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125 years of radiative transfer: enduring triumphs and persisting misconceptions

M. I. Mishchenko
NASA GISS, New York, United States (michael.i.mishchenko@nasa.gov)

The radiative transfer theory (RTT) was introduced 125 years ago by the German mathematician and physicist Eugene Lommel and the Russian physicists Orest Chwolson. The heuristic concept of radiance was formulated in 1906 by Max Planck and was supplemented by the seemingly obvious concept of a directional (well-collimated) radiometer. Since then, measurements with directional radiometers and calculations based on the radiative transfer equation (RTE) have been at the very heart of atmospheric radiation, remote sensing, and astrophysics.

Yet from the fundamental-physics perspective, both the discipline of directional radiometry and RTT have been based on phenomenological notions many of which are profound misconceptions. It has been demonstrated that contrary to the widespread belief, a directional radiometer does not, in general, measure the flow of electromagnetic energy along its axis, while the radiance cannot be interpreted as quantifying the amount of electromagnetic energy transported in a given direction.

It is thus fundamentally important to understand why RTT and directional radiometry have often "worked" in the practical sense and determine the range of their applicability. The ultimate way to achieve this key objective is via a microphysical approach that is based directly on the Maxwell equations and clarifies the physical nature of measurements with directional radiometers and the physical content of RTE. This approach has recently been developed and has demonstrated that the radiance has no fundamental physical meaning besides being a mathematical solution of RTE. Only under certain circumstances can it be used to compute the time-averaged local Poynting vector as well as be measured by a directional radiometer. These firmly established facts make the combination of RTE and a directional radiometer useful in some well-defined circumstances and help "rescue" the majority of documented applications of the phenomenological RTT. However, outside the range of validity of RTT the practical usefulness of measurements with directional radiometers remains uncertain.

The purpose of this plenary lecture is to outline the main milestones of the 125-year long history of radiative-transfer research (Lommel, Chwolson, Schuster, Planck, Schwarzschild, Eddington, Gans, Ambartsumian, Chandrasekhar, Rozenberg, Ishimaru, etc.) and the emergence of a new paradigm based on the direct and self-consistent use of the Maxwell equations. This paradigm solves the long-standing problem of establishing the fundamental physical link between RTT and phenomenological radiometry on one hand and the Maxwell equations on the other. It also establishes the link between RTT and the spectacular effect of weak localization of electromagnetic waves in particulate media. As a result, it becomes possible to clarify the physical content of measurements with directional radiometers and their relation to the solution of RTE. It also turns out that in many cases the reading of a directional radiometer must be modeled using a more sophisticated approach than RTT and that the use of directional radiometers in quantifying the energy budget of the Earth's climate system can be problematic and requires a detailed first-principle analysis.