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REFLECTANCE MODELING

Dr. James A. Smith

College of Forestry & Natural Resources
Colorado State University
Fort Collins, Colorado 80523

PROJECT OBJECTIVES

The overall goal of our work has been to develop a set of computational tools and media abstractions for the terrain bidirectional reflectance problem. The modeling of soil and vegetation surfaces has been emphasized with a gradual increase in the complexity of the media geometries treated. Pragmatic problems involved in the combined modeling of soil, vegetation, and atmospheric effects have been of interest and one of our objectives has been to describe the canopy reflectance problem in a classical radiative transfer sense permitting easier inclusion of our work by other workers in the radiative transfer field.

APPROACH

The application of radiative transfer theory to soil and vegetation media requires an abstraction of the scattering and absorbing properties of the medium in terms of biogeophysical attributes, a specification of the geometrical boundary of the medium, and a mathematical solution technique to the radiative transfer equations. We have abstracted our media to consist of a collection of discrete scatterers, e.g. leaf or soil facets, with individual diffuse and specular optical properties. Bulk properties of the media are usually derived from suitable averaging over the statistical distribution of the individual elements within the medium. For simple plane parallel media geometries, we are using classical solutions to the radiative transfer equations, e.g. the discrete ordinates/ finite difference method of Chandrasekhar, the Adding method of Van de Hulst, or the two stream method of Kaufman. For complex geometries with irregular rough surfaces, we are employing Monte Carlo techniques.

RESEARCH FINDINGS

We will briefly summarize three areas which have been addressed since the last SRAEC annual meeting. These are orthogonal expansion of our phase functions in terms of total scattering angle and example use with standard radiative transfer code, e.g. Kaufman's two stream approximation; our Monte Carlo reflectance modeling for complex soil surfaces which now include Fresnel facets; and our current work in modeling complex vegetation surfaces.

Orthogonal Expansion and Utilization of Canopy Phase Functions

We have previously described our calculational technique for averaging over leaf angle distributions and leaf optical properties to estimate the canopy scattering diagram as a function of the global incident and exitant

angles. The phase functions we presented were given in terms of incident angles, μ,ϕ and exitant angles, μ',ϕ'. As Ross has indicated, it appears that canopy phase functions, unlike some of the more symmetrical atmospheric cases, may not necessarily be explicitly formulated in terms of only a total scattering angle, Θ. We have spent some time pondering this circumstance. Recently, we have adapted an approach outlined by Liou for ice crystals whereby "average" phase functions can be computed. The procedure essentially averages over ranges of μ,ϕ and μ',ϕ' which yield the same total scattering angle, Θ, i.e.

$$\cos \Theta = \mu\, \mu' + (1-\mu)^{1/2}\ (1-\mu')^{1/2}\ \cos (\phi - \phi') \tag{1}$$

We term the resulting scattering diagrams, "stylized" phase functions. We do not believe the results are strictly correct in the fine details, because of both fundamental reasons and numerical problems. However, as Van de Hulst has indicated, for many calculations the fine details may not be all that important. Theoretically, the phase functions are much more tractable and be expanded, in Legendre polynomials, for example, as follows:

$$P(\cos \Theta) = u_0 + u_1\ P_1(\cos \Theta) + u_2\ P_2(\cos \Theta) + \ldots \tag{2}$$

and, thence, into a variety of useful forms. The table below shows an example calculation for a spherical leaf angle distribution for visible and near infrared wavelengths. The phase function, and, hence, expansion coefficients vary with the vegetation optical properties.

	$\lambda = 0.55\ \mu m$	$\lambda = 0.65\ \mu m$	$\lambda = 0.80\ \mu m$
u_0	1.009	1.018	1.018
u_1	0.057	−0.238	−0.271
u_2	0.174	0.180	0.183
u_3	−0.022	−0.053	−0.051
u_4	0.021	0.028	0.033
u_5	−0.001	−0.021	−0.024
u_6	0.021	0.022	0.026

NOTE: u_0 should be 1.0; some measure of the numerical precision of the calculations is indicated by the deviations from this value above.

Such expansions can be easily incorporated into standard radiative transfer code. We have used the above values in Kaufman's published modified two stream method—the program code was obtained from the Atmospheric Science Department at Colorado State University. Figure 1 is a plot of the (spline – smoothed) stylized phase functions at the three wavelengths above.

Monte Carlo Soil Reflectance Modeling

At last year's SRAEC some preliminary results from a Monte Carlo model for the reflectance of a rough soil were presented. The thrust of our work in this area over the past year has been to extend the usefulness of this model to surfaces having non-Lambertian elemental reflectance properties. In particular, we were concerned with the effect of a distribution of Fresnel facets superimposed on macroscopic surface irregularities . The reflectance properties of an element of area of surface covered by these facets was determined theoretically, and then this reflectance function was substituted for the original Lambertian one in the Monte Carlo model.

In the substitution of reflectance functions into the Monte Carlo model it was desirable to allow the most general forms possible. For this reason two alternatives were investigated: the approximation of the reflectance functions in terms of spherical harmonics, and the use of a lookup table generated from the value of the reflectance functions at discrete angles. After some preliminary testing it appears that the former approach is slightly better when the reflectance function in question is simple, however for more complex functions, and in particular for the functions arising from distributions of Fresnel facets, the lookup table approach is the only reasonable one.

Thus far, we have only considered the case when the Fresnel facets have a uniform distribution of inclination angles. An example of the sort of results obtained for a surface with a simple cosine undulation is given in Fig. 2a. In this case light was incident on the surface at a zenith angle of 45 degrees and an azimuth perpendicular to the direction of the rows. The results are given by plotting contours of equal reflectance factor on a polar plot in which distance from the center indicates the zenith view angle, and the azimuth of the view corresponds directly to that on the plot. Figure 2b shows the bidirectional reflectance distribution function for the same surface possessing purely Lambertian elemental scattering properties.

Reflectance From Complex Vegetation Surfaces

After reviewing the bidirectional reflectance distribution modeling work for vegetation media currently underway in the SRAEC fundamental research effort, we concluded that it would be useful to attack the problem of reflectance from a rough surface vegetation layer from a multiple scattering, radiative transfer perspective. The approach we chose is an outgrowth of Norman's work and complements Strahler's geometric optics approach utilizing stylized structures for tree crowns. Basically, we are adapting a Monte Carlo code by utilizing probability of gap expressions which take into account the varying optical path length through vegetation layers as a function of canopy density, macro-structure and look angle. Geometrical routines are used to compute required parameters from a canopy height profile. In practice we employ Fourier series expansion of canopy height profiles. Later we may examine statistical structures inherent in the data via power spectra analysis and formulate appropriate models. These ideas are partially generated from some thermal modeling work we are performing over a forested site at Oak Ridge National Laboratory and we are

capitalizing on the canopy structure data available for this site.

This work is in preliminary stages, but briefly our approach follows:

1. An adapted version of our Monte Carlo vegetation reflectance model will be used to handle the multiple scattering calculations.

2. Probability of gap expressions are computed for photon interactions by considering both micro (i.e. leaf angle distributions) and macro (canopy height profile) structure. Specifically,

$$P_o(\theta) = \exp - LAI*g(\theta)*D(\theta) /h \qquad (3)$$

   where $g(\theta)$ is the mean canopy projection in direction θ, LAI is leaf area index, and $D(\theta)$ is the geometric path length from the bottom of a canopy later to the top profile in direction θ, and h is the canopy layer thickness.

3. Appropriate geometrical computational routines have been developed to calculate $D(\theta)$ for an arbitrary canopy height profile. We have applied these routines to sample data transects from the Oak Ridge Site. In practice, the canopy height profile data are first "detrended" using least squares regression, and the the power spectra computed for the detrended data in order to develop Fourier series representations for the calculation routines. Figure 3 shows a sample detrended height profile, and schematically illustrates the varying path lengths through this canopy layer as a function of look angle. Multiple voids in the canopy are correctly handled.

SIGNIFICANCE AND NEXT MAJOR STEP

The main significance in our work is an increased understanding, expressed via a variety of computational procedures, of terrain bidirectional reflectance properties. To our knowledge, there were no macro soil reflectance models for complex surfaces incorporating the complete multiple scattering solution and accounting for shadowing effects. Our calculation, treatment, and utilization of canopy phase functions also appears to be somewhat novel, although we have built upon the efforts of earlier workers. Extensions could be made to our work to include, for example, the incorporation of media subelement models to account for physiological or polarization properties.

In the eight months remaining of our third year of funding the final step in our research focus will be to complete a tractable treatment of complex vegetation surfaces amendable to our Monte Carlo canopy reflectance modeling techniques. In addition, we will more gracefully complete several loose ends in our completed work including the generation of orthogonal expansions of our canopy phase functions and the utilization of the models developed under this study to illustrate soil/vegetation/atmospheric effects in such applications as AVHRR-derived vegetation index calculations.
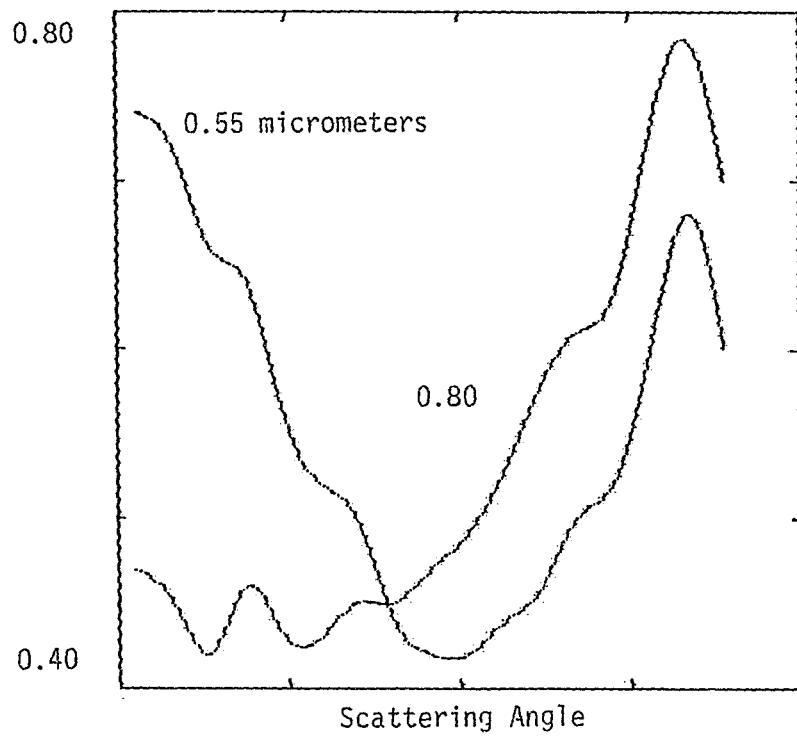
Figure 1. Stylized Canopy Phase Functions as a Function of Scattering Angle for wavelengths of 0.55 and 0.80 micrometers. (Normalization is incomplete)
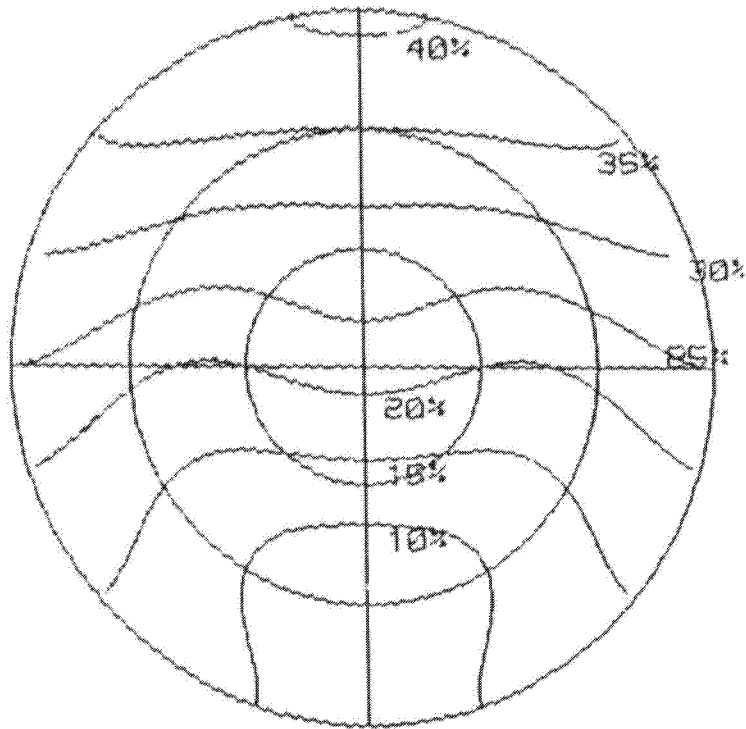
Figure 2a. Polar plot of bidirectional reflectance distribution function from a row soil surface with partially specularly reflecting Fresnel facets. Sun is at 45 degrees with azimuth perpendicular to rows. Elemental reflectance is 28%.
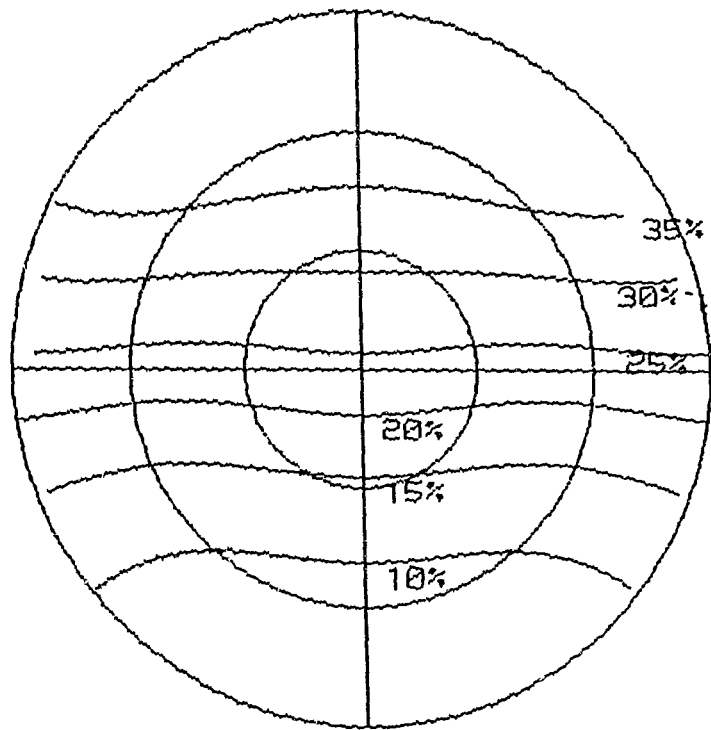
Figure 2b. Polar plot of bidirectional reflectance distribution function from a row soil surface with strictly Lambertian elemental reflectance properties.
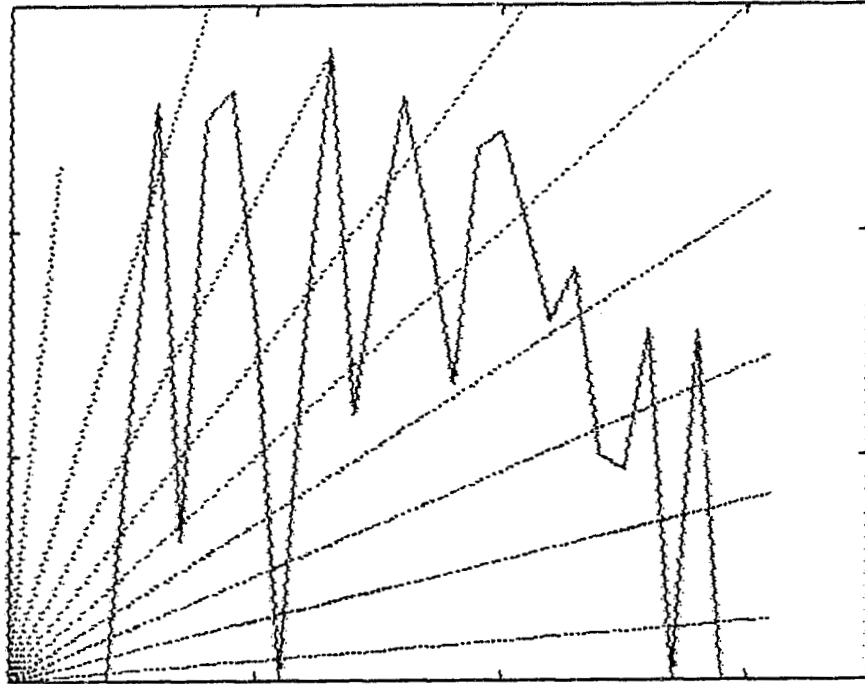
Figure 3. Detrended height profile for forest transect and probability of gap calculation for path length as a function of look angle.