# ANALYSIS OF INTERACTION PATTERNS BETWEEN VEGETATION CANOPIES AND SMALL FOOTPRINT, HIGH-DENSITY, AIRBORNE LIDAR

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**ABSTRACT:**

High resolution, small footprint, imaging lidar systems are becoming increasingly important for monitoring forest canopies. Without doubt they have the potential to dramatically change conventional methods of forest survey. It is often assumed that the first pulse of the laser beam interacts with the top of the vegetation canopy while the last pulse is assumed to come from the ground. In this paper we present results from a research programme which has been monitoring vegetation canopy dynamics at the UK Woodwalton Fen Site of Special Scientific Interest for the last twelve months using an Optech ALTM 33 airborne lidar. The instrument generates 33,000 laser hits per second. For each hit the first pulse, last pulse and intensity are recorded with an accuracy of plus or minus 15cm. Surveys have been conducted in both leaf-on and leaf-off states. In an examination of several types of canopy at the site we apply statistical analysis techniques to the distributions of heights contained in the first and last pulse data. We show that the different vegetation and stand types are characterised by different probability distribution functions which can be used to derive information about the structural properties of the vegetation canopies. We will further show that appropriate processing of lidar point clouds can yield structural information similar to that generated by less readily available large footprint systems. The results presented here are part of an on-going research programme funded by the Sir Isaac Newton Trust. The consortium includes the University of Cambridge Unit for Landscape Modelling and English Nature.

## 1. INTRODUCTION

A significant proportion of the world's landscapes are characterised by complex, semi-natural vegetation communities. In Northern Europe the moorlands and heaths are good examples of the type whilst in the Mediterranean, garrigue, maquis and mixed woodland provide classic examples. Frequently these landscapes are characterised by high scenic value and are of considerable ecological significance by virtue of their biodiversity. In the case of many Mediterranean sites, there are very high rates of endemism.

To date however, remote sensing has only played a very limited role in the mapping of these areas at the level of detail required for conservation and management. Notwithstanding issues of resolution, these areas are often hilly or mountainous, have a very fine grain and very complex patterns of vegetation. Often the vegetation types are not well differentiated by traditional spectral signatures. Communities are often mixed, and complex gradients of type and biomass sometimes occur. In Mediterranean areas in particular, it is well known that these properties lead to complex patterns of shadowing and texture in most types of imagery. These in turn lead to very high proportions of mixed pixels and in turn, this leads to problems of mapping from imagery (see for example, Hill *et al*. 1995).

Normally robust classifiers like maximum likelihood produce poor results because of high class variances and mixed pixels. Measures of vegetation amount such as NDVI are often biased by virtue of mixed soil/vegetation proportions within pixels and by the fact that they only record the outermost portion of dense canopies.

One possible area where substantial progress can be made with these problems is airborne laser scanning or LiDAR. LiDAR measurement involves firing short pulses of laser energy at the ground target and measuring the return time for the energy to be reflected back to the sensor. Vegetation canopies present a surface to the laser which is porous to energy. As a consequence each laser pulse potentially returns a distribution of energy in which the first recorded values come from the top of the canopy and subsequent values are returned from lower layers. If the laser pulse is sufficiently powerful and the canopy sufficiently open, the graph of return time against energy has a shape dependent on the vertical distribution of canopy components (ground, under-storey, stems, branches and photosynthetically active leaves in the canopy (Lefsky *et al*., 2002; Lim, *et al.* 2003)

Two types of system are currently in use. So called 'large footprint' systems have a wide divergence angle for the laser beam so that it illuminates a large (typically 10 – 30 metre), circular area (footprint) of the scene. Often just a few footprints (6 – 10) are recorded for each scan line but the entire return pattern of energy versus time (height) is recorded in great detail. Such devices are relatively specialist and confined to NASA based research (Means *et al*. 2000).

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By contrast small footprint devices have a narrow divergence angle resulting in footprints typically between 10 cms. and 1 metre. However, these systems operate at very high frequency and may generate anything up to 80,000 laser pulses per second. Bandwidth constraints mean that these systems only record a small part of the energy for each pulse. Typically the height of the first detectable energy return (first pulse) and the last detectable return (last pulse) is measured together with the overall light intensity. These devices are capable of generating extremely dense patterns of observations over the scenes being imaged recording up to 20 points per square metre. By virtue of their remarkable accuracy they have found widespread application in surveying, forestry and other environmental applications.

Given these basic differences in functionality it is not surprising that with respect to vegetation applications large footprint systems have been mainly used for examining the vertical structure of forest canopies (e.g. Lefsky *et al.* (1999), Harding *et al.* (2001), vertical patterns of photosynthetically active radiation (e.g. Parker *et al.,* 2001), and above ground biomass (Means *et al.* 1999). Small footprint systems on the other hand have been used primarily for forest survey and mensuration (e.g. Naesset, 2002, Persson *et al.* 2002). Generally, a modelling framework is used in which laser height observations are linked to ground based measurements of key forest parameters (e.g. height, numbers of stems, crown basal area) using regression techniques.

To date very few researchers seem to have considered the possibilities of using small footprint LiDAR for monitoring the vertical structure of canopies. Notable exceptions include Blair and Hofton (1999) who demonstrated that by integrating small footprint returns across an area equivalent in size to a large footprint it was possible to elucidate the vertical structure of complex rainforest canopies in Costa Rica. Riano et al. (2003) also suggested this possibility in the context of forest mapping for fire models.

## 2. AIMS AND OBJECTIVES

Given this background the present study aims to highlight the possibilities of using small footprint, airborne LiDAR to understand the structure of complex, semi-natural vegetation stands.

In particular it will:

- demonstrate how small footprint lidar can be used to characterise the vertical structure of dense, highly complex canopies.
- draw attention to its potential for mapping gaps, canopy openness, density and under-storey properties
- examine structural differences between woodland vegetation types and demonstrate the potential that LiDAR measurement of structure has for discrimination in classification exercises.

## 3. STUDY AREA AND SURVEY DATA

The study site for this work was Woodwalton Fen, an area of semi-natural wetland located just to the south of Peterborough in lowland East Anglia, UK (Figure 1). The Fen is one of Britain's oldest nature reserves and has variously been designated as a RAMSAR site, a Special Area of Conservation (cSAC) and a site of Special Scientific Interest (SSSI). It occupies an area of approximately 3km by 2 km bounded by

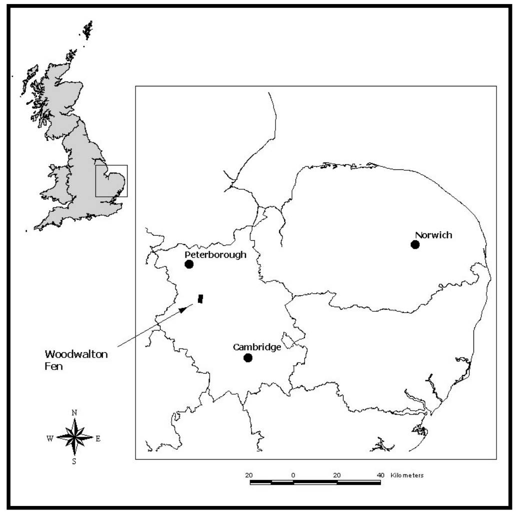


Figure 1. Location of the Woodwalton Fen study site

canals from the surrounding arable farmland. It is rich in its variety of fauna and flora with some 47 red data book species and two very rare plants. The site is managed by English Nature who plan to link it to its neighbour, Holme Fen as part of a novel and ambitious conservation scheme called 'the Great Fen Project'.

Internally, the fen is divided by a network of smaller drainage channels which split the area into a grid of grass and woodland habitats. A system of sluices enables control of the water levels and maintenance of the damp conditions needed for its conservation. Peat in the surrounding farmland has dried and become eroded leaving the fen perched several metres above the surrounding landscape. The entire site is virtually flat with a change in elevation of approximately 1 metre across the 3km of its length.

A network of grass walkways follow the internal drainage channels and provides pedestrian access to the different areas of the fen. In general cells of the grid defined by the waterways contain distinct vegetation habitats. It is the woodland habitats which were of interest to this study and four particular classes were examined:

**Mixed Woodland**

This class represents the tallest of the canopies reaching an average height of over twenty metres. It consists of a mixture of birch (*Betula spp*), Hawthorn (*Crataegus spp*.) and Alder (*Alnus spp.).* The top of the canopy is dominated by Birch whilst the Alder appears in isolated clumps. The Hawthorn tends to be lower, forming a sub-storey beneath the main canopy. The under-storey layer consists of grasses, nettles and other herbaceous plants emerging from a layer of litter.

**Hawthorn**

Pure stands of Hawthorn (*Crataegus spp*.) are relatively rare at the fen. However, where it is found in stands it forms a dense, twiggy canopy over a relatively open under-storey layer. Vegetation in the under-storey is similar to, but rather more sparse than that of the Mixed Woodland class. The canopy is supported on fairly evenly spaced, single stems creating a relatively open layer between under-storey and canopy.

**Sallow**

The grey willow (*Salix cinerea*) enjoys the damp conditions of the Fen and forms dense thickets. Because it spreads rapidly it is necessary to keep it in check by frequent removal along the margins of stands. It typically grows to a height of about five to six metres with a dense, leafy canopy above multiple stems. There is a distinct base to the canopy shading an under-storey of sparse grasses, nettles and herbaceous plants.

**Birch**

The stands of Birch typically reach a height of around 20 metres and form a relatively open canopy above randomly spaced stems. Whilst this sometimes leads to a fairly open under-storey layer it is more common to find young hawthorns and sallow together with other shrubs forming a distinct sub-canopy layer. Ultimately, these stands which are dominated by silver birch (*Betula pendula*) will form mixed woodland if left unchecked.

### 3.1 Collection of LiDAR data

The data used for this paper was collected on $8^{th}$ October 2002 as part of an ongoing monitoring programme for the fen aimed at exploring the value of LiDAR for understanding seasonal vegetation dynamics. First pulse, last pulse and intensity data were recorded using an Optech ALTM 3033 device carried on-board a Piper Chieftain Navajo aircraft. Weather conditions were good and the aircraft completed three, overlapping flight lines following the long axis of the site from an altitude of 1000 metres. With a scan angle of 20 degrees and a scan rate of 33 Hz this resulted in approximately one laser point per square metre. With a narrow beam divergence the laser footprint was in the region of 21 cm.

The ALTM was calibrated shortly before the flight using an established survey of the runway and a hangar roofline at Cambridge airport. The calibration data was collected to a high level of accuracy with a total station and was tied-in to the UK national survey, using known locations. Just over 1 km. of the runway was covered with a 5 metre grid of control points.

Ground control for the aerial survey was provided by locating a Novatel, 2 Hz differential GPS receiver over a known survey point at the same airfield. With a separation of just over 30 kms. between the ground station and the survey site the ALTM was operating well within its required operational parameters for generating data to an accuracy of plus or minus 15 cms. Over five million laser points were collected and processed with the GPS data to generate a point cloud using Applanix POSPAC and Optech's REALM software suites. Subsequent processing used a combination of ArcGIS and MSExcel.

At the time of the survey all of the deciduous vegetation was in 'leaf on' state and there was no evidence of the onset of autumn leaf fall. Under-storey conditions were relatively dry given the normally damp nature of the fen's soils.

## 4. ANALYSIS AND RESULTS

The analysis presented here relies on simple graphs and profiles to describe the properties of the data. In the first instance these will be used to demonstrate how first pulse data can be used to define the outer surface of the canopy. Following on from this combined first pulse and last pulse data will be used to characterise the internal, vertical structure of the canopy.

### 4.1 First pulse observations of the canopy surface

The first stage of the analysis focussed on the use of first pulse data to examine canopy surface properties. Experience with the ALTM has revealed that it is highly sensitive to very small objects in terms of triggering a first pulse response. For example, isolated clumps of reed heads left after clearance of reed beds can be clearly discerned in the imagery. This is despite there being only three of four flower heads standing 1 metre above their surroundings. From this it was inferred that first pulse data would provide an effective mechanism for recording the canopy top at the resolution of the selected footprint (21 cms.).

Accordingly, four areas of 100 metres by 100 metres were selected from stands of each of the woodland classes. First pulse data were collected for each of the cells and histograms showing the distribution of first pulse returns binned by height were produced. Figure 2 shows the result for Hawthorn and is typical of all the classes.

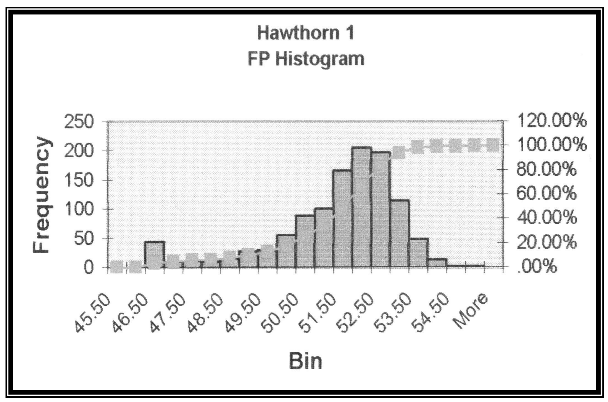


Figure 2. First pulse histogram for Hawthorn showing under-storey and canopy layers.

All four of the histograms show a distinctive pattern with a small peak of observations at very low level, increasing frequency with height and one or more distinct peaks higher up. It would appear that the first, low peak corresponds with under-storey vegetation. Relatively less energy is returned from intermediate levels and there is a distinct peak corresponding with the canopy top.

It is interesting to note that the form of these histograms is similar to that of the full return waveforms reported for large footprint sensors (Lefsky *et al,*. op. cit.). However, there is one important difference. In the case of these sensors energy is being measured from throughout the canopy in response to a single laser hit. In this case, first pulses are recorded as soon as the laser encounters a canopy component. This means that sub- and under-storey layers can only be recorded where the laser is able to pass through gaps larger than the footprint.

This observation leads to the conclusion that by thresholding the first pulse histogram to select only those first pulses which are close to the under-storey it is possible to map canopy gaps. Displaying the results of such a thresholding exercise overlaid onto aerial photography reveals a very clear representation of canopy gaps. These range from macro features (rides and clearings) to small gaps caused by fallen trees. As yet no detailed validation data has been collected to establish the accuracy of this technique.

Nevertheless, from these observations it might be concluded that the first pulse data gives a representation of *canopy surface morphology* without the possibility of canopy penetration.

### 4.2 Combined first and last pulse observations

The next stage of the analysis involved examination of combined first and last pulse data. Using the same sampling units as for the first pulse analysis histograms were again produced for each of the four classes. In addition, plots of laser height against easting were also produced. The results are shown in Figure 3. Detailed analysis of the last pulse data revealed that an unexpectedly high proportion of values coincided with their corresponding first pulse measurements raising the possibility that there is an under-representation of last pulse returns when they are close to the first pulse. However, no evidence was found that the measured last pulse data was inaccurate or that the basic patterns in the data were distorted.

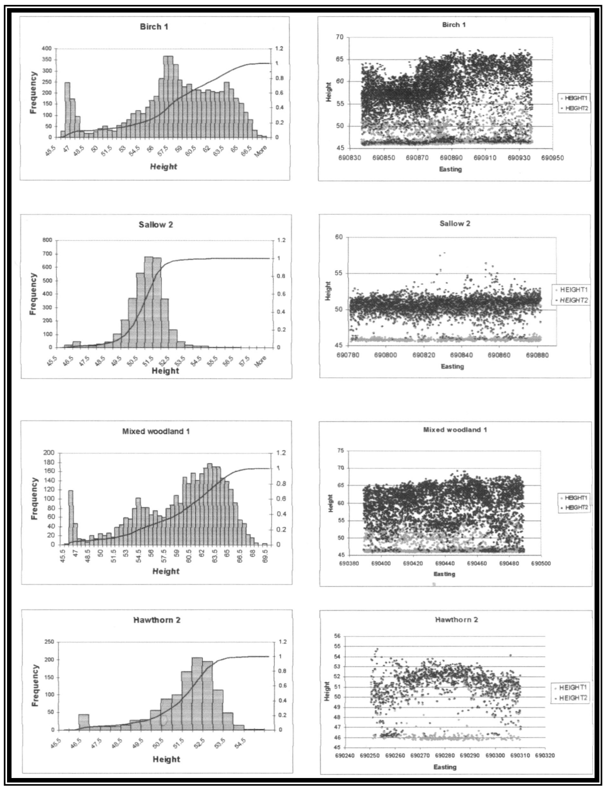


Figure 3. Combined first and last pulse data for the four sample sites and corresponding height profiles.

Inclusion of the last pulse component in the data opens up the possibility of visualising canopy 3d structure. Clearly, when there is a first pulse recorded near to the top of the canopy and a corresponding last pulse recorded below it, the difference reflects the degree of laser penetration for that particular pulse. Examination of Figure 3 thus confirms expectations about the canopy structure for the four woodland classes based on their descriptions from section 3.

The histogram for Birch reveals a significant under-storey component arising as a consequence of the relative openness of the canopy permitting the formation of a significant sub-canopy layer of shrubs and saplings. The variability in crown height is also clearly reflected in the histogram. The corresponding profile further highlights this variability in canopy height together with important boundary locations corresponding to the top of the under-storey and the base of the canopy. It is interesting to note the significant number of first returns from the under-storey layer again reflecting the degree of canopy openness.

In contrast Sallow exhibits a much more simple structure. There is a very uniform, dense canopy and a far less distinct under-storey layer. The canopy layer is uniform in height and is so dense that very little first return energy penetrates to the under-storey. However, last return data is returned from the under-storey confirming the ability of the LiDAR to reveal 3d structure even when the canopy is very dense. Again the boundaries between top of under-storey, stems amd base of canopy form distinct thresholds in the histogram.

The histogram for Mixed Woodland has three distinct peaks corresponding to under-storey, sub-canopy layer of Hawthorn and saplings and the outer layer of Birch/Alder. Despite the complexity and thickness of the canopy it is clear from the profile that first return energy still reaches the under-storey layer. This again reflects the openness of the dominant Birch canopy.

The final histogram for Hawthorn provides the strongest of contrasts. The upper layer is relatively thin in depth but extremely dense. Very little first return energy comes from below the canopy base. The relatively open layer of stems is clearly visible but possibly the issue raised earlier over last returns underestimates the amount of material in this part of the vertical profile.

From all of the histograms it is clear that integration of small footprints over appropriately sized areas can reveal detailed information about the structure of vertical canopies. This information accords well with expectations based on qualitative description of the stands and their species composition. Furthermore, unlike large footprint returns, it is clearly possible to discriminate between canopy gaps where both first and last return come from the under-storey and canopy penetration where there is a first return in the canopy and an associated last return from lower levels. This last observation opens up the possibility of deriving indices of canopy openness and density.

It is also evident from the graphs that the cumulative height profiles are very different for each of the four stand types in question. This opens up the additional possibility of integrating this type of information into broader classification schemes. Previous attempts to classify this site based on spectral data alone have met with very limited success due to spectral similarity between species, mixed stands, complex patterns of crown illumination and shadow and texture caused by gaps and variable canopy density.

## 5. CONCLUSIONS AND DISCUSSION

By integrating small footprints over an appropriately sized area it is possible to generate detailed descriptions of vertical structure in even the most complex, semi-natural vegetation canopies. Using simple graphical techniques, accurately calibrated LiDAR data from an ALTM 3033 sensor has been used to demonstrate the basic principle. First pulse interacts with the outer surface of the canopy and the frequency distribution of heights characterises the canopy surface morphology. First pulses which reach the under-storey layer of the canopy can be used to map the location of gaps in the canopy.

By combining both first and last pulse data it is possible to examine vertical structure *within* the canopy by virtue of the fact that last pulses associated with first pulses near the canopy top reflect the degree of laser penetration. In the Birch canopies studied here it was found that a significant number of both first and last pulses reached the under-storey underlining the openness of the canopy. By contrast, in Hawthorn and Sallow, which have very dense canopies, very few first returns penetrate the upper canopy layer. Nevertheless, last pulse data is still returned in sufficient quantities to characterise the under-storey layers. Even the vertical structure of the complex, multi-layered, mixed woodland category was evident in the combined first and last pulse data.

For all four of the canopy structures, boundary layers separating under-storey, stems and base of crowns could be identified. In all cases these were distinct, near horizontal features except for the case of Birch which showed considerable, vertical variability in the height of the layer. Ultimately, these layers may hold the potential for thresholding laser returns. First pulses reaching the under-storey provide a basis for identifying gaps and modelling the external canopy morphology (height and shape). Last pulses reaching the under-storey with associated first pulses above the base of the canopy could be used to provide a measure of canopy openness and dense canopy can be represented where both first and last pulse are returned from above the under-storey layer.

This ability to identify gaps, areas of open and areas of dense canopy is clearly of considerable significance for understanding light penetration to the under-storey and the impact it has on composition and vigour. The next stage of this work will involve implementation of this approach for wide area canopy mapping.

In addition to characterising vertical structure, the cumulative height distributions from the histograms also provided very clear discrimination between the vegetation classes involved. This suggests that their incorporation with spectral data in classification schemes will result in significant progress towards detailed mapping of semi-natural vegetation communities. As the introduction to this paper suggests, this progress is urgently needed in many parts of the world.

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