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Title: **ARE LEAF CHEMISTRY SIGNATURES PRESERVED AT THE CANOPY LEVEL**

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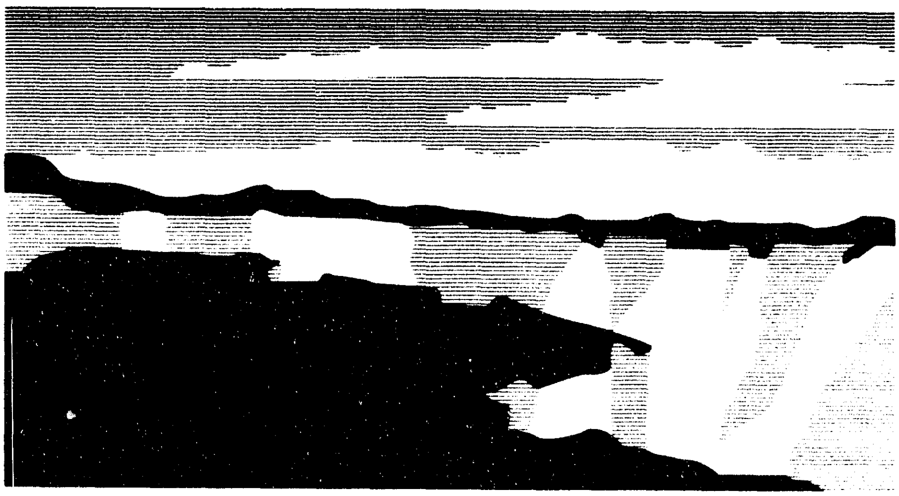

Los Alamos
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ARE LEAF CHEMISTRY SIGNATURES PRESERVED AT THE CANOPY LEVEL?

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Abstract

Imaging spectrometers have the potential to be very useful in remote sensing of canopy chemistry constituents such as nitrogen and lignin. In this study under the HIRIS project the question of how leaf chemical composition which is reflected in leaf spectral features in the reflectance and transmittance is affected by canopy architecture was investigated. Several plants were modeled with high fidelity and a radiosity model was used to compute the canopy spectral signature over the visible and near infrared. We found that chemical constituent specific signatures such as absorptions are preserved and in the case of low absorption are actually enhanced. For moderately dense canopies the amount of a constituent depends also on the total leaf area.

1 Introduction

The HIRIS team spent the last two years on a study called : "Accelerated Canopy Chemistry Program". The overall goal was to see if a hyperspectral instrument could be used to determine the leaf chemical content (i.e. nitrogen, cellulose, ...). Our task was to investigate how the canopy architecture might change the leaf chemical signature and by how much? Furthermore we were asked to investigate effects due to illumination, background and terrain on the spectral signatures.

Why is a change in the canopy chemistry signature expected? Since a canopy is a three-dimensional structure of leaves/needles, stems, branches, etc., the radiation emitted from any single phytoelement will interact with many others before it leaves the canopy. Such multiple reflections and transmissions modify the originally emitted leaf spectrum. This conclusion becomes intuitively clear when it is realized that all phytoelements (say leaves) in a canopy structure fall into 3 categories: fully illuminated, fully shaded, or partially shaded/illuminated by the incoming solar radiation; and it is obvious that a shadow spectrum is different from a sun-lit leaf spectrum. Thus, the magnitude of such spectral changes will depend on the canopy architecture and the external illumination direction.

First we reviewed existing canopy models and rated them on what their advantages and disadvantages in this application might be. Second, we gathered data on tree geometry for walnut trees, douglas fir seedlings and maple seedlings. Third, we investigated how an absorption feature in a plate is changed if the plate is part of a layered canopy. Fourth, we developed a fast hybrid raytracing/radiosity method to compute canopy spectral signatures for variable LAI, view angles and sun angles.

2 Modeling Requirements

We believe that the following features are necessary for a canopy model in order to simulate the spectral signatures at the canopy level :

1. Discrete phytoelements (leaves, needles, stems, fruits, etc.) with specified size, location, orientation, reflectance and transmittance.

2. Transmission and multiple reflections between leaves must be taken into account.

3. Direct and indirect illumination.

4. Shadowing within the canopy and on the ground.

5. Calculation at any wavelength with spectrum transfers between leaves must be possible.

Of all the methods we are familiar with, only the recently developed radiosity method (Borel, Gerstl and Powers (1991) and Goel et al. (1991)) meets all of the above requirements.

3 Tree Reconstruction

In order to reconstruct the tree geometry, selected measurements should be performed :

Number of Orders of Branching This characteristic can be determined by visual examination of a tree and simply counting the number of times branching occurs from the trunk to the most apical stems.

Branching Order of Leaf Bearing Stems The branching order of stems which bear leaves may be recorded. There are likely to be several orders which bear leaves.

<u>Stem Level Parameters</u>

Stem Diameter Diameter at the mid-length of a stem may be measured with a ruler.

Stem Length The length of a stem may be measured with a ruler or tape.

Number of Leaves per unit Length of Stem For leaf bearing stems, the number of leaves (or needle fascicles) can be counted so that the number of leaves per unit length of leaf bearing stem may be determined.

Branching Angle The angle of divergence between stems at all orders higher than 1, can be estimated with a protractor.

Phyllotaxis Angle For coniferous trees (or those with strong monopodial growth), the azimuthal angle of divergence from the main stem can be estimated with the help of a compass.

Walnut Tree Experiment.

In Fig. 1 we show a walnut tree reconstructed from detailed stem geometry measurements (Martens et al (1991)). The tree was generated from a linked list of stem angles (zenith, azimuth) and stem lengths. An example of a linked list for the tree is given below :

Linked List					
Segment Number	Parent Segment	Length in cm	Diam. in cm	Stem Zen.	Stem Azi.
1	0	77	13.9	0	0
2	1	59	6.5	51	180
3	1	192	6.0	45	81
4	1	65	5.0	51	355
5	1	76	11.8	13	345
6	2	20	5.2	55	155
...	...	...	...	...	...

An small portion of an image of an orchard with 25 walnut trees is shown in Fig.2. The image was raytraced using a public domain raytracer called *Rayshade* which is available by FTP from princeton.edu (128.112.128.1). A hierarchical description of each tree was generated from the linked list by a BASIC program.

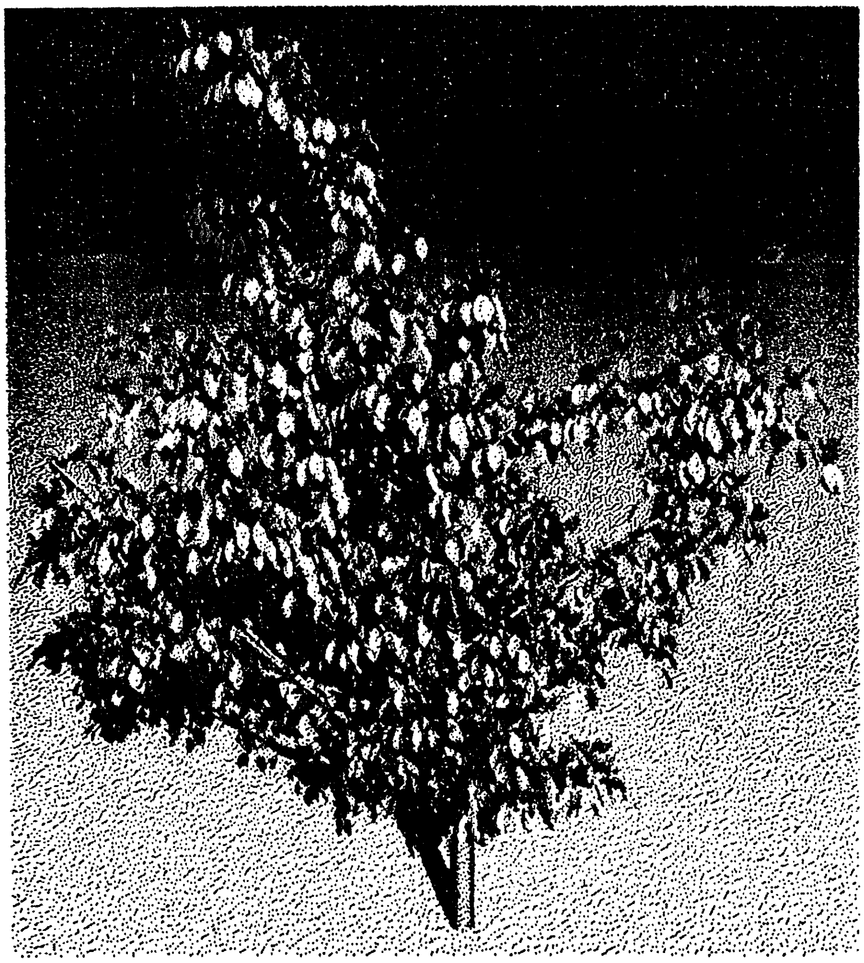

Figure 1: Reconstructed walnut tree rendered using raytracing

Figure 2: Portion of a walnut orchard rendered using raytracing

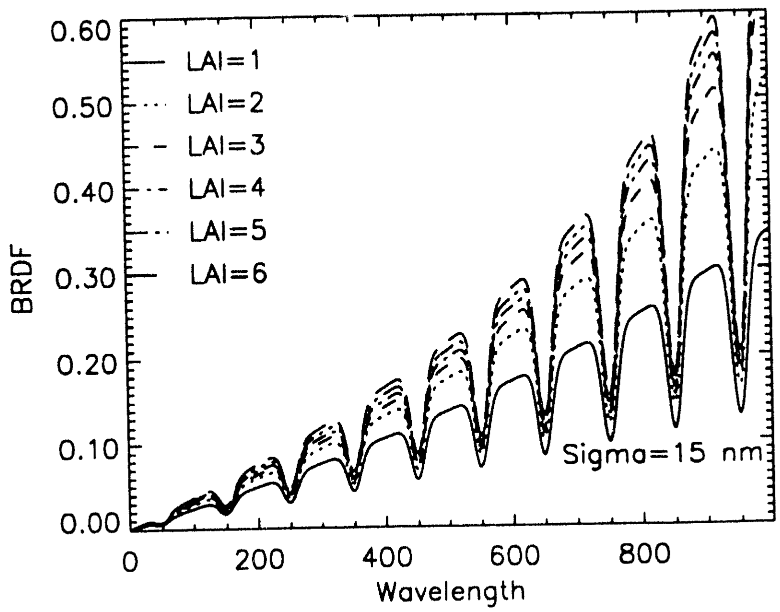

Figure 3: N-layer radiosity model demonstrates non linear effects on an absorption feature

4 Spectra for Simple Canopies

A simple model using artificial absorption features was developed to show the effect of non linear spectral mixing :

- Let $\rho = \tau$ be a linear function of wavelength from 0. to 0.5 and add 10 absorption features with a mean and standard deviation (Sigma)
- Compute BRDF of a layered canopy with $N = 10$ layers for 10 leaf layers from .1 to .6 per layer

In Fig.3 we show how the absorptions change as a function of LAI. The modulation depth was always set to 50 % of the level of the reflectance/transmittance near the absorption. Note that the higher the LAI gets the more a curve appears non linear . The location of the minima does not change significantly because light is absorbed in the leaves. From this model we concluded that absorption features in leaves are preserved at the canopy level and can even be enhanced. The relationship between the concentration of a leaf chemical constituent and spectral signature is non linear at the canopy level. Thus for quantitative canopy chemical retrievals it is necessary to model the influence of the canopy architecture.

5 Canopy Spectral Signature of Complex 3D Canopies

We developed a hybrid model to calculate the canopy spectral signature of an orchard of walnut trees. We chose a hybrid model because of its simplicity. We are not able to deal with large numbers of surfaces in our radiosity model yet. An orchard of 25 walnut trees contains about 10^6 polygons, cylinders and spheres.

The hybrid model has the following steps :

1. Raytrace images of a part (2 m x 2 m) of a reconstructed walnut tree for a given geographical location (e.g. Maricopa, Los Alamos, 45^0 North) and dates (e.g. 3-21, 5-26, 6-21) and given times (e.g. every hour from 8 am to 4 pm) for nadir view or off-nadir views ($\theta_v = -40^0, -30^0, .., +30^0, 40^0$).

2. Compute image statistics such as :

- Probabilities of seeing illuminated surfaces :

  P^{sun}_{leaf}, P^{sun}_{bark}, P^{sun}_{soil}

- Probabilities of seeing shaded surfaces :

  P^{shade}_{leaf}, P^{shade}_{bark}, P^{shade}_{soil}

- Average cosine of angle between the surface normal and sun vector for visible illuminated surfaces :

  $\overline{(\vec{n}_{leaf} \cdot \vec{n}_{sun})}$, $\overline{(\vec{n}_{bark} \cdot \vec{n}_{sun})}$, $\overline{(\vec{n}_{soil} \cdot \vec{n}_{sun})} = \cos\theta_s$

An example of how the probability of seeing illuminated and shaded surfaces changes as a function of sun direction is shown in Fig.4.

3. Approximate radiosities for the canopy by using the N-layer model with a total LAI similar to the walnut canopy ($LAI = 5$), measured leaf reflectances ρ and transmittances τ and assumed soil reflectance ρ_s ($\rho_{bark} = 0.$) :

$$\overline{B^{sun}_{leaf}} = \sum_{n=1}^{N} B^{sun}_{leaf,n} lai(1 - lai)^{n-1},$$

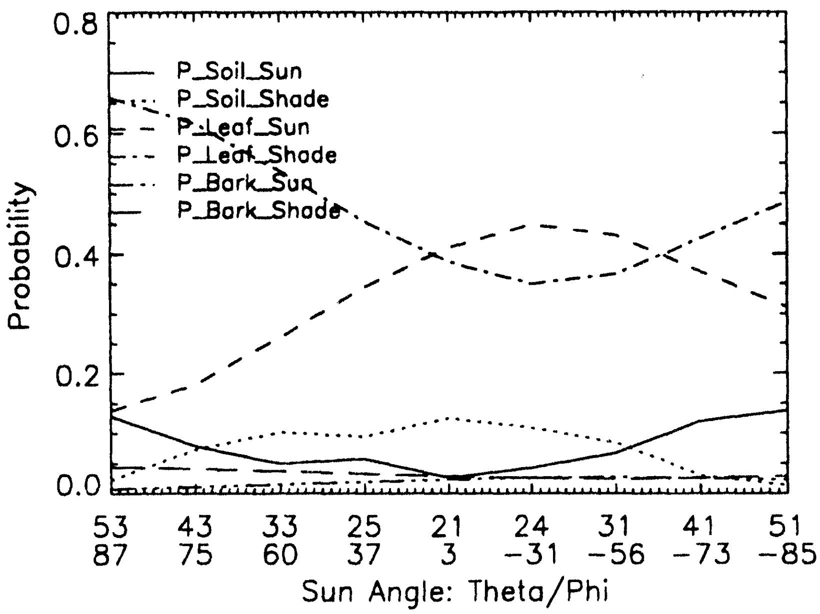

Figure 4: Canopy averaged probabilities of seeing illuminated and shaded surfaces for a walnut tree from nadir view

$$\overline{B_{leaf}^{shade}} = \sum_{n=2}^{N} B_{leaf,n}^{shade} lai(1 - lai)^{n-1},$$

B_{soil}^{sun} and B_{soil}^{shade}.

4. Approximate the spectral BRDF $f_{canopy}(\cdot)$ of the walnut canopy by :

$f_{canopy}(\theta_v, \phi_v; \theta_s, \phi_s; \lambda) =$

$$\frac{1}{E_0 \cos\theta_s}\Big[P_{leaf}^{sun}\overline{(\vec{n}_{leaf} \cdot \vec{n}_{sun})B_{leaf}^{sun}} + P_{leaf}^{shade} \cos\theta_s \overline{B_{leaf}^{shade}} + P_{soil}^{sun} \cos\theta_s \overline{B_{soil}^{sun}} + P_{soil}^{shade} \cos\theta_s \overline{B_{soil}^{shade}}\Big]$$

5. Plot spectral BRDF for given view/sun directions. In Fig.5 a scatterplot shows how the spectrum of a canopy differs from the reflectance spectrum of a single leaf. Note that the curves bend upwards for high leaf reflectances similar to Fig. 3.

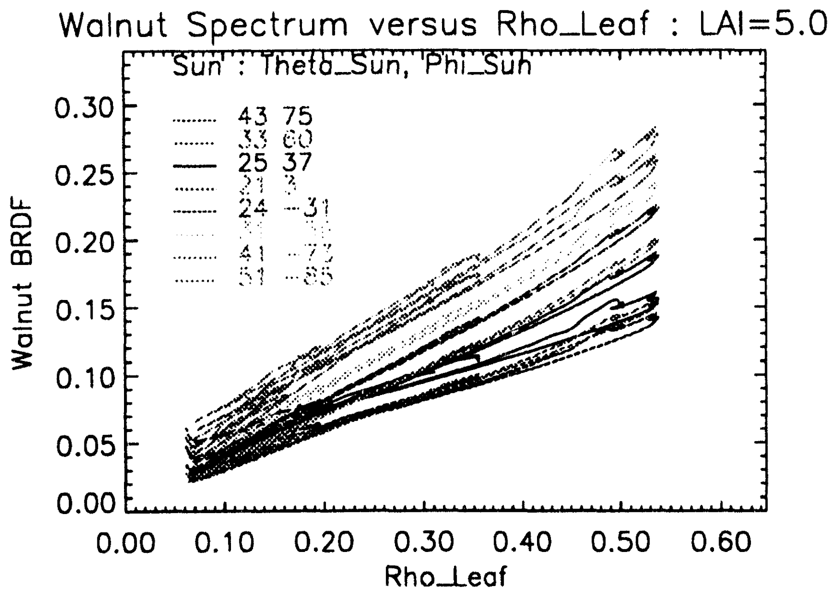

Figure 5: Canopy averaged BRDF for a walnut tree versus single leaf reflectance spectrum as a function of sun angles from 0.4 to 2.4 μm

6 Conclusions

- Radiosity models show nonlinear spectral mixing effects due to canopy architecture, varying illumination and viewing directions, soil ,bark, etc.
- For a given view direction and varying sun angles, the canopy architecture influences the probabilities of seeing illuminated surfaces and thus the spectral signature
- For a given sun angle and variable viewing directions, the canopy architecture has a small influence on the spectral signature

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