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Measurement of electromagnetic energy flow through a sparse particulate medium: A perspective

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ABSTRACT

First-principle analysis of the functional design of a well-collimated radiometer (WCR) reveals that in general, this instrument does not record the instantaneous directional flow of electromagnetic energy. Only in special cases can a sequence of measurements with a WCR yield the magnitude and direction of the local time-averaged Poynting vector. Our analysis demonstrates that it is imperative to clearly formulate the physical nature of the actual measurement afforded by a directional radiometer rather than presume desirable measurement capabilities. Only then can the directional radiometer be considered a legitimate part of physically based remote sensing and radiation-budget applications. We also emphasize the need for a better understanding of the nature of measurements with panoramic radiometers.

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1. Introduction

Measurements and computations of electromagnetic energy flow through a sparse particulate medium are traditionally viewed as an integral part of solving various radiation-budget and optical-characterization problems. For example, the physical state of a cloud of water droplets or ice crystals in the terrestrial atmosphere can be affected by an imbalance between the incoming and outgoing electromagnetic energy, while measurements of specific manifestations of electromagnetic energy flow with a suitable device can potentially be analyzed to infer useful information about the cloud. Conceptually similar problems are encountered in many other areas of science and technology.

Let us consider, for example, an idealized liquid-water cloud illuminated by a plane electromagnetic wave or, more generally, a quasi-monochromatic parallel beam of light with infinite lateral extent (Fig. 1). Suppose that we need to evaluate the radiation budget of a macroscopic volume element of the cloud ΔV bounded by the spherical surface ΔS. According to the Poynting theorem [1], the net average rate at which electromagnetic energy enters this volume element is given by the integral

$$W_{\Delta S} = -\int_{\Delta S} \mathrm{d}^2\mathbf{r} \langle \mathbf{S}(\mathbf{r},t) \rangle \cdot \hat{\mathbf{n}}(\mathbf{r}), \quad (1)$$

where $\mathbf{S}(\mathbf{r},t)$ is the Poynting vector at the point $\mathbf{r}$ at the moment t, the angular brackets denote averaging over a sufficiently long period of time, and the unit vector $\hat{\mathbf{n}}(\mathbf{r})$ is directed along the local outward normal to the boundary. If $W_{\Delta S} = 0$ then the incoming radiation is balanced by the outgoing radiation. Otherwise there is absorption of electromagnetic energy inside the volume element. The radiation budget of the volume V occupied by the entire cloud is evaluated similarly, except now the integral in Eq. (1) is taken over the closed boundary S (Fig. 1).

Suppose that we have at our disposal a Poynting-meter, i.e., a device that can measure both the direction and the absolute value of the time-averaged local Poynting vector. Then measuring $\langle \mathbf{S}(\mathbf{r},t) \rangle$ at a sufficiently

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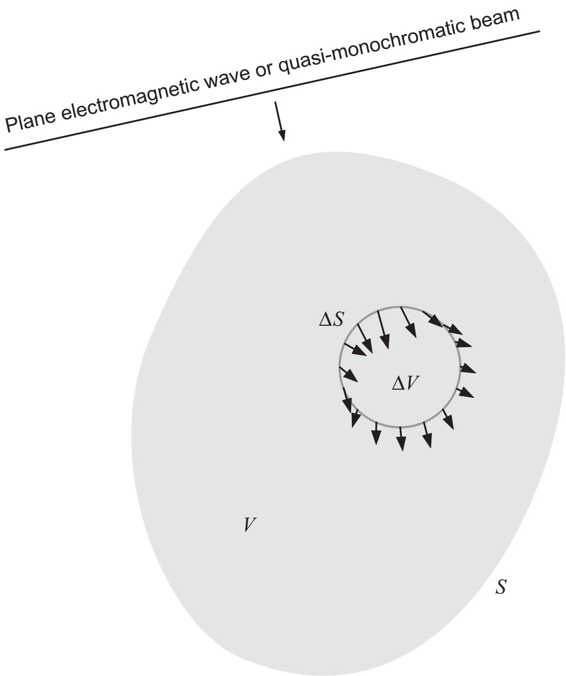

Fig. 1. Time-averaged radiation budget of a volume element ΔV of a cloud bounded by a closed surface ΔS. The arrows represent the distribution of $\langle \mathbf{S}(\mathbf{r},t) \rangle$ over the boundary ΔS.

representative number of points densely distributed over the boundary ΔS and evaluating the integral in Eq. (1) numerically would solve the above radiation-budget problem.

Unfortunately, none of the instruments that have ever been used in the disciplines of atmospheric radiation and remote sensing can, strictly speaking, be considered a Poynting-meter. Despite the wide variety of specific designs and the alleged ability to quantify the electromagnetic energy flow [2], the actual physical nature of the measurements afforded by these instruments has remained poorly understood and has rarely been formulated in the context of advanced theories of light–matter interactions. Furthermore, it is hardly recognized that the physical meaning of the signal generated by these instruments depends critically on the very nature of the electromagnetic field transporting radiative energy and hence on the object creating the electromagnetic field.

Applied radiometry still appears to be dominated by the two-and-a-half century old phenomenology introduced by Pierre Bouguer and Johann Lambert [3,4], whereas very little has been done by way of clarifying the electromagnetic content of heuristic photometric concepts and putting measurements of electromagnetic energy flow in the context of modern physics. Even the most recent monographs on this subject (e.g., Ref. [2] and references therein) fall quite short of achieving this objective and can be thoroughly misleading in their usage of terminology borrowed in an ad hoc fashion from classical electromagnetism and quantum electrodynamics (QED).

In a series of reviews [5–7], I have attempted to summarize recent progress in the clarification of the fundamental physical content of electromagnetic scattering by particles and particulate media. Among other subjects, those reviews have focused on the precise nature of the phenomenon of electromagnetic scattering, the purely mathematical notions of multiple scattering and specific intensity in the framework of classical electromagnetics, and the derivation of the theories of radiative transfer and coherent backscattering directly from the macroscopic Maxwell equations. They have also dispelled the so-called "photonic confusion" in the context of phenomenological radiative transfer as well as the misconception of multidirectional propagation of electromagnetic energy allegedly described by the heuristic specific intensity.

This sequel is closely related to Refs. [5–7]. Its main objective is to clarify the physical framework of the measurement with instruments that can be called "well-collimated radiometers" (WCRs). They represent by far the most widely used class of photometers, which makes it imperative to have a clear understanding of what these instruments can really measure and how their measurements are related to the requisite measurement of the Poynting vector. In particular, the following sections are intended to

- Summarize the basic operational principle of photoelectric detectors in the context of the QED theory of the photoelectric effect;
- Clarify the actual role of the optical tract of a WCR;
- Analyze the interaction of the electromagnetic radiation filtered out by the optical tract of a WCR with the end photodetector;
- Identify quantitative attributes of the electromagnetic energy flow that can be captured by a WCR depending on the specific measurement setting; and
- Discuss how these attributes can be modeled theoretically for morphologically complex scattering objects and thereby enter the solution of radiation-budget as well as optical-characterization problems.

2. Photoelectric detectors

Strictly speaking, the Poynting vector does not characterize the direction and rate of the local electromagnetic energy flow. Indeed, adding the curl of any vector field to $\mathbf{S}(\mathbf{r},t) = \mathbf{E}(\mathbf{r},t) \times \mathbf{H}(\mathbf{r},t)$ yields a vector field $\mathbf{S}'(\mathbf{r},t)$ which also satisfies the Poynting theorem for the same pair of the electric and magnetic fields $\{\mathbf{E}(\mathbf{r},t), \mathbf{H}(\mathbf{r},t)\}$ [1,8]. It is, however, important to recognize that if we can measure the (time-averaged) Poynting vector then we can use Eq. (1) to evaluate the radiative energy budget of the object in question irrespective of the physical meaning of the vector product $\mathbf{E}(\mathbf{r},t) \times \mathbf{H}(\mathbf{r},t)$. Therefore, it is the practical measurability of the Poynting vector that will be the focus of the following discussion.

Typical devices used for the detection and quantification of electromagnetic energy flow are photomultipliers, photodiods, and photoelectric charge-coupled devices (CCDs) illustrated in Fig. 2. A photomultiplier or a