arbitrarily complex object. Then we would not need any approximation and any physical concept not already contained in the MMEs in order to interpret laboratory or remote-sensing measurements of electromagnetic scattering. Indeed, the output of any measurement could then be modeled by solving the MMEs once for a fixed object or many times for a representative set of realizations of a random object (such as a cloud) supplemented by statistical averaging of the relevant optical observables.

Unfortunately, a direct solver of the MMEs applicable to a real cloud of liquid water droplets or ice crystals does not exist and is unlikely to become available in the near future. Hence the widespread use of "approximate" treatments of electromagnetic scattering by complex macroscopic objects.

Paraphrasing Keller [1] and using his terminology, all theoretical methods for treating electromagnetic scattering by a morphologically complex object can be classified into two categories: "honest" (or microphysical) and "dishonest" (or phenomenological).[1] An honest method is the result of solving the MMEs, perhaps after making one or more specific and well defined assumptions intended to simplify the solution. For example, the Rayleigh approximation [2] is the result of solving the MMEs under the assumption that the product of the wave number and the maximal particle dimension is much smaller than unity, while the Fresnel formulas and coefficients follow from the assumption that a plane wave is incident on a perfectly flat interface separating two homogeneous half-spaces with different real-valued refractive indices. The practical applicability of a microphysical method usually requires no validation provided that all underlying assumptions are indeed satisfied. However, if an honest method is used to model situations in which one or more of the underlying assumptions are violated then the quantitative applicability of this approach must be carefully examined [3].

Fundamentally, an honest method is by definition the result of an explicit direct solution of the MMEs, e.g., a closed-form analytical solution or a numerically-exact computer solution. The former is often the consequence of taking an asymptotic limit (e.g., assuming that the product of the wave number and the distance from the scattering object to the observation point is much greater than unity, which renders the far-field approximation). The latter is the outcome of running a direct computer solver of the MMEs generating numbers with a guaranteed number of correct decimals. The number of correct decimals may vary depending on the available computer resources and practical accuracy requirements. However, all reported decimals can, in principle, be validated by modifying computer program settings in order to accommodate a more stringent accuracy requirement.

Quite often the use of a microphysical analytical method allows one to identify certain idealized physical concepts. Typical examples would be the asymptotic short-wave concept of a light ray propagating in a continuous medium, the concepts of reflection and refraction of waves by a plane interface, the concepts of wave interference and diffraction, and the concept of far-field scattering. Such concepts are unnecessary in principle and are nothing more than verbal characterizations of formulas derived from the MMEs. However, they constitute what is usually called "physical understanding of the problem" and as such may have some positive heuristic value and facilitate qualitative "interpretation" of formulas, digital computer outputs, or experimental data,

[1] Of course, the words "honest" and "dishonest" are intended to characterize methods rather than human character traits. However, the terms "honest" and "dishonest theoretical methods" can be viewed by some as having the connotation of a moral judgment about the practitioners of such methods. Minding those who believe that Keller's terminology may be excessively figurative, we will often use the words "microphysical" and "phenomenological" as substitutes for "honest" and "dishonest", respectively.