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PRINCIPLES OF THE RADIOSITY METHOD FOR CANOPY REFLECTANCE MODELING

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Abstract—The radiosity method is introduced to plant canopy reflectance modeling. We review the physics principles of the radiosity method which originates in thermal radiative transfer analyses when hot and cold surfaces are considered within a given enclosure. The radiosity equation, which is an energy balance equation for discrete surfaces, is described and contrasted with the radiative transfer equation, which is a volumetric energy balance equation. Comparing the strengths and weaknesses of the radiosity method and the radiative transfer method, we conclude that both methods are complementary to each other. Results of sample calculations are given for canopy models with up to 20,000 discrete leaves. Keywords—canopy modeling, radiative transfer, radiosity method, reflectance.

The classical approach to modeling the radiation field within a vegetation canopy and at its boundaries in the visible and near infrared regime is based on the application of the radiative transfer (RT) equation (Ross, 1981)¹⁴, which takes the form

$$\mu \frac{\partial I}{\partial z} + \sigma_t I = \sigma_s \int P(z, \Omega' \cdot \Omega) I(z, \Omega') d\Omega' + Q(z, \Omega) \quad (1)$$

in one-dimensional geometry, where we used standard RT notation (cf. e.g. Gerstl and Zardecki, 1985)³. The RT equation (1) represents a balance equation for radiative energy (or the number of photons) in an infinitesimal volume element when the effects of absorption ($\sigma_a = \sigma_t - \sigma_s$) and scattering (σ_s) must be considered. The scattering phase function P describes the change of direction from Ω' to Ω that a photon undergoes in a scattering process, and the term Q represents the external (or internal) radiation sources. The solution of Eq. (1) is the radiance distribution function (specific intensity) $I(z, \Omega)$ which defines the directional radiation field at every spatial location (z). Wavelength and time dependencies are omitted from Eq. (1) for the sake of clarity.

Different authors solve the RT equation with different methods, using different approximations in maintaining varying degrees of detail and complexity. For example full spatial detail of the radiance is obtained with the three-dimensional RT solution techniques by Martonchik and Diner (1983)¹¹, Elmes (1984)⁹, Shultis and Moreland (1988)¹², and others, where the computational methods use Fourier transform

techniques, discrete-ordinates, finite-element, and brute-force numerical integration techniques.

Despite the breadth of applications, the intrinsic limitations of the problem description via the RT equation must not be overlooked. For example, in the RT Eq. (1) the radiative properties of a vegetation canopy are assumed to be completely described by the scattering and absorption cross sections σ_s and σ_a ($\sigma_t = \sigma_s + \sigma_a$), or their derived quantities τ (optical depth)⁸ and ω (single scattering albedo), the scattering phase function P , and the boundary conditions. In order to define these quantities for a vegetation canopy, it is necessary and straightforward to relate them to measurable parameters like the leaf area index (LAI), leaf angle distribution (LAD), leaf hemispherical reflectance (ρ), transmittance (τ), and absorptance (α), cf. e.g. Gerstl & Zardecki (1985)³. However, due to the nature of the RT equation as an energy balance equation per volume element, all measurable canopy parameters must be averaged over such volume elements. This averaging process eliminates the discrete nature of leaves, stems, etc. from the mathematical formulation. In a graphical description one might say that the real vegetation canopy with its finite number of discrete leaves and stems has been replaced by a gas-like medium whose radiative properties are equivalent to the real canopy in a volume-averaged sense.

However, certain radiative effects of natural canopies that are based on the discrete nature of its components are no longer described by the RT formulation and cannot be obtained by any whatsoever sophisticated and/or rigorous solution technique. Such effects are for example those that are due to leaf shape and the mutual shading or clumping of leaves. This difficulty and intrinsic limitation of the RT formulation of canopy reflectance models has been circumvented by geometric-optical canopy models (Li and Strahler, 1985; Otterman, 1984)¹³, Monte Carlo ray tracing models (Ross and Marshall, 1987; Gerstl et al., 1986)^{4, 15}, the use of semi-empirical correlation functions (Kousk, 1985)¹⁰, and hybrid models that combine the strength of the RT description with that of geometric optical models (Norman and Welles, 1983)¹².

Most recently a computational method, called the radiosity method, has been demonstrated to be very useful and effective in producing computer-generated images of scenes that consist of

reflecting surfaces, like a room filled with furniture and other objects under arbitrary illumination conditions (Greenberg, 1989)⁷. The radiosity method, which is the basis for such computer graphics, is also based on a radiation balance equation. However, in contrast to the RT equation, the radiosity equation balances incoming and outgoing radiation fluxes on discrete surface elements and has the form

$$B_i = E_i + \rho_i \sum_j F_{ij} B_j, \quad (2)$$

where B_i is the radiosity on surface element i , defined as the total radiation flux density leaving that surface (e.g. in W/cm² or J/cm²). E_i is the surface emission, ρ_i the reflection coefficient and F_{ij} the form factor or "view factor" which specifies the fraction of radiant flux leaving another surface j that reaches the surface i . Thus, the radiosity equation (2) also states a rigorous energy balance requiring the total radiation flux leaving any surface element i to be equal to the sum of its emitted and reflected flux originating from all other surfaces. This description of a radiative energy equilibrium has originated in thermal engineering to describe the transmission of radiant heat between surfaces of different temperatures (e.g. Hottel and Sarofim, 1967)⁸ and has been introduced to computer graphics by Goral et al. (1984)⁶ as a new procedure for realistic image synthesis. With the rapid development of advanced computer graphics hardware and software the radiosity method has become a cornerstone for modern image synthesis (Greenberg, 1989, Cohen et al., 1988)^{2,7}.

We demonstrate that with appropriate modifications to the governing radiosity equations it is possible to apply this methodology successfully to the computation of reflectance distributions from realistic 3-dimensional surfaces, such as a vegetation canopy that is composed of many discrete reflecting surfaces (leaves and stems). Moreover, since finite surface elements are considered as the base units of the computation, the radiosity method is capable of describing the radiative effects due to the discrete nature of leaves and stems (shading, clumping etc.). The solar irradiance on each individual leaf can also be computed. Such data is of crucial importance to analyzing photosynthesis, nutrient and other biochemical transport mechanisms within realistic plants. As long as the plant architecture can be satisfactorily described by a set of discrete surfaces with given orientation, the radiosity equation will provide a valuable complement to the RT description of the radiation field in vegetation canopies and on their boundaries.

The main strength of the radiosity method derives from the fact that leaves are treated as individual surfaces that reflect and transmit radiation. Thus, the discrete nature of leaves and other phytoclements within a vegetation canopy remains accurately described in the radiosity formulation. This is in contrast to the RT formulation where the discrete geometrical and optical canopy parameters such as leaf location, size, shape, and orientation are averaged over volume elements to create a continuous medium description. Therefore, the radiosity method is

expected to provide a valuable complement to the RT formulation in canopy reflectance modeling, because it allows the analysis of radiative effects due to the discrete nature of leaves and stems and their heterogeneous distributions. Examples of such effects are the mutual shading and clustering of leaves which can produce variations in BRDF values of up to factors of two as shown by field measurements on natural canopies. The radiosity method is particularly suited to model the angular reflectance signatures of vegetation canopies, such as the retro-reflectance peak, also called the canopy hot spot, cf. Borel et al. (1989)¹, Gerstl (1988)⁵.

REFERENCES

- [1] C.C. Borel, B.J. Powers, and S.A.W. Gerstl, "Modelling of the Angular Reflectance of an Artificial Canopy near the Retroreflection Peak in the Optical Regime," ICARSS '89 Proceedings, July 1989.
- [2] M.F. Cohen, S.E. Chen, J.R. Wallace, and D. Greenberg, "A Progressive Refinement Approach to Fast Radiosity Image Generation," SIGGRAPH Proceedings, 22(4), p. 75, 1988.
- [3] S.A.W. Gerstl and A. Zardecki, "Coupled Atmosphere/Canopy Model for Remote Sensing of Plant Reflectance Features," Appl. Opt. 24, pp. 94-103, 1985.
- [4] S.A.W. Gerstl, C. Simmer and B.J. Powers, "The Canopy Hot-Spot as Crop Identifier," Proc. Int. Symp. on Remote Sensing for Resources Development and Environmental Management, Enschede, The Netherlands, M.C.J. Damen et al. (Eds.) pp. 261-263, 1986.
- [5] S.A.W. Gerstl, "The Angular Reflectance Signature of the Canopy Hot Spot in the Optical Regime," Proc. 4th Int. Coll. on Spectral Signatures of Objects in Remote Sensing, Aussois, France, ESA report SP-287, pp. 129-132, 1988.
- [6] C. Goral, K.E. Torrance, D. Greenberg, and B. Battelle, "Modelling the Interaction of Light Between Diffuse Surfaces," SIGGRAPH Proceedings, 18(3), 1984.
- [7] D.P. Greenberg, "Light Reflection Models for Computer Graphics," SCIENCE 244, pp. 166-173, 1989.
- [8] H.C. Hottel and A.F. Sarofim, "Radiative Transfer," McGraw-Hill Book Company, New York, New York, 1967.
- [9] D.S. Kimes, "Modeling the Directional Reflectance from Complete Homogeneous Vegetation Canopies with Various Leaf Orientation Distributions," J. Opt. Soc. of Am. A1, pp. 125-132, 1984.
- [10] A. Funk, "The Hot Spot Effect of a Uniform Vegetative Cover," Soc. of Remote Sensing, 3, pp. 643-650, 1985.

- [11] J.V. Martonchik and D.J. Diner, "Three-Dimensional Radiative Transfer Using a Fourier-Transform Matrix-Operator Method," *J. Quant. Spec. Rad. Transf.* 14, p. 133, 1985.
- [12] J.M. Norman and J.M. Welles, "Radiative Transfer in an Array of Canopies," *Agron. J.* 25, pp. 481-488, 1983.
- [13] J. Otterman, "Albedo of a Forest Modeled as a Plane with Dense Protrusions," *J. Climate and Appl. Meteor.*, 23, pp. 297-307, 1984.
- [14] J. Ross, "The Radiation Regime and Architecture of Plant Stands," Dr. W. Junk Publ., The Hague, 1981.
- [15] J.K. Ross and A.L. Marshak, "Calculation of the Canopy Bidirectional Reflectance Using the Monte Carlo Method," *Remote Sens. Environ.*, 24, pp. 213-225, 1987.
- [16] J.K. Shultis and R.B. Myneni, "Radiative Transfer in Vegetation Canopies with Anisotropic Scattering," *J. Quant. Spec. and Rad. Transfer.*, 1988.