Stochastic Radiative Transfer Model Simulation of LIDAR Waveform over 3D Canopy from Three Field Campaigns in Support of DESDYNI Mission

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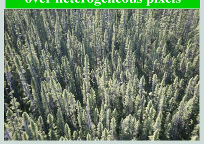
Abstract The three-dimensional structure of a forest – its composition, density, height, crown geometry, within-crown foliage distribution and properties of individual leaves – is related to its above-ground live biomass, and hence, the amount of carbon. The development of remote sensing technology for the estimation of forest biomass is therefore a high priority. Active waveform lidar sensors provide direct estimates of tree and crown height and vertical canopy profiles. The 3D canopy structure has a distinct impact on the lidar waveform, which makes it difficult to retrieve the vertical canopy structure in a straightforward way. In this study, we try to quantify the effect of 3D canopy structure on lidar waveform by utilizing the pair correlation function, which is a key input parameter to the stochastic radiative transfer equation. The pair correlation function is the most natural and physically meaningful measure of canopy structure over a wide range of scales. Sites in Harvard Forest, Sierra Nevada and La Selva were selected in the data analysis and the vertical distributions of pair correlation functions were retrieved from the 3D scenes constructed from allometry (in Harvard Forest and La Selva) and ground lidar system – Echidna (in Sierra Nevada). The simulated lidar waveforms were calculated using a simplified version of the time-dependent stochastic radiative transfer model. Airborne lidar data from LVIS over both sites were used to validate the simulated waveform. The results show that (a) one cannot simulate ground return for dense vegetation and thus much data could be interpreted incorrectly if spatial correlation is ignored, and (b) the spatial correlation has direct impact on the shape of the lidar waveform.

1D VERSUS 3D APPROACH

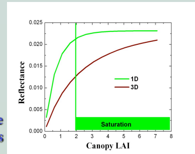
1D approach: First averages the canopy structure and then solves the 1D RT equation with the average characteristics

3D approach: First solves the 3D RT equation for each realization of canopy structure and then averages the solutions

Satellite-borne sensors measure *mean radiances* over heterogeneous pixels



This figure shows that the use of 1D and 3D approaches can result in different relationship between mean characteristics of canopy structure and canopy leaving radiation. In this example, the 3D approach has captured two important effects of canopy structure on canopy reflectance: the reflectance saturation occurs at a higher LAI and canopy reflectance is lower than 1D approach predicts.



Stochastic approach: Aims to derive and solve a closed system of equations whose solutions are mean characteristics of the 3D field.

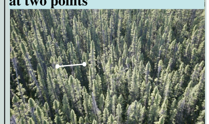
Vainikko-Titov equations:

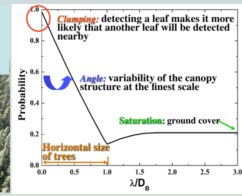
$$|\mu| U(z,\Omega) = \int_0^z K(z,\xi,\Omega)[S(\xi,\Omega) - \sigma(\Omega)U(\xi,\Omega)]d\xi + |\mu| U_0(z,\Omega), \quad \mu < 0$$

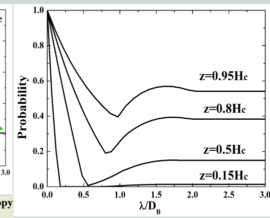
$$|\mu| \bar{I}(z,\Omega) = \int_0^z p(z,\xi)[S(\xi,\Omega) - \sigma(\Omega)U(\xi,\Omega)]d\xi + |\mu| U_0(z,\Omega), \quad \mu < 0$$

MEASURE OF 3D CANOPY STRUCTURE

Pair correlation function: probability of finding simultaneously phytoelements at two points

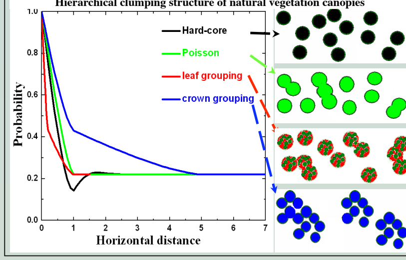






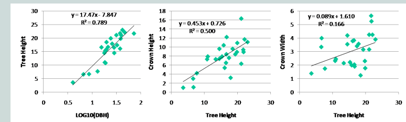
Monte Carlo generated conditional pair correlation function for a vegetation canopy consisting of identical cylindrical (middle panel) and conical (right panel) in shape trees.

Hierarchical clumping structure of natural vegetation canopies

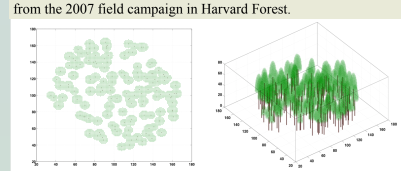


The pair correlation function is the most natural and physically meaningful measure of the canopy structure over a wide range of scales. The stochastic radiative transfer equations naturally admit the measure and thus provide powerful means to investigate the 3D canopy structure from space.

ANALYSIS OF FIELD DATA



The figure shows the linear regression relationships for DBH vs. tree height, tree height vs. crown height, and tree height vs. crown width. The analysis is based on measurements of 27 hemlock trees from the 2007 field campaign in Harvard Forest.



3D scene simulated from allometry of Harvard Forest. The upper left panel is an illustration of the view from above and the upper right panel is the same scene from a different view angle. Crowns were modeled as hemi-ellipsoidal for demonstration.

The figure to the right shows 14 LVIS waveform measurements within this study region used to evaluate the model performance.

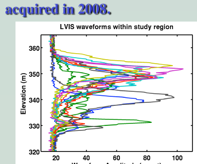
Data used:

Field measurements of canopy structural parameters at various locations were taken as part of the Echidna Validation Instrument (EVI) campaigns in August, 2007 and summer, 2008 (organized by Dr. Strahler of Boston University).

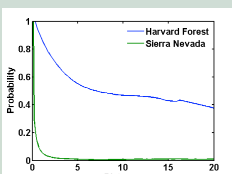
***First study site*: Hemlock stand in Harvard Forest, MA (HF).**

***Second study site*: low-density, high-elevation red fir stand in Sierra National Forest, CA (SNF).**

Airborne Laser Vegetation Imaging Sensor (LVIS) data for Harvard Forest were acquired in the summer of 2003. LVIS data for CA site were acquired in 2008.



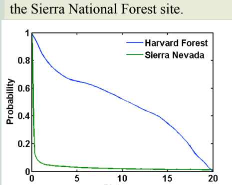
PAIR CORRELATION FUNCTION FROM FIELD



Finding 1:

The crown shapes and tree distributions follow stochastic geometry. It allows for the parameterization of vertical and horizontal canopy geometry in terms of the pair correlation function.

Conditional pair correlation function in the horizontal direction generated from field measurements collected at Harvard Forest and Sierra National Forest test sites. The pair correlation function (PCF) was calculated directly from the EVI point cloud for the Sierra National Forest site.

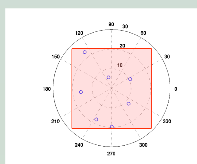


Finding 2:

The difference between HF and SNF is due to the use of different scales. The finest scale at HF is limited to crown level, while the SNF site uses a finer scale (leaf level) from the EVI instrument.

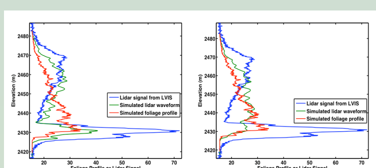
Conditional pair correlation function in the vertical direction generated from field measurements collected at Harvard Forest and Sierra Nevada test sites. Harvard Forest exhibits a decrease in PCF with large distance corresponding to the relatively low crown heights.

3D CANOPY IMPACT ON WAVEFORM SIMULATION



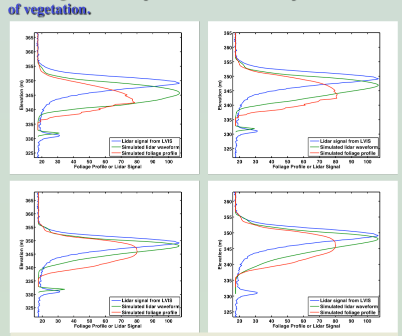
A mean waveform from several LVIS beams located within the study area is used for comparison. The center point corresponds to the center in the ground measurement. The red area is the area for the generation of 3D scene.

Ignoring spatial correlation can lead to a misinterpretation of lidar waveform



Comparison of simulated and measured lidar waveforms for the SNF. The left panel shows the 3D simulation. The right panel shows the 1D simulation using the same foliage profile calculated from EVI measurements. The LAI value is equal to 2, as per field measurement.

1D approach cannot simulate ground return in the case of dense vegetation. Shape of crown affects the spatial correlation of vegetation.

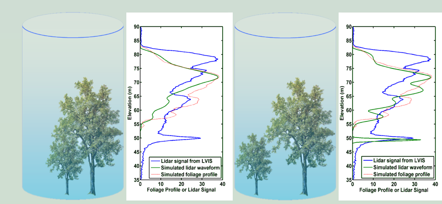


Comparison of simulated and measured lidar waveforms for the HF site. The top left panel shows simulations using conical crowns. The top right panel shows simulations using hemi-ellipsoidal crowns. The bottom left panel shows simulations using ellipsoidal crowns. The bottom right panel shows a 1D simulation using the same foliage profile as the bottom left panel. The LAI value in all cases is equal to 4, as per field measurement.

CONCLUSION WITH ANOTHER EXAMPLE

We conclude that:

- **one can not simulate ground return for dense vegetation if spatial correlation is ignored and thus a lot of data could be interpreted incorrectly**
- **the spatial correlation has direct impact on the shape of the lidar waveform**



Example showing that the impact of spatial correlation results for different lidar waveforms from the same vertical profile. The LVIS data and field measurements are from the tropical forest experimental site in La Selva, Costa Rica. Structural parameters (tree height, crown height, crown radius) are obtained from site-specific allometries. The left figure shows the foliage profile and return signal without horizontal clumping. The right figure shows the same foliage profile with the correct spatial correlation included. *Note that the simulation from the right figure can capture peak returns from lower tree crowns.*

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ACKNOWLEDGEMENTS

This research was funded by the JPL, California Institute of Technology under contract 1259071, by the NASA under Grants NNX08AE81G, NNX09AI30G, NNX08AL55G, NNX08AE89A, and by NASA Headquarters under the NASA Earth and Space Science Fellowship Program under Grant NNX07AO41H.