A Four-Level Bidirectional Reflectance Model Based on Canopy Architecture and its Inversion

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Abstract - Open boreal forests present a challenge in understanding remote sensing signals acquired under various solar and view geometry. Much research is needed to improve our ability to model the bidirectional reflectance distribution (BRD) for retrieving the surface information using measurements at a few angles. The geometric-optical bidirectional reflectance model outlined in this paper differs from Li-Strahler's model [4], [5], [7] in the following respects: *i*) the assumption of random spatial distribution of trees is replaced by the Neyman distribution which is able to generate the clumpiness of a forest stand; *ii*) the multiple mutual shadowing effect among tree crowns is considered using the combination of the negative binomial and the Neyman distribution theory; *iii*) the probability of observing the sunlit background is modelled using a canopy gap size distribution function which is shown to affect the size and width of the hotspot; *iv*) the branch architecture of conifer trees affecting the directional reflectance is simulated using a simple angular radiation penetration function; *v*) the tree crown surface is treated as a complex surface with small structures which themselves generate mutual shadows and a hotspot. All these levels of canopy architecture are shown to have important effects on the directional distribution of the reflected radiance from boreal forests. The model results compare well with a data set from a spruce forest. The model after validation is used as a tool to retrieve the leaf area index of plant canopies according to a vegetation index (NDVI) calculated from the modelled red and near infrared bidirectional reflectance factors at various solar and view angles. The importance of canopy architecture (tree density and distribution, and branch and shoot structure) in the retrieval of LAI will be demonstrated.

INTRODUCTION

In previous geometric-optical models, a forest stand is assumed to consist of randomly distributed objects containing leaves as turbid media. These two-level models mark a major advancement in simulating radiation regimes in forest stands compared with the one-level turbid-media models. However, two-level models can only be considered as much simplified mathematical descriptions of the physical reality. First, trees are generally not randomly distributed in space. They are clustered at large scales due to variations in the soil and topographic conditions. They are also not randomly positioned at small scales because of the natural repulsion effect. Second, leaves are not randomly distributed within tree crowns. In conifer trees, for example, leaves are grouped into shoots, branches and whirls. The 4-level directional reflectance model outlined in this paper includes these two additional levels of canopy architecture.

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TREE DISTRIBUTION

Tree distributions are commonly modeled by the Poisson theory. Measurements from a boreal forest shown in Fig. 1 indicate a clear departure from the random case. Based on Neyman [8], and Getis and Boots [3], it is assumed that trees are clustered in groups and the size of a group follows a Poisson process, centred around a certain size. This group must be confined into a quadrat. The probability of having a group inside a certain domain also follows a Poisson distribution. This process is a double Poisson distribution, better known as Neyman type A:

$$P_N(i;m_1;m_2) = e^{-m_1}\frac{m_2^i}{i!}\sum_{j=1}^{\infty}\frac{\left(m_1e^{-m_2}\right)^j}{j!} \quad \text{for } i = 0,1,2,... \quad (1)$$

where m_1 is the mean number of group per quadrat and m_2 is the cluster mean size. The mean number of trees in a quadrat is $m = m_1 \cdot m_2$. When the quadrats are small, or when the grouping is large compared to m, a Neyman process is more likely to give empty quadrats and create patchiness than the Poisson process. In Fig. 1, a Neyman with grouping of 3 gives results closer to the measurements than the Poisson theory. The measurements are taken from an area of 100×100 m^2 in a mature jack pine stand located near Candle Lake, Saskatchewan.

TREE CROWN

The present model is first used to simulate a black spruce forest. The top of a tree is modeled by a cone, and the lower part by a cylinder "on a stick." This situation occurs when the lower part of a tree has a trunk without much foliage. We denote S_g as the shadow on the ground surface and V_g the viewing shadow, i.e. the ground area blocked by trees in the viewing direction. The illuminated area on one tree crown is calculated according to the crown shape.

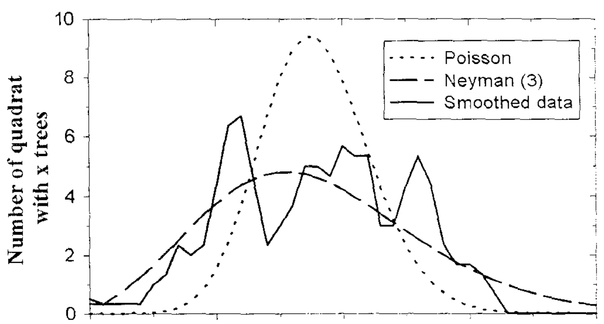

Fig. 1 Comparison between Poisson, Neyman and measurements of a Jack Pine forest

CANOPY GAP FRACTION AND THE HOTSPOT

The probability of seeing the ground is used for estimating the contribution of the underlying surface. If the trees are clustered, and overlapping is allowed we have:

$$P_{sg} = \sum_{j=0} P_{tj}(V_g)\cdot P^{j}_{gap}(\theta_v) + P_{to} \tag{2}$$

where $P^{j}_{gap}(\theta_v)=\prod_{1}^{j} P_{gap}(\theta_v)$ is the gap probability within j tree overlaping, θ_v is the view zenith angle, and $P_{tj}(V_g)$ is the probability of j overlapping:

$$P_{tj}(V_{gi}) = \sum_{i=0} P_N(i;m_1;m_2)\left\{\frac{(i+j-1)!}{(i-1)!\,j!}\right\}\left[1-\frac{V_{gi}}{A}\right]^{i}\left[\frac{V_{gi}}{A}\right]^{j} \tag{4}$$

In real forests, trees found in clusters are usually smaller than the average tree size. We have m trees on average in one quadrat. The model assumes that for the probability of having more than m trees in a quadrat, the size of the projection will decrease as $V_{gi} = V_g \cdot m/i$. The gap probability $P_{gap}(\theta)$ from Nilson [9] is used for a continuous medium. For a discontinuous canopy, we use a similar equation [7]. It has the advantage of being usable for any form of trees:

$$P_{gap}(\theta_v) = \exp\left(-\frac{G(\theta_v)\Omega}{DV_g\cos(\theta_v)}\right) \tag{5}$$

Additional equations are used to describe the foliage projection coefficient $G(\theta)$ and the clumping index Ω depending on the crown architecture. D is the density of trees. Similarly, the probability of having an illuminated ground surface (P_{ig}) can be found by replacing θ_v with θ_s in (2). Using (4), mutual shadowing of trees can be computed. The model assumes that the cone part is not affected by overlapping. The canopy gap size (λ) distribution [1] is used to model the hotspot. For an illuminated area on the ground, the viewer needs a minimum gap size, λ_m, to see the ground area through the same gap. The process is done on the crown level for the ground hotspot, and at the shoot and branch levels for the tree crown hotspot. The resulting hotspot function is:

$$f(\Delta\theta) = \frac{\int_{\lambda_m}^{\infty}\left[1-\Delta\theta/\theta_m\right]\cdot N(\lambda)d\lambda}{\int_{\lambda_m}^{\infty} N(\lambda)d\lambda} \tag{6}$$

where $\Delta\theta$ is the angular difference between the viewer and the sun, θ_m is the minimum angle difference required to see an illuminated area on the ground for a gap size of λ_m which can be predicted [1]. $N(\lambda)$ is the number density of a gap with size λ. Equation (6) is used as a hotspot kernel which equals one at the hotspot and zero where the viewing and illumination processes become independent. The reflectance is found by multiplying the proportion of illuminated and shaded tree crown or ground surface seen by the viewer, by their respective reflectivity in red or near-infrared wavelengths.

MODEL RESULTS

The model first computes the canopy gap fraction. Measurements from a black spruce forest were used as a validation. A density of 2800 trees per hectare, divided into 20 quadrats, a LAI of 4, a tree height of 13 m, a radius of 0.45 m, and an apex angle of 13° were assumed. To give an validation of the effect of the grouping, Fig. 2 shows the gap probability from (2) for values of grouping of 1, 5, 10, and 20. Because the stand is very open, the Neyman grouping effect becomes relatively small in the gap fraction near the vertical direction. The best curve is for $m_2 = 10$. With the same parameters, the reflectance in the red band is computed for 4 different solar zenith angles (Fig. 3). The model is able to simulate the measurements reasonably well. Compared with measured data points, the modelled curves show sharp

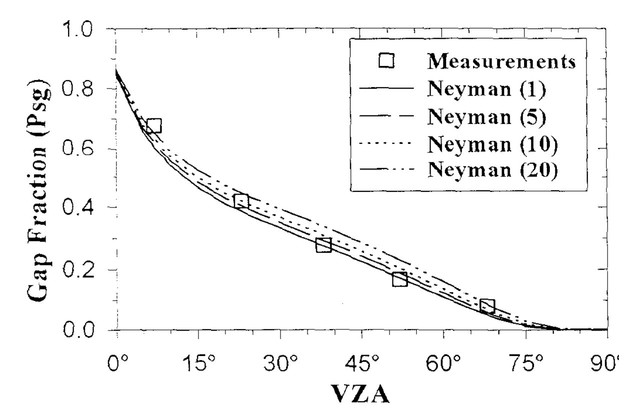

Fig. 2 Measured gap probability and different grouping factor output of the model.

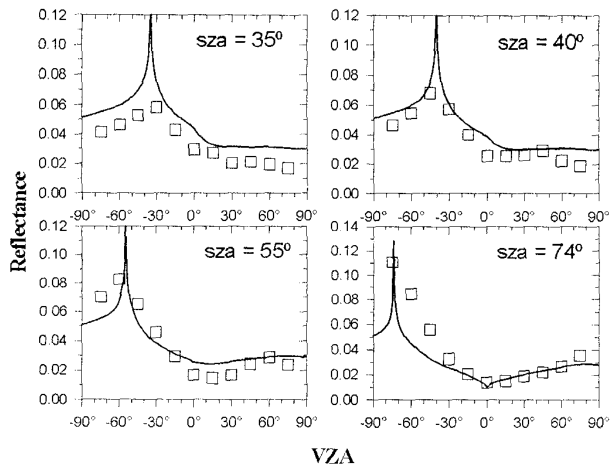

Fig. 3 Comparisons of boreal black spruce reflectance measurements in the red (□) with the model (—) in the principal plane.

spikes at the hotspot. The difference may be partly due to the small angular resolution (15°) in the measurements, which effectively average out the peak of a hotspot. The subtle differences in other angle ranges suggest that further improvements in the mathematical description of the sub-canopy architecture are needed.

INVERSION

The model offers enough variability to be used to retrieve forest canopy parameters. It can be used to estimate LAI from NDVI calculated from red and near-infrared reflectance. The NDVI found in Fig. 4a for the forwardscattering side is larger than that on the backscattering side. This is in agreement with measurements in black spruce forest [2]. The difference between the LAI-NDVI relationship at various view angles is largely determined by within-crown structures. The effect of the grouping is plotted in Fig. 4b for the forwardscattering side, showing how the NDVI changes with different Neyman grouping. The effect of Neyman grouping depends on the quadrat size. Larger effects are found in

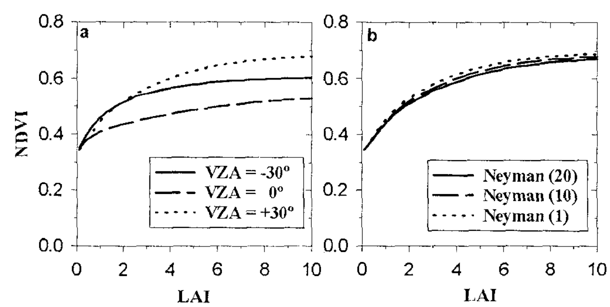

Fig. 4 Effect of different levels of the model on the inversion process.

larger quadrats with larger Neyman groups, suggesting that in coarse resolution remote sensing data, the grouping effect would be more important.

CONCLUSION

The four-level model represents a significant improvement over previous two-level geometric-optical models in its capability to simulate the directional reflectance behavior for complex plant canopies. Such a model provides the needed flexibilities in inversion for a wide range of plant canopy types.

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