Representation of vegetation and topography within satellite LiDAR waveforms for a mixed temperate forest

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Abstract

Identifying the signal returned from vegetation within large footprint LiDAR waveforms relies upon estimating a representative ground surface beneath the canopy. Two methods of identifying the vegetation return within Geoscience Laser Altimeter System (GLAS) waveforms are presented. The first uses maximum elevation difference within a coincident digital terrain model (DTM) to estimate the ground position, whilst the second uses Gaussian decomposition to distinguish ground and vegetation components.

Estimated ground elevations within the waveforms are compared with coincident mean ground surface elevations from airborne LiDAR data and the Ordnance Survey 10 metre resolution DTM. Smallest differences are found between the Gaussian decomposition method and the two validation dataset elevations with mean offsets of -0.14m and -0.02 metres respectively. However, ground slope was found to account for 39% of variation in error using Gaussian decomposition whilst use of a terrain index from the coincident DTM removed this error source. The two methods respectively explained 68% (RMSE 4.4m) and 63% (RMSE 4.7m) of variance in comparison with airborne LiDAR estimates of vegetation height.

The radiative transfer model, FLIGHT, is used to model the sensitivity of the GLAS waveform to canopy properties and topography. Close correspondence is found between returned and simulated waveforms.

Keywords: ICESat/GLAS, Airborne LiDAR, FLIGHT, Topography, Vegetation

1. Introduction

Small footprint airborne LiDAR data provide a unique means of modelling complex topography beneath forest canopies (Figure 1), allowing the identification of hydrological systems, archaeological remains, potential access routes for forest management and the assessment of slope stability. This ability to represent a dynamic surface allows overlying vegetation to be related to topography to accurately demonstrate vegetation distribution for inventory or management purposes or to provide model inputs.

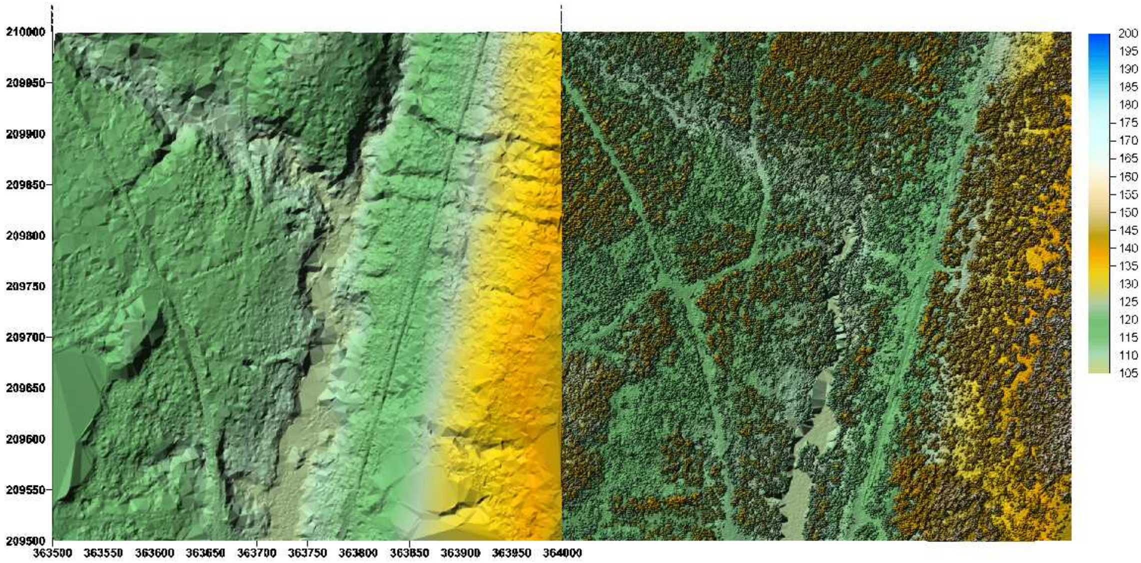

Figure 1. (left) Digital terrain model (DTM) of a 0.5km x 0.5km area of the Forest of Dean. (right) Coincident digital surface model (DSM) from airborne LiDAR data. Both models are 0.5m resolution and were produced with Golden Software Surfer 8 using linear interpolation with Delaunay triangulation.

Large footprint satellite LiDAR has great potential for monitoring vegetation presence and change on unprecedented scales (Hese *et al.*, 2005) and studies have successfully demonstrated the capabilities of LiDAR profiling in this respect (Harding and Carabajal, 2005; Helmer and Lefsky, 2006; Lefsky *et al.*, 2005; Lefsky *et al.*, 2007; Nelson *et al.*, 2008; Nelson *et al.*, 2004). However the broad footprint diameter poses the challenge of signals from the ground surface and vegetation being combined for footprints with complex terrain and vegetation distribution (Figure 2). This raises the question of whether a representative ground surface can be identified within waveforms, a factor which may be important in the estimation of vegetation height.

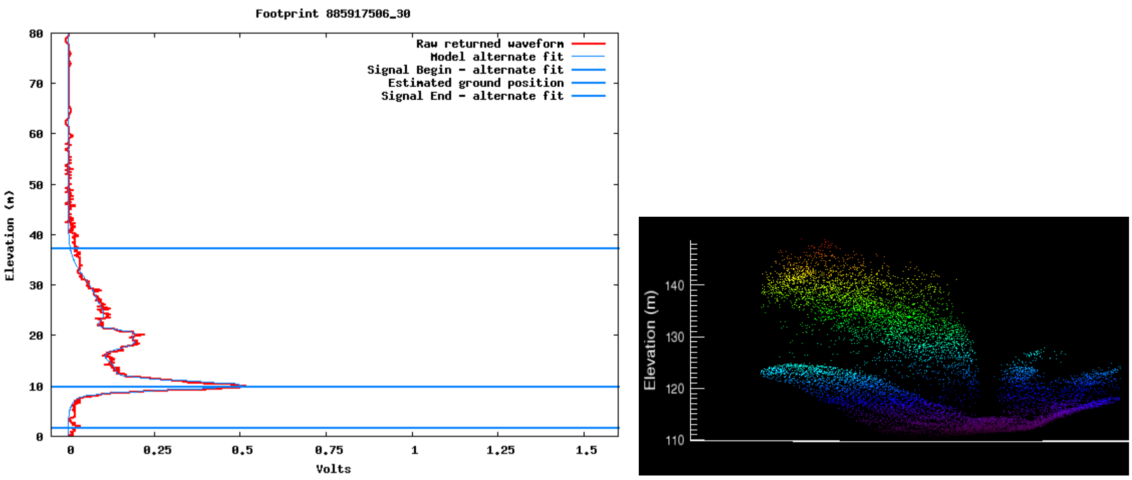

Figure 2: ICESat/GLAS waveform and coincident airborne LiDAR point cloud for a vegetated footprint with complex topography in the Forest of Dean.

This study therefore aims to assess the degree to which a representative ground elevation beneath vegetation can be estimated using large footprint full waveform LiDAR and the influence of slope on this estimate. From this, a comparison of estimates of maximum canopy height from satellite and airborne LiDAR are presented. The radiative transfer model, FLIGHT (North, 1996), is also used to model the effect of slope and vegetation properties on waveform shape.

2. Method

2.1 Study area

The Forest of Dean, Gloucestershire, UK, is a highly mixed forest in England which borders south Wales and covers an area of approximately 11,000 hectares. The forest falls under the responsibility of the Forestry Commission, a division of which, Forest Enterprise, maintains a database of site conditions, species composition and management criteria at a sub-compartment level. The forest is unusual in terms of the UK, containing approximately 50% conifers and broadleaves comprising pockets of ancient woodland as well as managed stands. Surface relief is also varied within the forest, ranging from near-flat terrain to elevation differences of up to 20 metres (m) within 70x70m sample areas used in this study. Both species heterogeneity and topography create a challenging study area for the application of satellite LiDAR.

2.2 Satellite LiDAR

The data source used within this project is the Geoscience Laser Altimeter System (GLAS), a full waveform LiDAR profiler, aboard the Ice, Cloud and land Elevation Satellite (ICESat). GLAS emits 1064nm pulses at a rate of 40 shots per second from an altitude of 600km. This produces footprints which are distanced at 172m intervals on the ground surface and, for the laser 3D operation used in this study, footprints have approximately 52m diameter and were acquired in October 2005. The laser is operated for an approximately month-long period, two-three times annually, aiming to repeat the same ground tracks and therefore providing the potential for changes over time to be monitored. Further information regarding the mission and system are provided by other authors (Abshire *et al.*, 2005; Brenner *et al.*, 2003; NSIDC, 2003; Schutz *et al.*, 2005; Zwally *et al.*, 2002).

2.2.1 Waveform processing

Two methods of estimating vegetation returns within GLAS waveforms (Rosette *et al.*, 2008) were used in this study. The first of these uses a multiple regression with waveform extent (the elevation difference between the beginning and end of the waveform signal) and a terrain index using the Ordnance Survey (OS) Land-Form PROFILE 10m digital terrain model (Lefsky *et al.*, 2005). Product GLA14 (NSIDC, 2003) provides a model fit to the raw waveform decomposed as the sum of six Gaussian peaks. The second method estimates the ground elevation as the centroid of either Gaussian Peak 1 or 2 whichever has greatest amplitude. Maximum vegetation height is estimated as the distance between this position within the waveform and the beginning of the waveform signal. These methods are hereafter referred to as R_{WT} and GP_{amp} respectively.

Elevations of the estimated ground positions within waveforms were calculated in order to assess the ability of each ICESat/ GLAS method to estimate ground elevation with respect to airborne LiDAR and OS DTM mean elevations. Waveform ground surface elevations were calculated as follows:

$$\text{d\_elev} + \text{d\_ld\_RngOff} - \text{d\_SigBegOff} - \text{GLAS}_{ht} - \text{d\_gdHt} \qquad (1)$$

whereby d_elev is the reference elevation of the ellipsoid; the land range offset, d_ld_RngOff, indicates the offset position within the waveform of d_elev; d_SigBegOff provides the offset of the beginning of the waveform signal; $GLAS_{ht}$ represents maximum vegetation heights estimated using GLAS data (methods described above); d_gdHt is the height of the geoid above that of the ICESat ellipsoid. All waveform parameters used are from product GLA14 as original units converted to metres. Offset positions are provided as a negative number with reference to the final data bin, furthest from the spacecraft, recorded in each 150m waveform ‘window’ and indicate the distance from this position in metres.

2.2 Airborne LiDAR system

Airborne LiDAR data were captured using the Optech Airborne Laser Terrain Mapper (ALTM-3033) during August 2006. The Natural Environment Research Council Airborne Research and Surveying Facility offers this service through the Unit for Landscape Modelling, University of Cambridge. The flight was undertaken for the Forestry Commission of Great Britain Forest Research Agency. This first and last return laser scanner emits 1064nm pulses and produced approximately 20cm diameter footprints with 45cm average point spacing.

2.2.1 Data processing

Subsets of airborne Lidar data were created using a radius of 35m about each geo-located ICESat footprint position. This aims to compensate for some uncertainty in footprint position and eccentricity.

Using the airborne LiDAR ground class, mean slope within footprints was calculated with the aim of assessing the extent to which any differences observed between estimates from the two systems or field measurements may be a function of slope.

Since points were regularly distributed with little variation in point density across the study area, ground class surface models for each footprint area were created using linear interpolation with Delaunay triangulation. Maximum canopy height within each airborne LiDAR subset was calculated to allow a comparison to be made with satellite LiDAR estimates.

Projected plant cover was then calculated for each footprint using return point counts above the interpolated ground surface. A 0.5m height threshold was used to exclude the effects of low cover by ferns, brambles or grass to prevent artificial estimates of cover but to include energy distribution throughout the canopy in order to be comparable as far as possible with the waveform energy profile. 0.15m height bins were used for consistency with waveform resolution. Using these criteria, canopy cover was estimated as the number of all canopy points expressed as a fraction of total returns to provide input data for the radiative transfer model FLIGHT.

2.3 FLIGHT

To analyse theoretical sensitivity of the GLAS waveform to topography and canopy structure, we have developed a model of the interaction of waveform LiDAR with a three-dimensional canopy representation. The model is developed from the FLIGHT radiative transfer model (North, 1996), based on Monte Carlo simulation of photon transport. Foliage is represented by structural properties of leaf area, leaf angle distribution, crown dimensions and fractional cover, and the optical properties of leaves, branch, shoot and ground components. Important characteristics of the model are that it can represent multiple scattering of light within the canopy and with the ground surface, simulate the return signal efficiently at multiple wavebands, and model the effects of topography. Spatial and temporal sampling characteristics of the LiDAR instrument are explicitly modelled.

2.3.1 Model Inputs

Estimates of canopy cover from airborne LiDAR data were used as a model input to FLIGHT. The use of this dataset as an approximation of ground truth was supported by hemispherical photography calculations which produced R^2 of 0.77 and RMSE of 2% despite the small data range available (Rosette *et al.*, submitted). Inputs of crown dimensions were based on field observations for a selection of ICESat footprint areas. Airborne LiDAR ground class data were used for the input of mean footprint slope. Species vegetation height and crown shape were determined from field observations or using the Forest Enterprise sub-compartment database and corresponding yield model estimates.

3. Results

Figure 3 shows estimations of within-footprint mean ground elevations from Ordnance Survey DTM and airborne LiDAR plus ICESat/GLAS estimated ground surface using both GP_{amp} and R_{WT} methods. The Gaussian decomposition method underestimated the airborne LiDAR (AL) and Ordnance Survey 10m resolution Land-Form PROFILE DTM (OS) mean ground elevations by 0.14m and 0.02 m respectively for the Forest of Dean pass. A summary of results is found in Table 4.

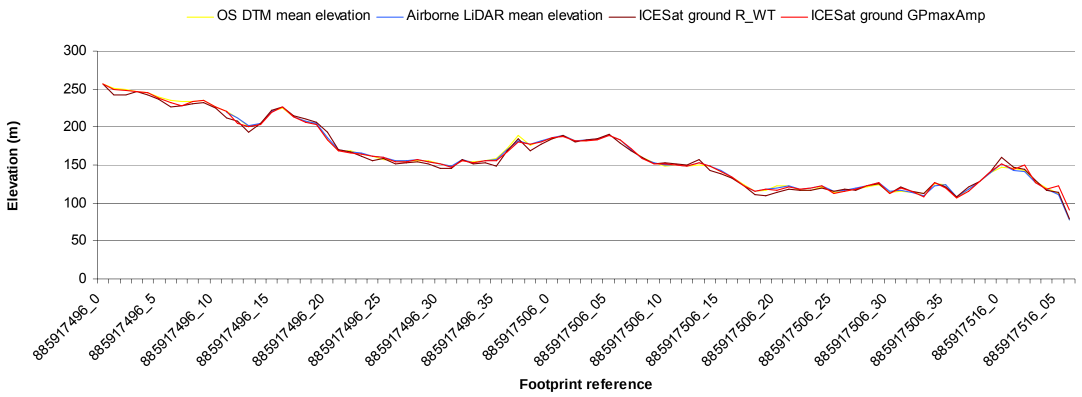

Figure 3. Identification of ground elevation using airborne and satellite LiDAR.

When compared with airborne LiDAR ground surface, mean slope calculated from the airborne LiDAR ground class explained 39% and 0.5% of the error using GP_{amp} and R_{WT} estimates of the ground surface respectively.

Table 4. Comparison of estimated ground surfaces using Ordnance Survey and LiDAR data.

Comparison (m)	R_{WT}-AL	GP_{AMP}-AL	AL-OS	R_{WT} -OS	GP_{AMP} -OS
Mean offset	-0.97	-0.14	0.12	-0.84	-0.02
Max. difference	9.02	12.73	3.05	12.07	13.11
Min. difference	-9.64	-7.36	-8.56	-10.43	-8.63

The method of identifying the vegetation return using Gaussian decomposition from product GLA14 corresponded slightly closer than use of signal limits with a terrain index in comparison with vegetation height estimates from airborne LiDAR. Regression analysis for the two methods produced R^2 of 0.68, RMSE 4.4m and R^2 of 0.63, RMSE 4.7m respectively. The correlation using Gaussian decomposition is shown in Figure 4 and a further comparison between satellite and airborne LiDAR vegetation estimates are discussed in detail within (Rosette *et al.*, submitted).

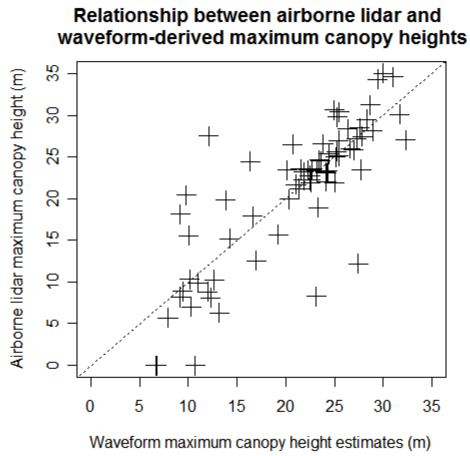

Figure 4. Relationship between airborne and satellite LiDAR maximum canopy height estimates using Gaussian decomposition (product GLA14).

The following figures show examples of ICESat/GLAS waveforms plus corresponding simulated returns from FLIGHT using inputs of footprint surface and overlying vegetation properties. A summary of estimated and measured vegetation heights is found in Table 5. For these examples in fact, better estimates of maximum canopy height were produced using multiple regression analysis with Waveform Extent and a Terrain Index.

Table 5. Examples of estimated vegetation heights from satellite and airborne LiDAR and coincident field measurements.

Vegetation height estimation:	GP_{AMP}	R_{WT}	AL	Field
Footprint 885917506_14	24.2m	30.8m	30.6m	31
Footprint 885917506_29	21.2m	21.9m	23.4m	-
Footprint 885917516_05	17.4m	26.4m	24.2m	24.75m

Figure shows a vegetated slope of 17.8° with species coverage of 60% Douglas Fir towards the top of the slope and the remaining area comprising oak beneath. Calculated top heights from records within the sub-compartment database and corresponding yield models for the two species are respectively 23.9m and 17.6m. The maximum observed field measurement from within the estimated footprint boundaries was 24.75m.

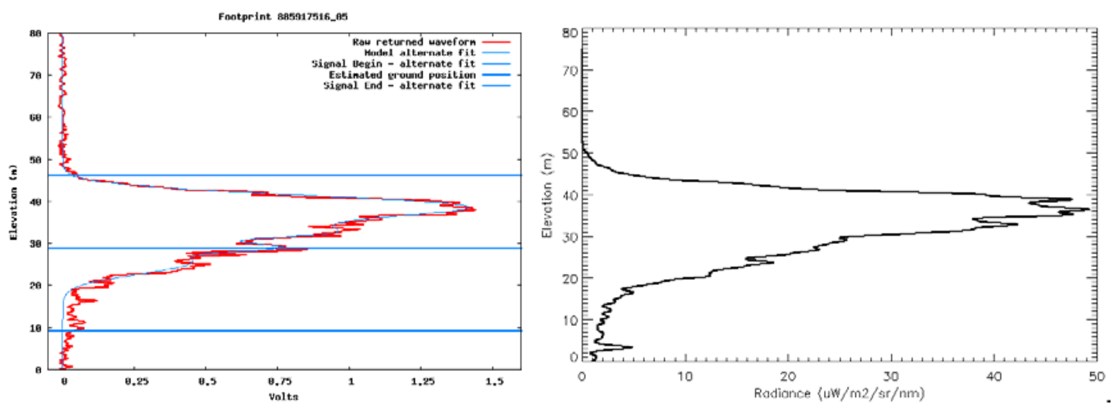

Figure 5: GLAS and simulated waveforms for a steep and continuously vegetated slope.

The footprint shown in Figure6 covers a pure stand containing 100% oak with top height estimated as 21.3m. Field measurements are not available for this site. Slope from airborne LiDAR data was calculated as 1.7°.

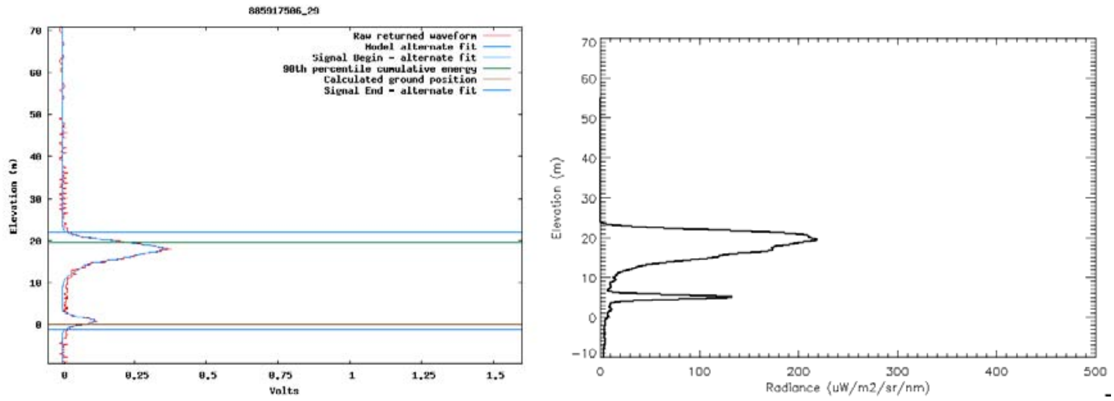

Figure 6: Returned waveform and simulation for a single layer canopy on level terrain.

Figure 7 shows an example of a footprint on a gentle slope (4.9°) which samples a stand of predominantly Douglas Fir of two ages: 29% of the area has estimated top height of 28.6m whilst 6% had calculated top height of 22.8m. The stand also contains 21% Oak (21.5m top height) with the remainder of the area being unplanted. Maximum tree height from field measurements was 31m.

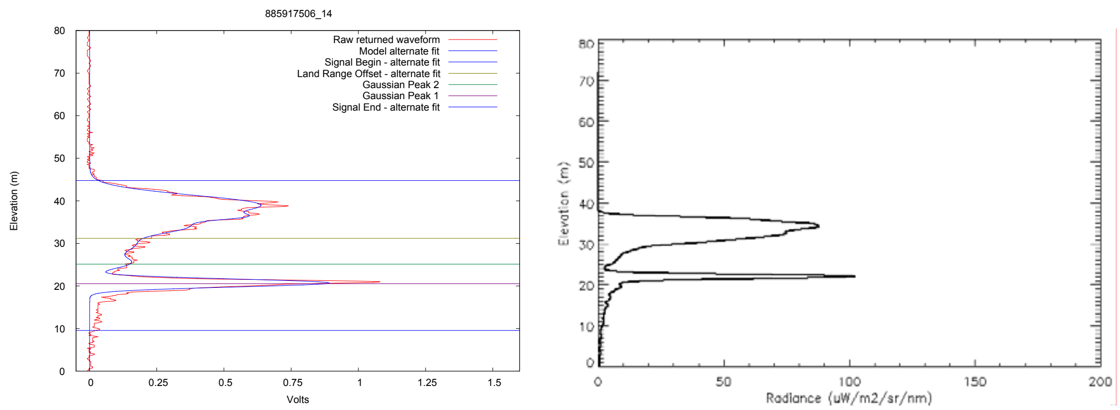

Figure 7: GLAS waveform and FLIGHT simulation for a multi-layered canopy on a gentle slope.

4. Discussion

This study has shown the ability to identify the vegetation signal from satellite LiDAR waveforms. For the Forest of Dean, the method using Gaussian decomposition to estimate ground elevation within the waveform ground peak produced the smallest mean error in comparison with both airborne LiDAR and Ordnance Survey Land-Form PROFILE DTM mean ground elevations. However, ground elevation for the ICESat/GLAS pass crossing the Forest of Dean was estimated with a mean error of less than 1m using both methods.

Slope was identified as a contributory factor for the minor negative offset using Gaussian decomposition whereas this had been successfully addressed using the Waveform Extent/Terrain Index method. A further explanation may be offered by the fact that the model fit is produced by the sum of Gaussian peaks and therefore the centroid of the Gaussian Peak with greatest amplitude may not always represent the most common ground elevation. Use of the largest amplitude inflexion point within the ground return may address this small error. For both methods a negative bias is seen in the estimation of the ground surface. For the R_{WT} method, this may be a result of the waveform 'tail' extending below the true lowest ground surface.

The results suggest that, for situations such as the Forest of Dean in which dense canopy cover or extreme slope do not prevent a representative ground surface from being detected, Gaussian decomposition may offer an appropriate means of estimating ground elevation. Furthermore, GLAS estimations of ground elevation have shown considerable consistency across different laser operations (Sun *et al.*, 2008).

Estimates of maximum canopy height using R_{WT} and GP_{amp} methods compared well against airborne LiDAR estimates of the same. Regression analysis produced R^2 of 0.68, RMSE 4.4m and R^2 of 0.63, RMSE 4.7m for the two methods respectively.

Inputs of generalised crown shape and crown dimensions, vegetation height, canopy cover and slope were used for LiDAR waveform modelling within the radiative transfer model FLIGHT. Returned and simulated waveforms show similar properties.

The returned and modelled waveforms in Figure show the effect of combined returned signals from a sloped ground surface with relatively dense vegetation throughout the slope. Energy is therefore returned from ground and vegetation surfaces at similar elevations. This is one of the few sites at the Forest of Dean for which a ground peak cannot be distinguished within the waveform.

The GLAS waveform seen in Figure (left) shows the effect of a single layer oak canopy with most energy interception towards the uppermost canopy. However the simulated waveform anticipates that energy will also be returned from within the canopy. The low amplitude and laser penetration seen in the GLAS waveform may be a result of signal dampening due to variations in atmospheric transmittance. This remains to be determined.

The modelled and returned waveforms in Figure show signals from a multi-layered canopy on a gentle slope. Energy is returned throughout the canopy and the effect of multiple scattering between intercepted surfaces is seen in the ‘tail’ visible beneath the ground peak in both simulated and GLAS waveforms.

5. Conclusions

This study has shown the possibility of extracting representative ground surfaces from large footprint full waveforms which are comparable with airborne LiDAR and Ordnance Survey mean ground elevations. Slope was found to be a contributory factor in the small error found where Gaussian decomposition was used to estimate ground elevation. Estimates of maximum canopy height from satellite LIDAR waveforms corresponded closely with those using coincident airborne LiDAR. The effects of topography and canopy properties on waveform composition were successfully modelled using the radiative transfer model FLIGHT which aims to assist future waveform interpretation.

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