Using Monte-Carlo ray tracing to investigate the measurement of forest parameters with the Echidna™ laser scanner.

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ABSTRACT:

A Monte-Carlo ray tracer has been developed from a previous system to simulate a ground based, full waveform laser ranger, such as the Echidna™. Overlapping scans have been simulated using a geometric model of a Scots pine forest, with a sampling density far higher than would be feasible to collect in reality. An initial investigation has been carried out into the use of the simulated data to create a 3D volumetric canopy model. The algorithms needed are described and the impact of extra information, such as a second waveband on model accuracy is discussed.

INTRODUCTION

Satellites are the only realistic way to measure forests on a global scale. Passive systems and synthetic aperture radar tend to saturate with only moderately dense woodland (Lefsky et al. 1999) and are not suitable for measuring forests for the understanding of global processes. Active systems have, so far, only measured in one view direction. Unfortunately the parameters of interest couple together within the signal and cannot be measured from a single zenith.
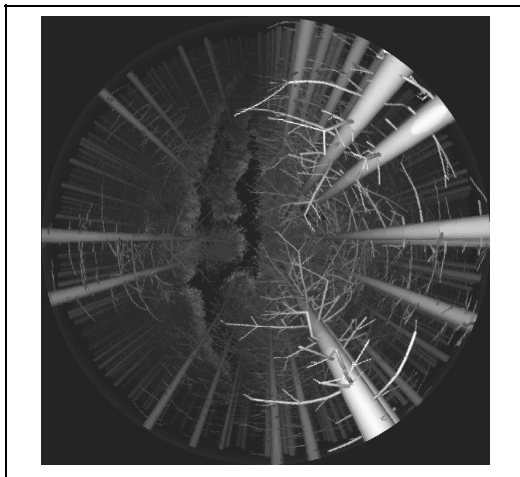

Figure 1. Hemispherical ray traced image of the Thetford model as seen by Echidna™. Brightness is scaled by range.

Lovell et al. (2003) have developed a ground based, full waveform, multi-angular laser scanner called Echidna™ which has the potential to decouple many of the contributing factors. Laser scanning can provide more accurate data than all but the most labour intensive direct methods (Danson et al. 2007) and will allow calibration of air and space borne instruments.

Through computer simulations it is hoped to gain a better understanding of how light interacts with a canopy to produce the measurements of an instrument like Echidna.

A Monte Carlo ray tracer has been developed from the earlier ray tracers of Lewis (1999) to simulate echidna. In addition to the data available to the echidna prototype, beams with additional wavelengths can be simulated and parameters that would be impossible with a real instrument, such as the contribution from multiple scattering and information about the materials visible to the beam can be recorded. Results inverted from the data available to a real instrument can be compared to this extra information to assess the accuracy of the inversion.

Inverting lidar data

There has been considerable work put in to deriving forest information from lidar and other remotely sensed data. Some of these methods have been shown to be successful; however they tend to make estimates of just a few forest parameters (Danson et al 2007) or are not directly based upon the physical properties of the scene, relying upon species specific look up tables created from simulations (Koetz et al. 2007) or upon fitting an empirical model to the observations (Coops et al 2007). This investigation has tried to keep the assumptions physically based.

A grid of scans covering an area of forty by forty metres with a scan every twenty metres has been simulated. This is an unrealistic sampling density but it will allow the investigation of the difference such a density makes to the accuracy of the inverted parameters. Because of the density of measurements available it should be possible to create a volumetric representation of the canopy with no assumptions about homogeneity. In order to arrive at a manageable and solvable set of equations some assumptions have been made. These are;

All elements are perfect Lambertian reflectors and with known reflectances. Reflectance cannot be derived from a radiance measurement unless the structure and size of that element are known.

Layers of a canopy show no preferential alignment (either a tendency to occlude or to fill gaps) from any direction. This follows from Fisher's (1992) finding that computer generated trees are more realistic and photosynthetically efficient if

the elements follow a random distribution than a regular pattern. From this it can be said that on average the light reflected from an area divided by the gap fraction up to that point is directly related to the objects at that region and so attenuation can be corrected for.

Some of these assumptions are valid within the simulation but do not hold in reality. Other methods for constraining the results, taking the uncertainty in the reflectances into account, will be needed.

THEORY

For an element of material e, of area δA_e with a reflectance of ρ_e at an angle of incidence ϑ_i to a laser beam of intensity I_0, at a range r_e the radiant flux from direct reflection, Φ summed over all elements within a field of view is;

$$\Phi = I_0 \sum_e \frac{\rho_e}{r_e^2} \int \cos^2 \vartheta_i \delta A_e \quad (1)$$

This becomes easier to invert if the surface area is taken outside of the sum and the projected area weighted mean angle of incidence, $\hat{\vartheta}$ used. From simulations it has been found that;

$$\Phi = I_0 \sum_e \frac{\rho_e}{r_e^2} A_e \cos^3 \hat{\vartheta}_e \quad (2)$$

The range to each element will only be known to plus or minus half the range resolution of the instrument. In the case of Echidna this is an uncertainty of 7.5cm leading to an error in the corrected radiance of up to 3% at 5m, decaying exponentially with increasing range. If elements are randomly arranged within the bins this effect should cancel out. It can be investigated with the ray tracer.

The intensity of radiation reaching the surface will be the intensity leaving the laser multiplied by the fraction of the field of view that has not been blocked up to that point. There is then an attenuated radiant flux; η.

The equations are much easier to deal with if a factor, Ψ, the fractional contribution of leaves to the lidar signal within a single range bin is defined.

$$\Psi = \frac{A_l \cos^3 \hat{\vartheta}_l}{A_l \cos^3 \hat{\vartheta}_l + A_b \cos^3 \hat{\vartheta}_b} \quad (3)$$

Where l and b subscripts represent leaf and bark respectively.

If, like the echidna prototype only one wavelength is available Ψ would have to be estimated with another, possibly direct measurement method. If lasers of more than one wavelength are available Ψ can be calculated using the equation;

$$\Psi = \frac{\eta_\lambda \rho_{b\lambda} - \eta_\omega \rho_{b\omega}}{\eta_\lambda (\rho_{l\omega} - \rho_{b\omega}) + \eta_\omega (\rho_{l\lambda} - \rho_{b\lambda})} \quad (4)$$

Where λ and ω are the two wavelengths, with radiant fluxes of η_λ and η_ω and reflectance for each material, e of $\rho_{e\lambda}$ and $\rho_{e\omega}$.

Element distribution function

Campbell's ellipsoidal distribution (Campbell 1986) will be used to relate $\hat{\vartheta}_e$ to the view zenith and azimuth angles. For simplicity in this first attempt it will be assumed that the elements are azimuthally symmetric, reducing the ellipsoids to spheroids with one vertical radius and two identical horizontal radii.

The ray tracer was used to measure $\hat{\vartheta}_e$ at zeniths, ϑ_z between 0º and 90º for a range of different eccentricities. The results are shown in the first graph.
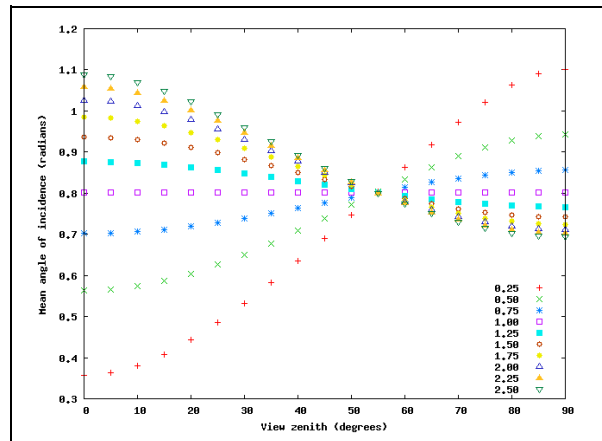
Graph 1. $\hat{\vartheta}_e$ against view zenith for spheroids of different eccentricities. The key shows the ratio of the vertical to horizontal radii.

These simulations agreed with the work of Roberts (1998), that all spheroids have a $\hat{\vartheta}_e$ of $\pi/4$ radians at a zenith angle of μ (roughly equal to 54.75º). $\hat{\vartheta}_e$ can then be calculated from the equation;

$$\hat{\vartheta}_e = \left(\frac{\pi/4 + \cos 2\mu}{1 + \cos 2\mu} + \hat{\Omega}_e \right) \cos 2\vartheta_z + \frac{\pi/4 + \cos 2\mu}{1 + \cos 2\mu} \quad (5)$$

The element angular distribution can be uniquely defined by $\hat{\Omega}_e$, the mean angle of incidence looking along the vertical axis of a spheroid. This can be calculated by numerical integration. The above function, with $\hat{\Omega}_e$ calculated by integration fitted to the simulated data with a root mean square error of less than 0.4%, well within the errors from stochastic ray tracing.

All clumping at scales larger than the lidar bins has been explicitly taken into account. Clumping need only be corrected for at the scale of lidar bins. For echidna this is about the size of a pine shoot. Echidna has a constant azimuth step for all zeniths and so scans overlap for annuli near the vertical. If it is assumed that the canopy is equally clumped in all directions within a voxel (a safe assumption with pine shoots) the variation in measured surface areas between beams should be related to the clumping.

Inverting the lidar signal

A program has been written to use the above equations to convert full waveform lidar data into a voxel representation of the canopy. It is possible to solve two separate angle distributions from multi-frequency data, but to simplify the problem for this first attempt it has been assumed that leaves and bark have the same angular distribution. Ψ is then independent of view direction. Each voxel is described by a fractional area, A_e for each material, angle distribution, $\hat{\Omega}_e$ and the fraction of total surface area made up by leaves, Ψ. Having a separate $\hat{\Omega}_e$ for each voxel makes no assumptions about the homogeneity above the scale of a voxel though it may prove to be an unnecessary level of detail. The voxel canopy should cover the origin of each scan to allow a correct estimate of the attenuation of the beams.

Multiple lidar bins may lie within a voxel and a lidar bin may lie within many voxels, in which case the measured flux will be due to the elements from all intersecting voxels weighted by the overlaps. In this first attempt the weighting has been ignored. It will have an effect upon the accuracy of the results, but not the overall method, which is the focus of this investigation.

Once the lidar bins have been associated with the appropriate voxels Ψ can be calculated if more than one wavelength is available. This depends only on the reflectances and uncorrected fluxes so will not alter during the iterative process. In future it may be sensible to weight the value of Ψ calculated by each beam by the gap up to that point since the signal from a beam passing through a larger gap will be more representative of the scene. In which case Ψ will alter during the iterations.

The gap is calculated by summing the projected areas of spheroids with surface areas calculated from the measured radiant flux (η), the fraction of the return from leaves, Ψ and eccentricities calculated from $\hat{\Omega}_e$ for all lidar bins up to that point. This calculation makes no assumption about the alignment of the different canopy layers. If the angular distributions, fractional contribution factor and the reflectances are known this calculated value will be the true gap up to that point.

A gap cannot close until after the last return. Gaps depend only upon Ψ and $\hat{\Omega}_e$. Initially the angle distributions is assumed to be spherical ($\hat{\Omega}_e = \pi/4$) for all voxels. $\hat{\Omega}_e$ is adjusted until no beams are prematurely blocked.

An initial estimate of A_e is then made, averaged over all contributing voxels and wavelengths. Once the initial values have been chosen the iterative process to refine the estimates of voxel parameters can be started.

All beams should see the same surface areas with a different orientation ($\hat{\vartheta}_e$). If a voxel has returns from different zeniths, remembering the symmetry of a spheroid, $\hat{\Omega}_e$ can be calculated. These factors can be used to calculate A_e for each beam and averaged together to get a value for the voxel. Every time $\hat{\Omega}_e$ is adjusted the gap for all voxels intersected by bins later in that beam's path will also be affected.

The process is repeated until the radiant flux predicted by the model matches that measured by the simulated lidar, within a tolerance.

RESULTS

It has not yet been possible to compare the initial results to the original object file. A function to convert the raw object file into a volumetric representation is in development. Figure 2 shows a horizontal slice through the voxel representation, 5m above the floor. The initial results, using a set of low resolution scans, suggest that there is a large variation in both leaf area and leaf angle distribution between metre cubed volumes, justifying the high measurement density.
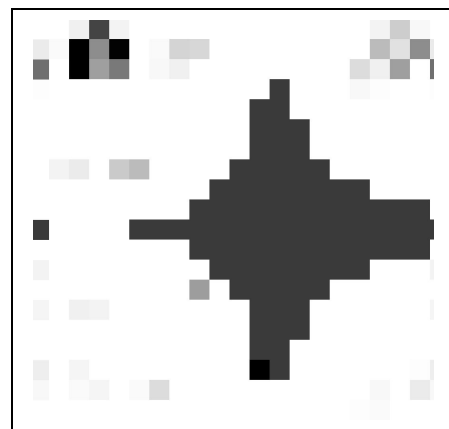

Figure 2. 10m by 10m horizontal slice through a voxel representation. The darkness indicates the area of bark projected upwards.

DISCUSSION

This method has only taken light reflected directly from the scene into account. The second graph shows that multiple scattering makes a significant contribution to the lidar signal, even with a beam divergence of 0.5° and a field of view of 0.8°. Multiple scattering is much more significant at lower zeniths, where the beam is reflected off many small needles, than near the ground, were light is reflected from a few large, solid objects. This effect needs to be understood. A future investigation will find how this percentage changes with laser beam divergence and field of view, and how much of the scene from outside the field of view contributes to the signal.

If the inverted voxel representation is found to be a poor description of the "truth" it would be fairly simple to use a separate angular distribution for bark and leaf. Also, a single large branch passing through a voxel cannot be described by a spheroid. It would be possible to allow the spheroids to tilt to better fit reality. The effect of the detail of the angular distribution on inversion accuracy should be investigated.

At some point in a canopy a lidar beam will become so attenuated that the returned signal cannot be said to be representative of the canopy at that point. The maximum distance between scans needed to describe canopies of different element area densities will be investigated.
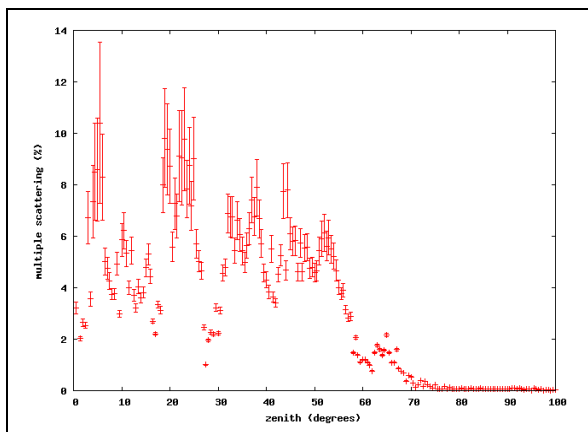
Graph 2. Contributions to the lidar signal from scattering for a hemispherical scan looking up from beneath a Scots Pine canopy. The results of annuli are averaged together with the bars representing variance.

This investigation has suggested a set of equations to convert full waveform lidar data collected in a forest into a volumetric representation. Algorithms for correcting for clumping are still needed. A second waveband will help a great deal with the inversion, removing the need for costly direct measurements. The accuracy of this method and the number of scans needed to describe a forest of a certain element area density will be evaluated in the near future.

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