A Multi-Scale Analytical Canopy (MAC) Reflectance Model Based on the Angular Second Order Gap Size Distribution

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Abstract - **Anisotropy in direction hemispherical reflectance of vegetation canopies has been exploited both as a source of information regarding canopy structure and has been considered a source of noise. Geometric optics canopy reflectance models have had some success in relating canopy structure to observed top-of-canopy anisotropy, especially within wavelengths where multiple scattering is not important. However, these models are often scale specific. Furthermore, most models use simplified methods for treating the "hotspot effect" where both the view and illumination direction vectors from a point in the canopy pass through the same gap in the vegetation. We present a multi-scale analytical canopy model (MAC) that deals with an arbitrary number of scales of canopy organisation. The angular gap size distribution defined as the probability of a gap of length λ along the plane containing both view and illumination direction vectors is applied to describe the extent of the "hotspot" effect in a manner that includes all scales. Validation of the MAC model is presented over boreal stands in terms of both top-of-canopy BRDF's as well as sub-canopy gap size distribution. The possibility of using high-resolution imagery to characterize crown clumping using second order reflectance distributions is discussed.**

I. INTRODUCTION

Canopy reflectance models are often used to understand photon-vegetation interactions, predict within and above canopy radiative fluxes and constrain inversions of observed radiation fluxes to estimate canopy structure or biochemistry [1]. Recently, increasingly complex reflectance models have been developed, especially for characterizing bi-directional distribution functions (BRDF) [2]. While these models have shown promise when applied to simulated canopies, small managed stands or even selected natural, but uniform cover, field sites the reality of remote sensing is that the sensor field of view (FOV) often samples a region of spatially variable vegetation structure. Some models now attempt to capture this structure, often termed "clumping", at various spatial scale. Analytical geometric optics models offer a compromise between complexity and the ability to match in-situ observations. This is especially the case when single scattering dominates photon-vegetation interactions although there have also been attempts to include multiple scattering corrections [3]. This class of models does not always conserve energy but what is important to consider is that they do conserve matter – i.e. they actually represent vegetation elements in realistic spatial arrangements in at least a statistical sense. Canopy gap fraction is one diagnostic test that has been used to determine if models are adequately parameterized in terms of structure [4]. The gap size distribution, a measure of second order structural patterns, has been included in one G-O model to resolve between and within-crown hotspot effects [4]. The goal of our paper is to

1. extend the gap size distribution concept to the angular gap size distribution.
2. apply the angular gap size distribution to resolve the single scattering component in canopy BRDF within a statistical geometric optical model
3. generalize the description of clumping to an arbitrary number of scales.

The developed Multi-Scale Analytical Canopy (MAC) model is validated with airborne POLDER measurements over Boreal conifer stands within the BOREAS site. Strategies for using the model to characterize clumping using second order spatial BRDF measurements are discussed.

II THEORY

Derivation of the Multi-Scale AngularGap Size Distribution s

Assume that the canopy consists of elements corresponding to K spatial scales within a stand with elements of each scale nested within the next coarser scale. For example, the successively coarser scales within a stand could correspond to needles, shoots, branches, crowns and patches. Assume that the elements at scale k are distributed according to a binomial (positive or negative) process such that their cast shadows have density $\rho_k(Z, \Omega_\lambda)$ within a given projected shadow of scale k+1 elements; where shadows of both scales are the orthographic projections of elements along direction Ω_I onto Z. The union of the projection of an opaque version of an element at scale k on Z in direction Ω_i and Ω_v is given by:

$$X_k(z,\Omega_i,\Omega_v) = S_k(z,\Omega_i) + S_k(z,\Omega_v) - O_k(z,\Omega_i,\Omega_v) \qquad (1)$$

Where $S_k(z, \Omega)$ is the region of a shadow cast in direction Ω on the plane Z and $O_k(z, \Omega_i, \Omega_v)$ is the overlap region of the shadows cast in direction Ω_i and Ω_v. Extending the result of [5] from one dimensions to two dimensions, the area on Z where a line $L(\lambda, \Omega_\lambda)$ of length λ oriented along the ray Ω_λ connecting unit vectors of view and illumination directions overlaps with X_k is given by:

$$A_k(\lambda,Z,\Omega_\lambda)=\overline{Mes}[L(\lambda,\Omega_\lambda)*X_k(z,\Omega_i,\Omega_v)] \quad (2)$$

Where $\overline{Mes}$ is the expected value of the measure operator corresponding to the area in Z where its argument is positive. An exact estimate of the overlap area could require rather complicated analytical formulae or numerical approaches. Furthermore, this level of detail may be excessive given the existing assumptions of a stationary orientation distribution and mean element shape and size. Each element scale is treated using approximations that strive to provide a balance between complexity and realism when estimating the shadow projected are and overlap area. We include five. scales: patches, crowns, branches, shoots and foliage described a cone-on-cylinders or cylinders when applied to conifers.

The, extending [6], angular gap size distribution on Z along direction Ω_λ is :

$$P_{k+1}(n,Z,\Omega_i,\Omega_v)=\exp[-\Phi_k(n,Z,\Omega_\lambda)\rho_k(Z,\Omega_\lambda)\ A_k(n,Z,\Omega_\lambda)] \quad (3)$$

Here Φ_k is an index of clumping (deviation from random placement) of scale k elements within an element at scale k+1 corresponding to:

$$\Phi_k(n,Z,\Omega_\lambda)=\frac{-\ln\{1-[1-P_k(n,Z,\Omega_\lambda)][1-GI_k(Z,\Omega_\lambda)]\}}{1-GI_k(Z,\Omega_\lambda)} \quad (4)$$

where GI_k is the Fisher's dispersion index of scale k elements within a scale $k+1$ element.

$$GI_k(z,\Omega_\lambda)=1\mp\rho_k(z,\Omega_\lambda)\sigma_k(z,\Omega_\lambda) \quad (5)$$

The term $\sigma_k(Z, \Omega_\lambda)$ corresponds to the "element living area"as defined in [7].

Derivation of the Multi-Scale Top of Canopy BRDF

The BRDF for irradiance I_s along angle Ω_i is:

$$R_I(\Omega_i,\Omega_v)=\frac{\begin{bmatrix} I_{Fvi}(\Omega_i,\Omega_v)+I_{Fvz}(\Omega_i,\Omega_v) \\ +I_{Gvi}(\Omega_i,\Omega_v)+I_{Gvz}(\Omega_i,\Omega_v)\end{bmatrix}}{I_s(\Omega_i)} \quad (6)$$

Where the terms I..(Ω_i, Ω_v) correspond to mean component radiances in view direction Ω_v. The subscripts F and G denote foliage and ground respectively and the prefixes v,i and z denote viewed, illuminated and shaded respectively. Mean sunlit and shaded viewed foliage and surface radiances are decomposed into the contributions of respective fractional areas from each plane Z over the canopy height H:

$$I_{Fvi}(\Omega_i,\Omega_v)=\int_{0^+}^{H}F_{vi}(z)[I_S(z,\Omega_i,\Omega_v)+I_D(z,\Omega_i,\Omega_v)]dz \quad (7)$$

$$I_{Fvz}(\Omega_i,\Omega_v)=\int_{0^+}^{H}[F_v(z)-F_{vi}(z)]I_D(z,\Omega_i,\Omega_v)dz \quad (8)$$

$$I_{Gvi}(\Omega_i,\Omega_v)=F_{vi}(0)[I_S(0,\Omega_i,\Omega_v)+I_D(0,\Omega_i,\Omega_v)] \quad (9)$$

$$I_{Gvz}(\Omega_i,\Omega_v)=[1-F_{vi}(0)]I_D(0,\Omega_i,\Omega_v) \quad (10)$$

Where $F_v(z)$ is the fraction of Z containing viewed surfaces and $F_{vi}(z)$ is the fraction of Z containing surfaces both viewed and illuminated. I_D corresponds to upwelling diffuse radiance of canopy elements in the view direction estimated by applying a two-stream turbid media radiative transfer model [8] using the canopy effective LAI and a modified single scattering albedo (Smolander, S. personal communication) to account for within shoot scattering.

The canopy above Z is separated into areas treated as uncorrelated for the purposes of computing joint view and illumination probabilities and areas subject to the "hotspot effect" where view and illumination occur through the same gap in the foliage. The fraction of Z occupied by sunlit foliage is given by:

$$F_{vi}(z)=F_i(z)F_i(z)[1-f_{HS}]+[F_v(z)F_i(z)]^{0.5}f_{HS} \quad (11)$$

The terms $F_i(z)$,$F_v(z)$, f_{HS} corresponding to the fraction of Z containing viewed and illuminated foliage alternatively and gaps contributing to the hotspot effect respectively:

$$F_v(z)=\frac{\partial p(z,0,\Omega_v,\Omega_v)}{\partial z} \quad (12)$$

$$F_i(z)=\frac{\partial p(z,0,\Omega_i,\Omega_i)}{\partial z} \quad (13)$$

$$f_{HS}=\frac{p(z,\lambda_z,\Omega_i,\Omega_v)}{p(z,0,\Omega_i,\Omega_v)} \quad (14)$$

III VALIDATION

The MAC model was validates over conifer stands within the BOREAS sites due to the availability of both in-situ parameters and top of canopy BRDF measurements. Structural parameters and POLDER airborne measurements documented used are from 9]. Element reflectance values and parameters governing patch scale clumping were selected to provide the best match to the observed BRDF while falling within the range of published values. This fitting was performed given the relatively large variability in element reflectance both within and between BOREAS sites. Agreement between observed and modelled BRDF's is good as indicated in Figure 1 for the principal plane for three BOREAS conifer sites. Root mean square errors are similar to those reported for the 5-Scale model. Comparisons of modelled versus measured below canopy gap fraction [10] shown in Figure 2 suggest that the fitted reflectance and clumping parameters did not compromise the physical validity of the model.

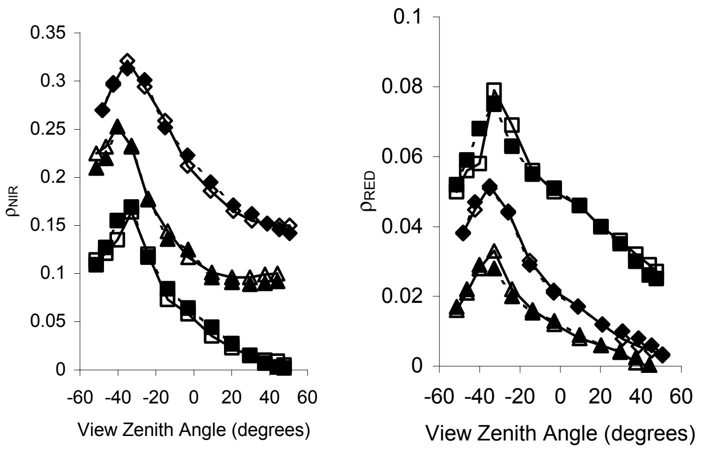

Figure 1: Comparison of airborne POLDER observations (solid) over three conifer stands within the BOREAS southern study area MAC model estimates (hollow/dashed) for OBS (trinagles), OJP(diamonds) and YJP (squares) sites.

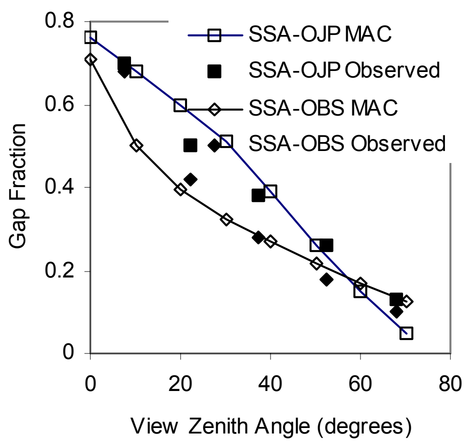

Figure 2: Comparison of MAC modelled and observed below canopy gap fractions for OBS and OJP sites.

IV. CONCLUSION

The theory relating canopy structure to gap size distribution was extended to consider multiple spatial scales and arbitrary angles. Two critical developments were the generalization of the theory in [5] to multiple scales and to two dimensions. The gap size distribution theory was then used to estimate the joint and independent probabilities of illuminating and viewing surfaces at a given height in the canopy. The joint probability relied on the use of the direction vector between rays corresponding to unit vectors along view and illumination directions to specify the angle at which the gap size distribution is evaluated. The model was validated over Boreal conifer sites with reasonable success for top of canopy BRDF and canopy gap fraction over a range of angles.

Improvements could be made in the multiple scattering parameterization. The two stream approach used here may not be sufficient where there is substantial anisotropy in multiply scattered top of canopy exitance. The current model also does not account variability in element dimensions. An extended version including multiple covarying elements at each scale is under development. The model implicitly resolves the size distribution of sunlit and shaded gaps at the top of the canopy. High resolution imagery could potentially be applied to measure these gaps and hence provide estimates of canopy structure. As a first step in this regard we are testing this model with LIDAR data where all viewed gaps are illuminated by the active sensor.

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