A hybrid Radiosity/Raytracing Model to interpret hyper-spectral Data over Vegetation

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1 Introduction

Project: Accelerated Canopy Chemistry Program, 1992-96

Goals:

- Investigate how the canopy architecture changes the leaf chemical signature
- Investigate effects due to illumination, background and terrain on the spectral signatures.

Tools:

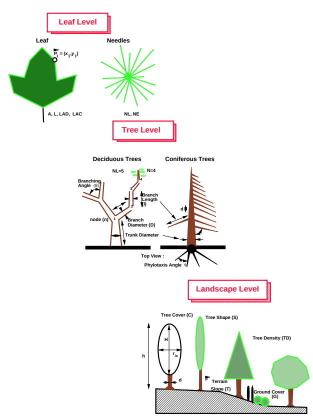
- Leaf and soil reflectance models
- Hybrid radiosity / raytracing model
- Hyperspectral data from AVIRIS, HYDICE,...
- Realistic tree geometry generators (new since 1996!)

2 Modeling Requirements

- Leaf Level Reflectance Models: Compute leaf reflectance and transmittance as a function of water content in $[cm]$, chlorophyll pigment a+b concentration in $[\mu g cm^{-2}]$ and cell structure ⇒ PROSPECT, Jacquemoud and Baret (1990) (www.diderotp7.jussieu.fr/Led/LED_prospect_e.htm)
- Soil Reflectance Models: Compute soil BRDF as a function of soil type, roughness and water content ⇒ SOILSPEC, Jacquemod and Baret (1992)
- Canopy Reflectance Models:
  1. Represent discrete phytoelements (leaves, needles, stems, fruits, etc.) with specified size, location, orientation, reflectance and transmittance.
  2. Include transmission and multiple reflections between leaves must be taken into account.
  3. Allow direct and indirect illumination.
  4. Consider shadowing within the canopy and on the ground.
  5. Allow calculation at any wavelength with spectrum transfers between leaves.

  ⇒ Radiosity model, Borel and Gerstl (1993)

3 Leaf, Canopy and Landscape Level Reconstruction



Levels of reconstruction

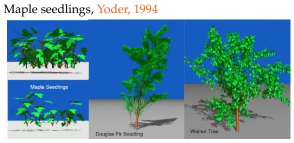
4 Sensitivity Analysis of Canopy Chemistry Signatures

1. Atmospheric conditions
2. Sun / View geometry
3. Sensor characteristics, such as spectral and spatial resolution
4. Adjacent terrain
5. Canopy spectral BRDF

4.1 Tree Reconstruction

Existing measurements:

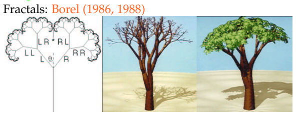
- Walnut tree geometry, Martens et al. (1991); Ustin et al. (1991)
- Douglas fir, Vanderbilt, Dungan et al, (1994)
- Maple seedlings, Yoder, 1994



Examples of reconstructed canopies

Existing theoretical models:

- Fractals: Borel (1986, 1988)



Examples of fractal trees generated (Borel, 1987)

- Lindenmayer systems:

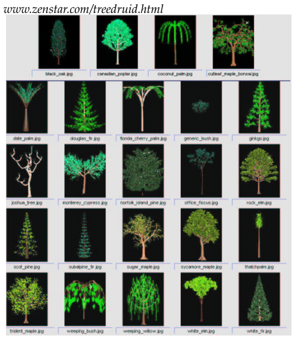
Prusinkiewicz and Lindenmayer (1990); Goel, Knox and Norman (1991)

Example of an L-system description and its 3-D tree:

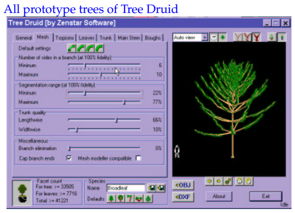
```
#A=F[&(a0)'(r2)!(wr)BL ]>(c)'(r1)!(wr)A
#B=F[-(a2)'(r2)!(wr)$CL]    '(r1)!(wr)C
#C=F[+(a2)'(r2)!(wr)$BL]    '(r1)!(wr)B
```

- Hybrid L-system & fractal models:

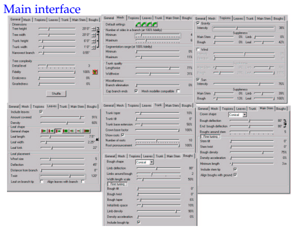
TreeDruid: *www.zenstar.com/treedruid.html*



All prototype trees of Tree Druid

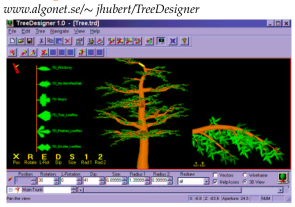


Main interface



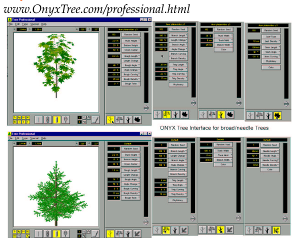
Detailed interface

Tree Designer: *www.algonet.se/~ jhubert/TreeDesigner*

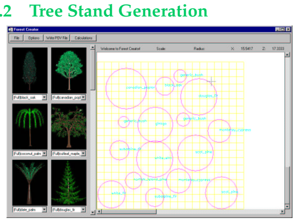


TreeDesigner interfaces

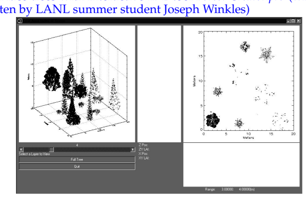
Onyx Tree: *www.OnyxTree.com/professional.html*



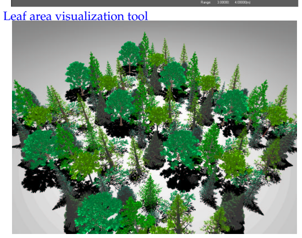
4.2 Tree Stand Generation



Place trees with interactive IDL tool *Forest Creator.pro* (written by LANL summer student Joseph Winkles)



Leaf area visualization tool

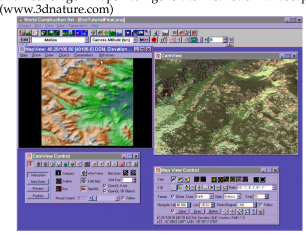


Rendered tiled tree stand using POVRAY 3.1 www.povray.org

4.3 Landscape Reconstruction

Generate landscapes with different ecosystems to model large scale BRDF effects using digital terrain models (DTM), land cover classification maps,...:

World Construction Set Allows import of DEM and coverage maps to generate realistic landscapes (www.3dnature.com)



Bryce 4 A terrain generation and visualization program with many procedural capabilities to model different land forms (www.metacreations.com)

5 Hybrid Radiosity/Raytracing

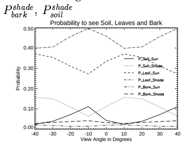
Problem: Radiosity calculations numerically difficult for hyperspectral scenes (Solve large (~ 100k x 100k) matrix $N_{channel}$ times and render the solution from M directions → Tera FLOPS).

Solution Steps (short):

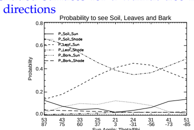
1. Calculate probabilities of seeing illuminated and shaded surfaces as a function of view angles.
2. Use a simpler radiosity model (N-layer model) to calculate the average spectra on sunlit and shaded leaves, branches and ground.
3. Combine steps 1 & 2 to compute an approximation of the hyperspectral BRDF

Solution Steps (long):

1. Raytrace images of a part of a reconstructed tree for a given geographical location, dates and given times. Use nadir view or off-nadir views ($\theta_v = -40^0, -30^0, .., +30^0, 40^0$).
2. Compute image statistics such as (see Borel and Gerstl (1994)):
   - Probabilities of seeing illuminated surfaces : $P^{sun}_{leaf}, P^{sun}_{bark}, P^{sun}_{soil}$
   - Probabilities of seeing shaded surfaces : $P^{shade}_{leaf}, P^{shade}_{bark}, P^{shade}_{soil}$

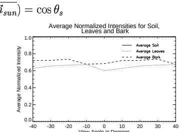


Canopy averaged probabilities of seeing illuminated and shaded surfaces for a walnut tree from different view directions

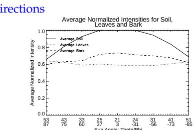


Canopy averaged probabilities of seeing illuminated and shaded surfaces for a walnut tree from nadir view

- Average cosine of angle between the surface normal and sun vector for visible illuminated surfaces : $\langle\vec n_{leaf}\cdot\vec n_{sun}\rangle$, $\langle\vec n_{bark}\cdot\vec n_{sun}\rangle$, $\langle\vec n_{soil}\cdot\vec n_{sun}\rangle = \cos\theta_s$



Average cosine of angle between the surface normal and sun vector for visible illuminated surfaces as a function of view directions



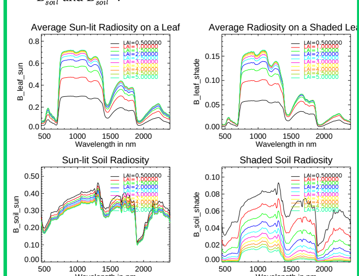
Average cosine of angle between the surface normal and sun vector for visible illuminated surfaces as a function of illumination directions

3. Approximate radiosities for the canopy by using the N-layer model (see Borel and Gerstl (1994, p.409)) with a total LAI similar to the canopy ($LAI \sim 5$), measured leaf reflectances ρ and transmittances τ and assumed soil reflectance ρ_s ($\rho_{bark} = 0.$) :

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

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

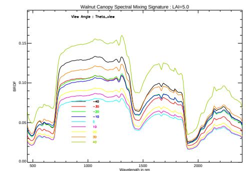
B^{sun}_{soil} and B^{shade}_{soil}.



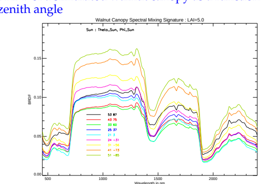
Canopy averaged spectra for a walnut canopy

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

$$f_{canopy}(\theta_v,\phi_v;\theta_s,\phi_s;\lambda) = \frac{1}{E_0\cos\theta_s}\Big[P^{sun}_{leaf}\langle\vec n_{leaf}\cdot\vec n_{sun}\rangle B^{sun}_{leaf} + P^{shade}_{leaf}\cos\theta_s B^{shade}_{leaf} + P^{sun}_{soil}\cos\theta_s B^{sun}_{soil} + P^{shade}_{soil}\cos\theta_s B^{shade}_{soil}\Big]$$



BRDF of a simulated walnut canopy as a function of view zenith angle

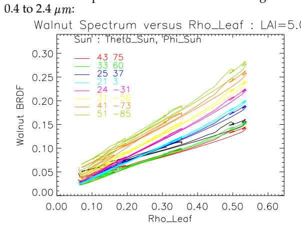


BRDF of a simulated walnut canopy as a function of illumination direction

6 Results:

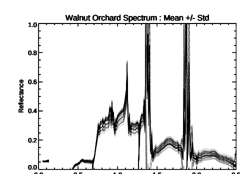
The following statements can be made from our simulations :

- 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:



→ Curvature for high reflectances due to nonlinear spectral mixing

- For a given view direction and varying sun angles the canopy architecture influences the probabilities of seeing illuminated surfaces and thus the spectral signature (e.g. for a location 45^0 N on June 21 between 10 am and 2pm the spectrum changes are about 20 % in the NIR (800-2400 nm) and about 25 to 35 % in the visible for an LAI=0.5,...,5).
- For a given sun angle and variable viewing directions the canopy architecture has an effect on the spectral signature (e.g. for LAI=.5,..,5. and view angles from -40^0 to 40^0 the spectrum changes are about 15 % in the NIR and up to 40 % in the visible).
- AVIRIS data over a walnut orchard shows spectral variability due to canopy architecture



AVIRIS derived reflectance over a walnut orchard in Winters, CA.

7 Conclusions

- Highly realistic geometric descriptions are now widely available to model canopy spectral effects
- Spectrum of each leaf is a very complex function of its surroundings
- 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 an effect on the spectral signature for sparse canopies
- For the model-constructed walnut tree over 90% of the signal comes from the canopy leaves and less than 2% from illuminated bark

8 Future Work

More theoretical & field work in this area is needed to quantify the spectral variability as a function of landscape parameters, tree architecture and phytoelement size and orientation.

9 Acknowledgements

Scott N. Martens (UC Davis and LANL) provided the geometric data for the walnut trees and reconstructed them using special QBasic programs and Rayshade. Barbara Yoder (Oregon State), Vern Vanderbilt, Jenifer Dugan and Lee Johnson (NASA Ames) provided the geometric and spectral data for the maple and douglas fir seedlings. The ACCP and Remote Sensing Science Program provided funds for this research was managed by Diane Wickland (NASA HQ).

Data availability: *ftp://ftp.nis.lanl.gov/pub/users/borel/*