# ATMOSPHERIC AND SCENE COMPLEXITY EFFECTS ON SURFACE BIDIRECTIONAL REFLECTANCE

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## 1. Justification and Objectives

Among the tools used in passive remote sensing of Earth resources in the visible and near-infrared spectral regions are measurements of spectral signature and bidirectional reflectance functions (BDRFs). Determination of surface properties using these observables is complicated by a number of factors, including (a) mixing of surface components, such as soil and vegetation, (b) multiple reflections of radiation due to complex geometry, such as in crop canopies, and (c) atmospheric effects. Differences in surface conditions, spectral coverage, viewing and illumination geometry, and atmospheric conditions make comparison of observations obtained in the laboratory, in the field, and from aircraft and spacecraft extremely difficult. In order to bridge the diversity in these different approaches, there is a need for a fundamental physical understanding of the influence of the various effects and a quantitative measure of their relative importance. In particular, we consider scene complexity effects using the example of reflection by vegetative surfaces. The interaction of sunlight with a crop canopy and interpretation of the spectral and angular dependence of the emergent radiation is basically a multidimensional radiative transfer problem. In the first step of the radiation history, sunlight is directly and diffusely transmitted downward through the Earth's atmosphere. The downward radiation field then interacts with the plant canopy. Each element of the canopy (leaves, stems) reflects (and transmits) light according to its intrinsic bidirectional reflectance (and transmittance) properties. The complex canopy geometry, underlying soil cover, and presence of diffuse as well as collimated illumination will modify the reflectance characteristics of the canopy relative to those of the individual elements. Finally, upwelling radiation emergent from the canopy will be directly and diffusely transmitted by the atmosphere to space, and some contamination of the spectral signature with radiation reflected from neighboring surface regions will occur due to scattering associated with the adjacency effect. The intent of this research program is to develop some of the tools needed in order to achieve a quantitative understanding of such phenomena, using a combination of experimental and theoretical methods.

## 2. Technical Approach

The tools which are needed in order to study this radiative transfer problem include (a) knowledge of the bidirectional scattering properties of individual canopy elements, primarily leaves, as well as of the canopy as a whole, (b) a model describing the interaction of radiation with the canopy, and (c) a radiative transfer algorithm for describing the interaction of a nonuniform radiation field with the atmosphere. In order to obtain realistic leaf bidirectional reflectance functions for incorporation into canopy and scene models, we are using laboratory spectrogoniometry to study the intrinsic scattering properties of individual leaves. These measurements provide a data set which obviates the need for nonphysical model assumptions, such as Lambertian leaf BDRFs. We have been using a goniometer located

at the University of California, Los Angeles to obtain spectra of individual leaves for a variety of illumination and viewing geometries. The instrument operates in the spectral range 0.4 to 2.5 μm. The illuminating source may be placed at an inclination of 0 to 90° relative to the surface normal and essentially the entire range of emission and azimuth angles may be measured, including near-zero, grazing, and high phase angles. An important attribute is the ability obtain data out of the principal plane of scattering. The leaf BDRFs obtained in this manner will be made available to other researchers for incorporation into canopy models. With regard to atmospheric effects, including extinction (absorption and scattering); addition of path radiance; multiple reflections between atmosphere and ground; and adjacency effects (whereby radiation reflected from surface regions not in the field of view are scattered into the line of sight), we have been developing comprehensive computational tools for solving multidimensional radiative transfer problems. Our technique incorporates a two dimensional spatial Fourier transform of the radiative transfer equation, and the resulting expressions for each Fourier component of the radiation field are computed. The full 3-D intensity field is then reconstructed using the inverse Fourier transform. The mathematical description is of general form so as to include consideration of non-Lambertian BDRFs. Our technique has been specifically designed to overcome some of the approximations employed in previous methods and has been implemented on a minicomputer. The method is nearly as general as Monte Carlo but has the advantage of providing deterministic solutions for the upwelling and downwelling radiations fields at many altitudes, zenith angles, and azimuths from a single computer run.

## 3. Research Results

Experimental data have been acquired using the UCLA goniometer on camellia, cucumber, and cauliflower leaves. In order to monitor the effect of using cut leaves versus leaves still attached to the plant, the reflectance of a cucumber leaf was monitored for several hours following clipping. Reflectivity at 0.98 μm increased during this period, indicating water stress and a decrease in the strength of the water band. To study spectral dependence of leaf BDRF, we obtained spectra of a camellia leaf at view angles of 0 and 30 degrees for illumination at normal incidence. The ratio of these spectra in the 0.4 - 0.9 μm region is displayed in Fig. 1. The increased noise level at the short wavelength end is due to lower detector response and decreased source light levels. This plot shows that the leaf BDRF deviates markedly from Lambertian behavior in a spectrally dependent fashion. The greatest departure from Lambertian reflectance is observed in the 0.68 μm chlorophyll absorption feature, possibly as a result of a decrease in the amount of multiple scattering within the leaf.

As an example of the success of our multidimensional radiative transfer algorithm, we consider the albedo step function problem, in which two semi-infinite fields of differing albedo are adjacent to one another. This model is useful in that it provides (a) an evaluation of the diffusion of radiation across the sharp albedo boundary separating the two regions, and (b) the ability to verify that the solution asymptotically approaches the correct result for a homogeneous surface at large distances from the boundary. This surface model may be considered to represent a coastal boundary, in which a large expanse of low albedo water borders a broad land area of higher reflectivity. We compare results obtained using the Fourier transform method with Monte Carlo results for an atmospheric model consisting of a clear atmosphere with a scale height of 8 km and an optical depth of 0.189, corresponding to Rayleigh scattering at 0.47 μm. The two half-planes are Lambertian with albedos of 0.0 and 0.6, and the solar zenith angle is 40°. This set of condi-

tions is referred to as Model 1. Figure 2 shows the results of calculations for Model 1 using the Fourier transform technique, along with selected points from the Monte Carlo results. The total upwelling intensities are shown as the sum of the diffuse (multiply scattered) radiation field and the direct field, which consists of photons transmitted to space without being scattered. The agreement between the two methods appears to be excellent. We also show at large distances from the boundary the intensities calculated using the one-dimensional matrix operator method for uniform albedos of 0.0 and 0.6, demonstrating that the Fourier transform results approach the expected values away from the boundary. In the vicinity of the boundary, the adjacency effect is apparent. Due to scattering within the atmosphere, the upwelling intensities on either side of boundary are affected by photons reflected from the surface on the opposite side of the boundary and then scattered into the line of sight. In effect, the atmosphere "blurs" the boundary with a point spread function whose width is a few kilometers. The Fourier transform technique is useful in that its underlying mathematical formalism demonstrates how the atmosphere filters high spatial frequency information from the upwelling radiation field. This filtering can be described by the computation of atmospheric modulation transfer functions (MTFs). Figure 3 is a comparison of MTFs calculated using our technique for a Rayleigh atmosphere and an aerosol laden (hazy) atmosphere, each of total optical depth 0.3 and 5 km scale height. These MTFs indicate that the more highly forward scattering haze phase function results in a greater observability of the adjacency effect.

Another area in which the 3-D radiative transfer algorithm is proving useful is in the development of a technique for determining atmospheric transmittance from surface images acquired at off-nadir view angles. The basis of the method is as follows: As shown in Fig. 2, the total upwelling radiance is the sum of a direct and diffuse component. Radiation directly transmitted to space is proportional to the surface albedo distribution, and a sharp discontinuity in the surface albedo gives rise to a similar discontinuity in the direct field. The diffuse field, on the other hand, while exhibiting a qualitative similarity to large scale variations in surface albedo, exhibits a much smoother character, owing to the filtering effects of the atmosphere, as discussed above. The direct field, which is also proportional to atmospheric transmittance $\exp(-\tau/\mu)$, where $\tau$ is the optical depth and $\mu$ is the cosine of the view angle, thus has a very different spatial character from the diffuse field. If we compute the spatial Fourier transform of upwelling radiances within an image, the spatial "smoothness" of the diffuse field means that it will make a negligible contribution at high spatial frequencies. Thus, if we eliminate low frequency Fourier components we are left with a measurement that is directly proportional to the atmospheric transmission factor $\exp(-\tau/\mu)$. By obtaining images of the same surface region at several view angles, it should in principle be possible to solve for $\tau$, provided non-Lambertian surface effects can be minimized. Our calculations suggest that acquisition of images in the vicinity of 60° off-nadir should be sufficient to accomplish this and recover atmospheric transmittance with an accuracy of 5-10%.

4. Significance of Results and Future Directions

Many investigators have studied the spectral properties of a wide variety of crop samples. The spectral reflectance of the foliage is modified by changes in the internal structure of the leaves associated with various forms of stress, such as water or mineral stress. The specularity of the reflected radiation increases at wavelengths where increased absorption occurs, presumably due to reduced depth of penetration of the incident radiation into the leaf resulting in fewer multiple

reflections between layers. Therefore, we expect changes in leaf structure resulting from stress to affect the angular as well as spectral reflectance properties. Thus, it is important to incorporate realistic (non-Lambertian) leaf bidirectional reflectance functions into canopy and scene models. The spectrogoniometric leaf measurements will provide such data.

The Fourier transform radiative transfer algorithm which we have developed is a useful tool for studying the effect of the atmosphere on high spatial resolution imaging of the Earth's surface. As discussed above, the sharpness of the adjacency effect in the vicinity of albedo boundaries is dependent upon the vertical distribution of the atmospheric scatterers. We are using our radiative transfer method to perform a systematic study of the variation of atmospheric point spread functions with aerosol vertical distribution, phase function, single scattering albedo, and optical thickness. The results of such calculations will permit evaluation of the possibility of observing atmospheric blur directly in high resolution images of the Earth's surface, with the goal of determining aerosol properties. Conversely, these calculations will lead to techniques for removing spectral contamination associated with the adjacency effect.

Further work is necessary in order to demonstrate the feasibility of implementing the multiple view angle optical depth retrieval technique on a space platform. The major uncertainty at present is the manner in which the unknown angular reflectance properties of the surface should be taken into account. For the model BDRF we used in our simulations, off-nadir imaging near 60° appears appropriate to compensate for lack of a priori knowledge of the shape of the surface BDRF. Whether this range is appropriate for natural surfaces can only be determined by experimentation in the field. A number of portable field spectrometers are available for obtaining BDRF measurements. The success of this technique would be significant because it provides a means of monitoring tropospheric opacity, which is important not only for atmospheric studies but also because it is one of the most important parameters governing the effect of the atmosphere on surface images. An extension of the optical depth retrieval technique is to near infrared spectral regions where water vapor absorption occurs. In its current form, the technique relies on the assumption that atmospheric transmittance varies as $\exp(-\tau/\mu)$. In the water vapor bands, any finite bandwidth spectral channel will incorporate many individual lines and this law may not be followed. In order to study the view angle dependence of transmittance in such regions, we are developing a radiative transfer algorithm which permits calculation of broadband radiances for channels containing many absorption lines in the presence of aerosol scattering.

Finally, we plan to investigate the applicability of our 3-D radiative transfer method to scattering in plant canopies. In principle, our algorithm is applicable to heterogeneous media and has the advantage of providing a true solution to the multidimensional radiative transfer equation. In addition, solutions are obtained at many view and illumination angles and azimuths, thus providing the full canopy BDRF. Variation of the BDRF of the individual leaves will permit study of the effect of changing reflectance properties of the individual canopy elements on the canopy angular and spectral reflectance as a whole. Such calculations will mesh nicely with the goals of the experimental portion of this investigation.
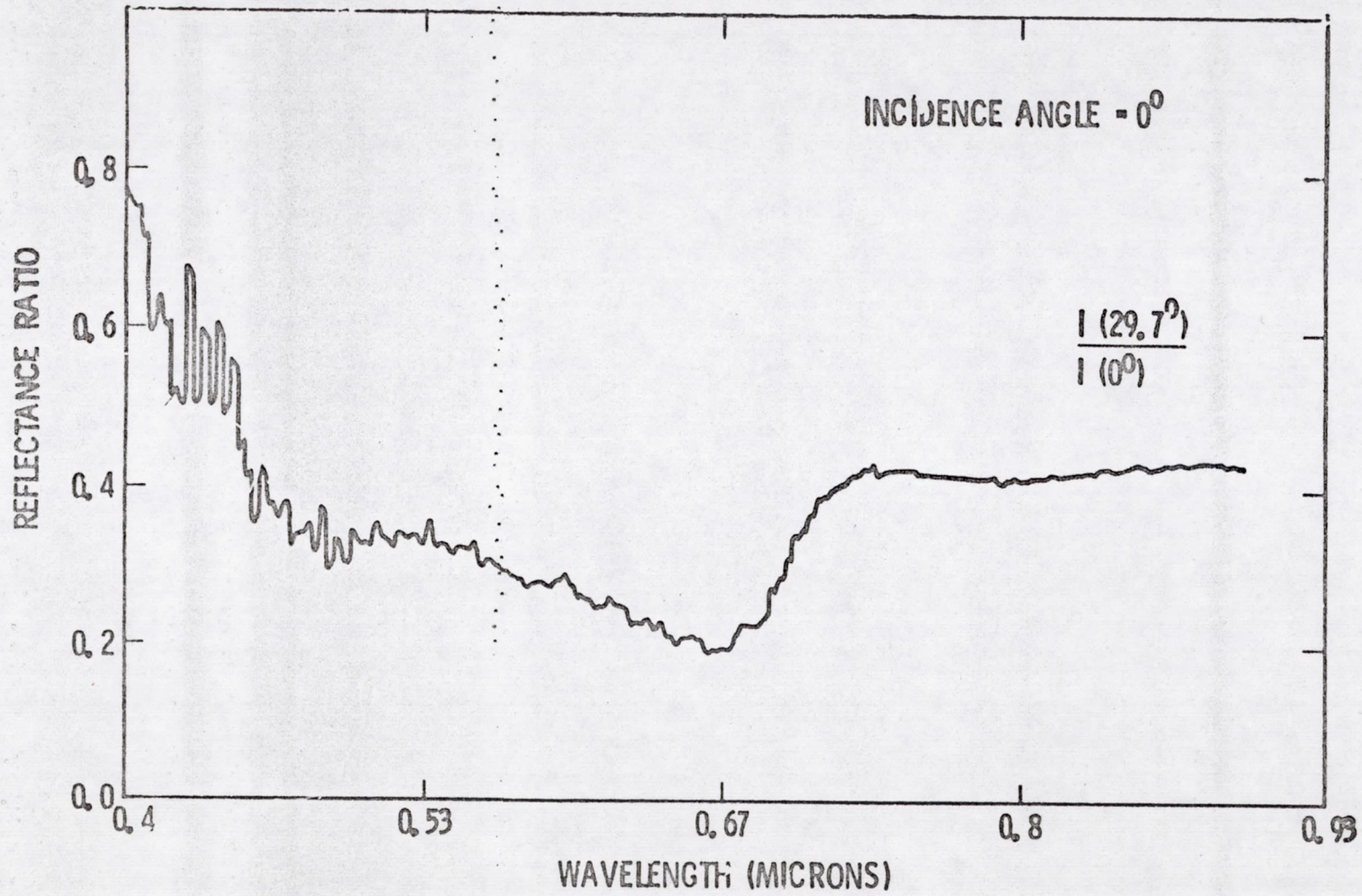
# CAMELLIA LEAF



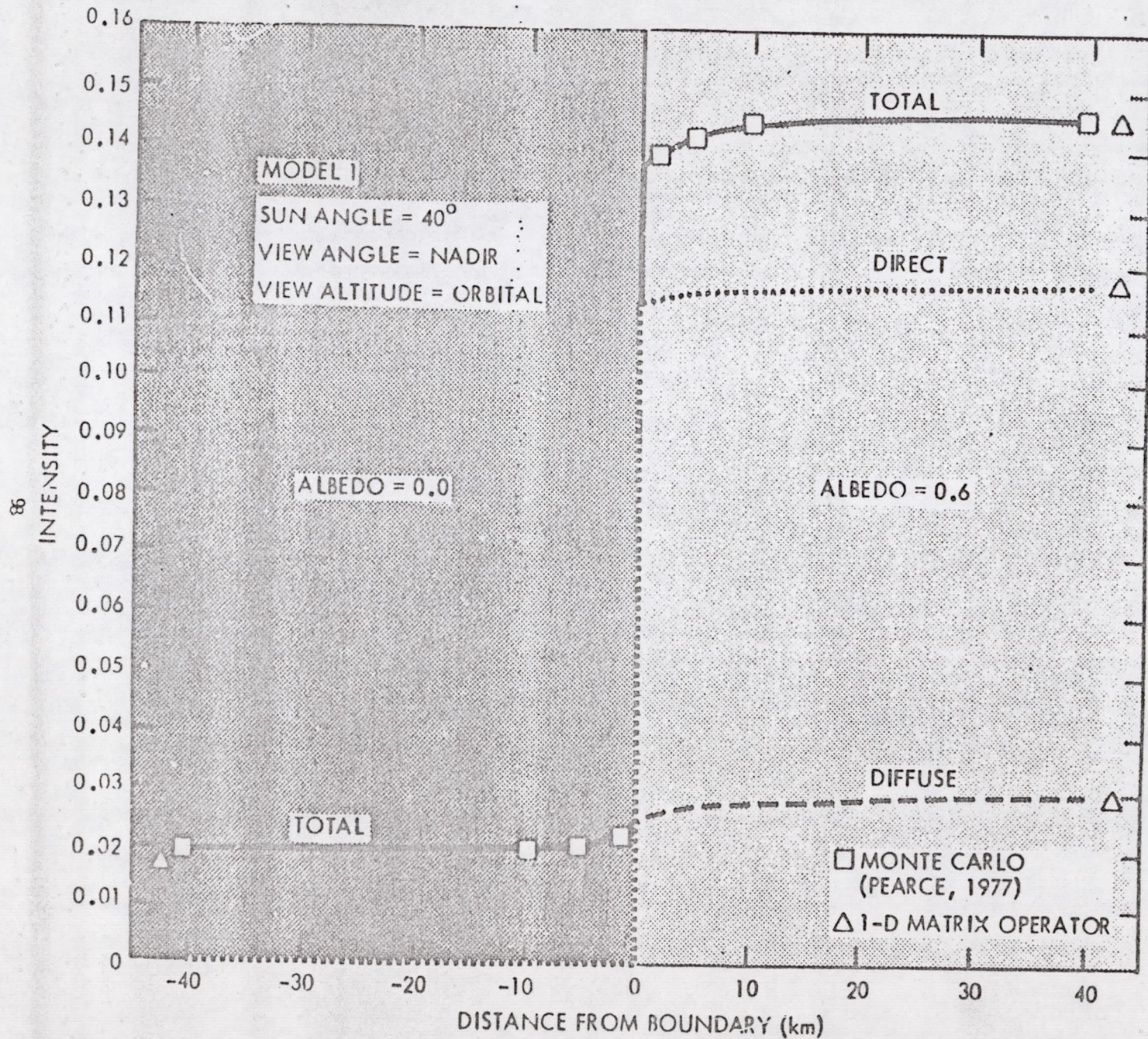Fig. 1.  Ratio of reflected intensity at 30° view angle to 0° view angle for camellia leaf.

Fig. 2. Upwelling intensity in vicinity of albedo discontinuity for Model 1.

The following labels appear within the figure:

- Y-axis: INTENSITY (0 to 0.16)
- X-axis: DISTANCE FROM BOUNDARY (km), from −40 to 40

MODEL 1
SUN ANGLE = 40°
VIEW ANGLE = NADIR
VIEW ALTITUDE = ORBITAL

ALBEDO = 0.0

ALBEDO = 0.6

TOTAL
DIRECT
DIFFUSE
TOTAL

□ MONTE CARLO (PEARCE, 1977)
△ 1-D MATRIX OPERATOR

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