VEGETATION STRUCTURE FROM QUANTITATIVE FUSION OF HYPERSPECTRAL OPTICAL AND RADAR INTERFEROMETRIC REMOTE SENSING

Gregory P. Asner,[1] Robert N. Treuhaft,[2] Beverly E. Law[3]

1. Introduction

One of today's principal objectives of remote sensing is carbon accounting in the world's forests via biomass monitoring. Determining carbon sequestration by forest ecosystems requires understanding the carbon budgets of these ecosystems, including carbon stored in plant mass above and below ground, and in soils. The net carbon uptake per year, which is related to the rate of change of biomass, is extremely important in long-term full carbon accounting. Foliage can account for up to 40% of the rate of change of biomass. Aboveground vegetation biomass is difficult to estimate from any type of remote sensing observation because the radiation field (at any wavelength) is not uniquely sensitive to variation in biomass. A combination of vegetation properties such as canopy height and shape and the characteristics, amount and architectural placement of foliage and wood creates non-unique radiative signatures that cannot be directly interpreted as biomass. Inference of any one of these structural parameters, let alone biomass, from remote sensing observations is an under-determined inverse problem. Therefore, methods that employ observations most sensitive to a diverse array of vegetation structural properties are needed together in linking radiative signatures to structure and, by robust correlative linkage, to aboveground biomass.

The objective of this project is to demonstrate a novel approach to estimating three-dimensional vegetation structure by combining the information in hyperspectral optical Airborne Visible Infrared Imaging Spectrometer (AVIRIS) and microwave interferometric and polarimetric Topographic Synthetic Aperture Radar (TOPSAR) data. Recent work shows the very high sensitivity of hyperspectral-optical remote sensing signatures to canopy cover and leaf area index (LAI) (e.g., Asner et al. 1998, Asner and Lobell 2000, 2001). Recent work with interferometric and polarimetric synthetic aperture radar (IP-SAR) shows strong sensitivity to canopy height and the vertical distributions of scatterers (Treuhaft et al. 1996, Treuhaft and Siqueira 2000). Together, optical and IP-SAR methods provide a well-populated observation vector which, theoretically, can be used to both improve canopy parameter estimates and to develop completely new measurements previously unavailable through a single-signature remote sensing approach.

The work of this project began with data acquisition from TOPSAR and AVIRIS over coniferous forest sites in central Oregon. During this period, 20 one-hectare coniferous forest stands, which spanned the structural diversity of the region, were identified and characterized with field measurements of biomass, LAI, vertical tissue density profiles, and other parameters. A tight interactive loop between these field measurements and the remote sensing analysis enabled two firsts: 1) Quantitative analysis of multi-baseline interferometric data yielded estimates of relative vegetation density profiles of some of the field-measured stands, and 2) Analysis of hyperspectral data produced simultaneous estimates of LAI and fractional vegetation cover for these forest stands. In our first approach to combining this vegetation structure information, the AVIRIS-derived biophysical properties were used normalize the TOPSAR-derived relative density profiles to estimate LAI. A second, more aggressive approach, involves simultaneous estimation of profile parameters from the combined microwave and hyperspectral data set, which will be attempted in 2000-2001.

2. Methods and Results

2.1 Site Description

We conducted the study on the east side of the Cascade Mountains in central Oregon, where there is a strong climatic gradient and forest transition from Douglas-fir (*Pseudotsuga menziesii*) and grand fir (*Abies grandis*) to the dry eastern extent of ponderosa pine (*Pinus ponderosa* var. Laws). The climate of the ponderosa pine zone is semi-arid (annual rainfall: 350-760 mm), with minimal summer precipitation. The overall study region was approximately 576 km^2. Within this region, we located twenty 100 x 100-m plots along an east-west swath that includes Douglas fir,

[1] Department of Geological Sciences and Environmental Studies Program, University of Colorado, Boulder, CO
[2] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
[3] Department of Forest Science, Oregon State University, Corvallis, OR

grand fir, larch (*Larix occidentalis*), cedar, and ponderosa pine forests. About 75% of the plots are totally *P. ponderosa* or mixes with Douglas fir, grand fir (*Abies grandis*), or cedar (*Calocedrus decurrens*). The soil texture in the study area ranges from a gravelly loam surface in the *A. grandis*/*P. menziesii* forests closer to the mountains, to sandy pumice soils in *P. ponderosa* forests. A few of the pine sites were less productive, existing on a perched water table on a clay layer closer to the surface. We selected plots to encompass a range of stand densities (trees/area). Two of the plots were primarily *A. grandis*/*P. menziesii*, two were *L. occidentalis* (one of which had been heavily logged and only had a few trees on it), and one was dominated by *C. decurrens*. The pine sites include young regenerating forests (< 10 m tall), mature, and old-growth forests.

Here, we only report the results from plots 1-3 of our study. All other plots are currently being analyzed and evaluated against field data.
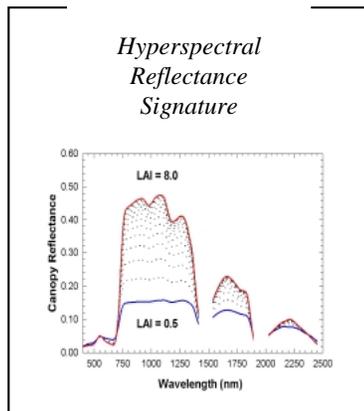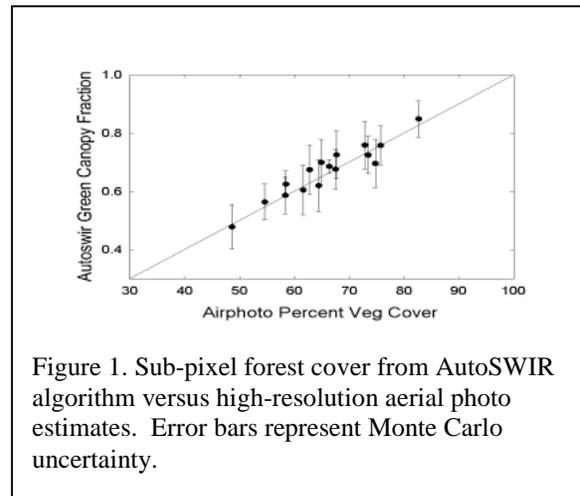
2. 2 AVIRIS Data

NASA's AVIRIS collects upwelling radiance data in 224 optical channels (~10 nm bandwidth at full-width half-maximum [FWHM]) covering a spectral range of 380-2500 nm (Green et al. 1998). AVIRIS was flown over the study region on June 10, 1999 on the NASA ER-2 aircraft at 20 km altitude, creating approximately 17 x 17 m pixels in the resulting image data. Radiance data were converted to apparent surface reflectance using the ATREM atmospheric code (Gao et al. 1993), which employs the 6S model scattering code for atmospheric gases (Vermote et al. 1996). Further corrections for reflectance were made by using a large (dark) lake and (bright) cumulous clouds in an empirical line fitting routine (Environment for Visualizing Images [ENVI™] software, BSD Inc., Boulder, CO). The Atmospheric Removal Program (ATREM)-corrected reflectance values were used to create a gain and offset for each band, which were then applied to complete the reflectance calibration.

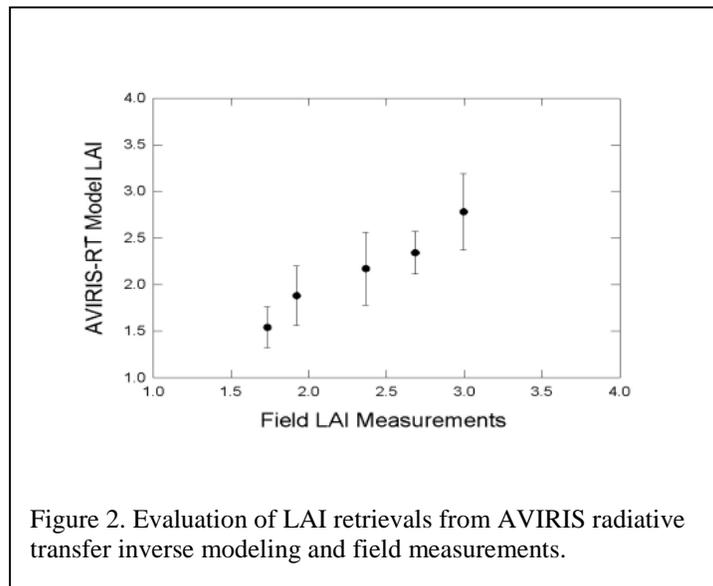## 2.3 LAI and Vegetation Cover from Imaging Spectrometry

AVIRIS data were used to estimate both the fraction of green-canopy cover and its LAI within each image pixel. Canopy cover was derived using a method that isolates the effects of cover variation from LAI in the shortwave spectrum (Asner and Lobell 2000, 2001). This method employs the derivative (shape) of the pixel reflectance spectrum in the shortwave infrared (SWIR) region of 2080-2280 nm. These spectra were used in a linear mixture model to estimate cover, as was done by Lobell et al. (in press) with proven accuracy (Figure 1). The result was a map of canopy cover fraction within each AVIRIS pixel, which was then used to constrain this parameter within a physical model of radiation transport in the hyperspectral-optical domain (Asner 1998, 2000).

Figure 1. Sub-pixel forest cover from AutoSWIR algorithm versus high-resolution aerial photo estimates. Error bars represent Monte Carlo uncertainty.

The physical model follows the form:

Hyperspectral Reflectance Signature

Solar/Viewing Geometry
Green Canopy Cover
Canopy LAI
Canopy Leaf Angle Distribution
Leaf Optical Properties

(1)

From these parameters, a pixel-level reflectance spectrum is simulated. The model was numerically inverted to estimate LAI, while using as input the vegetation cover fraction derived from spectral mixture analysis in the SWIR region. Other parameters, including leaf optical properties and background reflectance, were estimated from a large spectral database constructed by Asner (1998) and updated with spectra from Oregon. These parameters were randomly selected from the database 50 different times, and a Monte Carlo analysis was performed on the LAI estimates. Viewing and solar geometry as well as leaf angle distribution were fixed; geometry was known from the AVIRIS ephemeris data, while leaf angle distribution was set to plagiophile (deWit 1965). The model inversion (n = 50 times per pixel using randomly selected leaf optical and surface spectra) was achieved using a numerical optimization approach that minimizes the difference between simulated and measured (AVIRIS) spectra. For the selected study plot, the LAI derived from inverse physical modeling closely matched the value derived in the field (Figure 2). Error range represents uncertainty in leaf and background surface optical properties during the Monte Carlo analysis.

Figure 2. Evaluation of LAI retrievals from AVIRIS radiative transfer inverse modeling and field measurements.

2.4 TOPSAR Data

Interferometric TOPSAR data (Zebker et al. 1992) were acquired from three different altitudes, 8 km, 4 km, and 2 km, over the region and study sites. Because interferometric sensitivity is proportional to the baseline divided by the altitude (Treuhaft et al. 1996), flying multiple altitudes is equivalent to acquiring multiple baselines. At each altitude, single-transmit and ping-pong mode produced two baselines. The physical baseline is 2.45 m at C-band, and that is effectively doubled with ping-pong mode. Polarimetric zero-baseline data were also acquired at the 8-km altitude.
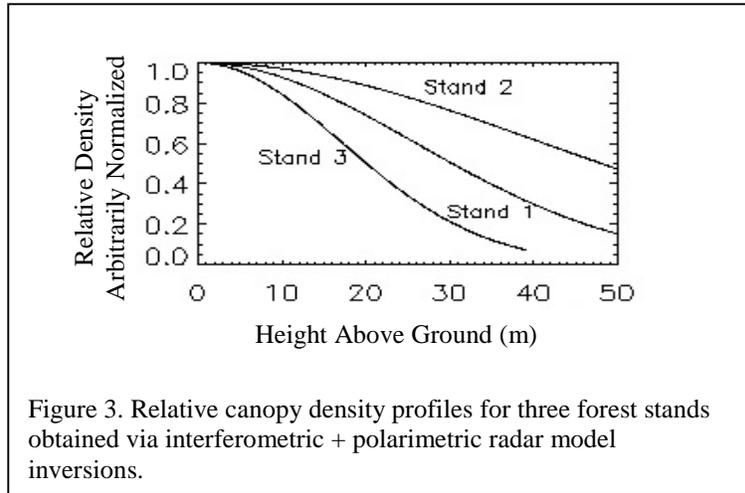
2.5 Canopy Height and Relative Vertical Canopy Density from Interferometric Radar

A discrete-scatterer physical model was used to estimate canopy height and relative vertical canopy density. The model simulates a randomly oriented vegetation volume over a slightly rough ground surface. The vegetation volume is allowed to have a scatterer-number density dependence on altitude. Gaussian or multiple Gaussian density profiles are allowed in the model. The choice of a Gaussian model is based on many field observations indicating Gaussian-like profiles. From Treuhaft et al. (1996) and Treuhaft and Siqueira (2000), at C-band, the interferometric cross-correlation of signals, and the polarimetric horizontal to vertical power ratio (HHHH/VVVV) can be expressed in terms of vegetation parameters:

$$\begin{pmatrix} IntAmp_{8\,km} \\ IntPhase_{8\,km} \\ IntAmp_{8\,km-ping} \\ IntPhase_{8\,km-ping} \\ IntAmp_{4\,km} \\ IntPhase_{4\,km-ping} \\ IntAmp_{2\,km} \\ IntPhase_{2\,km-ping} \\ PolHHHH/VVVV \end{pmatrix} = M \begin{pmatrix} VegetationHeight \\ PeakExtinction \\ DensityCenter \\ DensityStd \\ Ground/Vol \\ GroundDiel \\ Topography \end{pmatrix} \qquad (2)$$
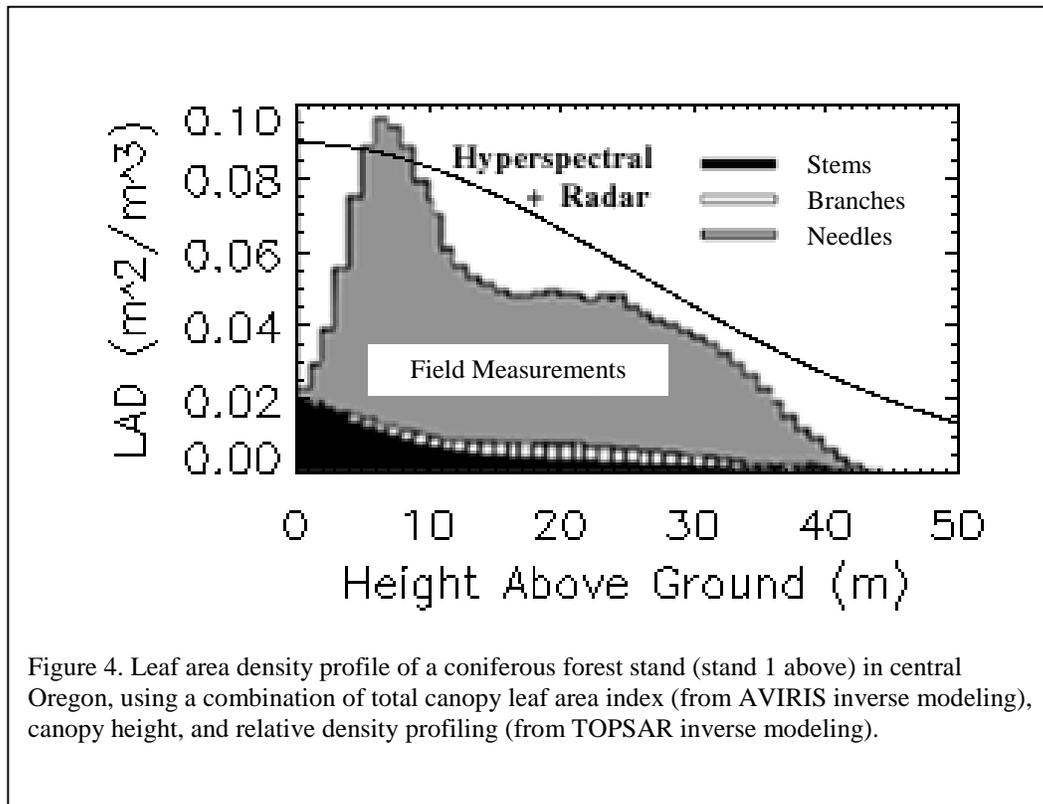
Here, *IntAmp* is the interferometric amplitude and *IntPhase* is the interferometric phase. The physical model (M) relating the observations on the left in equation (2) to the parameters on the right relies on randomly oriented volumes over slightly rough ground surfaces. For this first attempt at estimating the Gaussian vertical profile parameters, the interferometric amplitudes, the polarimetric horizontal to vertical power ratio, and only the 8-km interferometric phases were employed.

Figure 3 shows three Gaussian profiles of scatterer number density for three forest stands, calculated from the first, third, and fourth parameters in equation (2). The profiles are relative in that the peak density for each stand is set to 1.0. Stand 1 is a mixed-height ponderosa pine canopy with most trees about 12 m tall and a smaller number of trees at about 40 m. Stand 2 is old growth, and it has a more uniform density profile with an average canopy height of 40 m. Stand 3 is a young, dense stand about 15 m in height. The profiles exhibit qualitative agreement with field measurements, but some discrepancies are apparent as well.

Figure 3. Relative canopy density profiles for three forest stands obtained via interferometric + polarimetric radar model inversions.

2.6 Combining the Results from Imaging Spectrometry and Interferometric Radar

The canopy-level LAI results derived from AVIRIS data and inverse modeling were combined with the canopy height and density profiles from IP-SAR inverse modeling to estimate leaf area density (LAD) in a forest canopy (Figure 4). The LAD profile roughly matches the profile that was measured in the field for this study plot. Further advances are under way as the relative density profile analysis from TOPSAR is being improved. For a first attempt, we contend that the current result is both ecologically realistic and within the overall variability of LAD found across all field plots. To our knowledge, this is the first leaf area density profile retrieved through the fusion of hyperspectral-optical and interferometric + polarimetric radar analysis.

Figure 4. Leaf area density profile of a coniferous forest stand (stand 1 above) in central Oregon, using a combination of total canopy leaf area index (from AVIRIS inverse modeling), canopy height, and relative density profiling (from TOPSAR inverse modeling).

3. Conclusions

Imaging spectrometry and interferometric + polarimetric radar provide access to unique vegetation parameters. These data can be combined after individual sensor-based parameter estimation (as demonstrated here) or in a unified physical modeling approach (not shown but currently being done by the authors) to estimate a suite of ecologically and biophysically important parameters. These include:

- Sub-pixel vegetation cover
- Canopy leaf area index
- Canopy height
- Canopy leaf area density

The unified physical modeling approach, in which optical and radar signatures are ingested into the single physical model simultaneously, may be more robust, since the solution domain for a larger observation vector is usually narrower. That is, by increasing the number of unique observations, both the number and accuracy of the estimated parameters usually increase. As we finish the *post priori* fusion of spectrometer and radar parameters for all of our study plots in Oregon, we will also be deriving this unified optical and microwave physical model.

4. Acknowledgements

5. References

Asner, G.P. (1998), Biophysical and biochemical sources of variability in canopy reflectance, *Remote Sens. Environ.* 64:234-253.

Asner, G.P. (2001), A hyperspectral photon transport system to simulate imaging spectrometer observations of terrestrial ecosystems. *Summaries of the Ninth JPL Airborne Earth Science Workshop.*

Asner, G.P., and Lobell, D.B. (2000), A biogeophysical approach to automated SWIR unmixing of soils and vegetation. *Rem. Sens. Environ.*, in press.

Asner, G.P., and Lobell, D.B. (20001), AutoSWIR: A spectral unmixing algorithm using 2000-2400nm endmembers and Monte Carlo analysis. *Summaries of the Ninth JPL Airborne Earth Science Workshop.*

Asner, G.P., Wessman, C.A., and Schimel, D.S. (1998), Heterogeneity of savanna canopy structure and function from imaging spectrometry and inverse modeling, *Ecol. Applic*. 8:1022-1036.

deWit, C.T., *Photosynthesis of Leaf Canopies*, Agricultural Research Report 663, Pudoc Publications, Wageningen, The Netherlands, 1965.

Gao, B.-C., Heidebrecht, K.B., and Goetz, A.F.H. (1993), Derivation of scaled surface reflectance from AVIRIS data. *Rem. Sens. Environ.* 44:165-178.

Green, R.O., Eastwood, M.L., and Williams, O, Imaging spectroscopy and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), *Rem. Sens. Environ.,* 65, 227-240, 1998.

Lobell, D.B., Asner, G.P., Law, B.E., and Treuhaft, R.N. (in press), Sub-pixel canopy cover estimation of coniferous forest using SWIR imaging spectrometry. *Journal of Geophysical Research*

Treuhaft, R.N., Madsen, S.N., Moghaddam, M., and van Zyl, J.J. (1996), Vegetation characteristics and surface topography from INSAR. *Radio Sci* 31:1449-1485.

Treuhaft, R.N. and Siqueira, P.R. (2000), Vertical structure of vegetated land surfaces from interferometric and polarimetric radar. *Radio Sci.* 35:141-177.

Vermote, E.F., et al. (1996), Second simulation of the satellite signal in the solar spectrum, 6S: an overview. *IEEE Trans. Geosci. Rem. Sens*. 35:675-699.

Zebker, H.A., Madsen, S.N., Martin, J., Wheeler, K.B., Miller, T., Lou, Y., Alberti, G., Vetrella, S., and Cucci, A. (1992), The TOPSAR interferometric radar topographic mapping instrument. *IEEE Trans. Geosci. Rem. Sens.* 30:933-940.