A METHOD OF DIRECTLY ESTIMATING STEMWOOD VOLUME FROM GLAS WAVEFORM PARAMETERS

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ABSTRACT:

Methods of estimating stemwood volume from ICESat/ GLAS lidar waveforms are explored for a mixed temperate forest, the Forest of Dean, Gloucestershire, UK. Previous methods have used maximum canopy height estimations incorporating a digital terrain model (DTM) and requiring calibration using a sample of within-footprint tree heights. This study focuses on deriving methods which do not require such supplementary data. Maximum canopy height is estimated as the distance between Signal Begin and the ground peak within the waveform. The ground peak is determined using the centroid of either Gaussian Peak 1 or 2, identified by whichever has the greatest amplitude. This canopy height estimation was used to isolate the region of the waveform returned from the vegetation, from which heights of cumulative energy percentiles were calculated. For the tallest species within footprints, stemwood volume estimates for conifers produced R^2 of 0.59, RMSE 98.3 m^3/ha and for broadleaf species, R^2 of 0.75, RMSE 59.1 m^3/ha were found. Stemwood volume estimates taking account of the mixed species composition within stands were also calculated. For mixed stand estimates, R^2 of 0.66, RMSE 82.5 m^3/ha was found for stands dominated by conifers whilst stands with greatest percentage cover provided by broadleaf species produced R^2 of 0.47, RMSE 75.6 m^3/ha. Potential is shown for satellite lidar stemwood volume estimates to be derived directly from waveforms and therefore suggests that similar techniques could be applied where a suitable DTM or field measurements are not available.

1. INTRODUCTION

Quantifying changes in biomass distribution is acknowledged by the Global Climate Observing System as an essential variable for the monitoring of global climate. Satellite-derived estimates can contribute to biomass estimation on a global scale; the aim being to achieve an accuracy of 10-20% which is comparable with *in situ* methods (GCOS 2006).
Airborne lidar has been shown to offer a means of estimating biophysical parameters such as above ground biomass at a local scale. This has been demonstrated using discrete return lidar (e.g. Hyyppä *et al.* 2001, Patenaude *et al. 2004*) and waveform recording devices (e.g. Lefsky *et al.* 1999, Drake *et al.* 2003). Opportunities for USA state-wide biomass estimation using first return lidar profiling are also shown by Nelson *et al*. (2004) and Nelson *et al.* (2006), whilst Bufton (1989), Gardner (1992), Harding *et al.* (1994), Brenner *et al.* (2003) and Hese *et al.* (2005) discuss the concepts of full waveform satellite lidar.
Therefore, given the near-global coverage of the Ice, Cloud and land Elevation Satellite (ICESat), there is potential for satellite lidar to contribute to regional or national scale forest monitoring and quantification (e.g. GCOS 2004, Hese *et al.* 2005, Helmer and Lefsky 2006). However, previous methods of estimating above ground biomass/ volume have relied upon supplementary data to estimate maximum canopy heights. This has involved a two-stage process, deriving maximum canopy height from a multiple regression using the Waveform Extent (distance between Signal Begin and Signal End) plus a terrain index (using a DTM centred on the footprint co-ordinates) and calibrating against field measurements of within-footprint tree height. These maximum canopy height estimates were then used to develop methods of estimating stemwood volume (Lefsky *et al.* 2005, Rosette *et al.* submitted).
This paper explores an alternative means of estimating stemwood volume which does not necessitate additional information and therefore aims to simplify the process, potentially allowing broader application.

2. METHODS

2.1 Study Site

The Forest of Dean, Gloucestershire, UK covers an area of approximately 11,000 hectares and was crossed by ICESat between 51.74° N and 51.88° N latitude and 2.54° W and 2.51° W longitude. The data used for this study were captured on 22nd October 2005 while vegetation was predominantly still in leaf. Most frequently occurring species within stands sampled by ICESat were Norway Spruce (Picea abies), mixed broadleaf species, Oak (Quercus spp), Corsican Pine (Pinus nigra var maritima), Douglas Fir (Pseudotsuga menziesii), Scots Pine (Pinus sylvestris) and European Larch (Larix decidua). It is a highly mixed, temperate forest managed by the Forestry Commission of Great Britain. Forest Enterprise is responsible for maintaining a sub-compartment database for management purposes which lists details of species, habitat conditions and management criteria for each discrete component contained within sub-compartments (Forestry Commission 2006).

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2.2 Yield Models

The sub-compartment database allows reference to be made to yield models which predict stand parameters including top height, individual tree volume, volume per hectare and mean diameter at breast height by age (Edwards and Christie, 1981). These models are empirically-derived and initial spacing of individuals, species, yield class (annual increment m^3/ha/year) and management (e.g. thinning regime) determine the anticipated growth curve.
Stemwood volume is defined as living over-bark volume in m^3/ha (for conifers this comprises the main stem diameter greater or equal to 7cm). Forestry Commission yield models were used to calculate stemwood volume for stands covered by ICESat footprints and, for this study, two calculations of stemwood volume were used:

2.2.1 Single species stemwood volume: Few footprints covered stands containing a single species and therefore, to indicate the potential for pure stands, a proxy was used. Stemwood volume was calculated for the tallest species within each footprint (identified from the sub-compartment database). This was based on the principle that this species could also be identified within waveforms (maximum canopy height estimates). Differentiation was then made between footprints in which the tallest species was broadleaf or coniferous to consider whether this would improve the relationship with waveform parameters described in 2.3.2.

2.2.2 Mixed stand stemwood volume: Sub-compartments may contain several distinct components and additionally, a number of ICESat footprints crossed sub-compartment boundaries. The second measure of stemwood volume therefore represents the mixed composition of stands and is calculated using the percentage cover of species within all components of each sub-compartment sampled by footprints. Footprints were then discriminated according to whether broadleaf species or conifers formed the greatest percentage cover and correlations with waveform parameters (section 2.3.2) were calculated.

2.3 GLAS Data

2.3.1 Data description: The Geoscience Laser Altimeter System (GLAS) is carried on the Ice, Cloud and land Elevation Satellite (ICESat) and is operated at intervals to capture measurements for three seasons each year: usually for approximately month-long periods during February-March, May-June and October-November. GLAS simultaneously emits 1064nm and 532 nm pulses which produce NIR elliptical footprints of 64m average equivalent circular area diameter at 172m intervals along the ground track. Footprint horizontal geolocation is unknown for the laser operation used in this study (L3D), however is expected to vary between 0.0 ± 2.7 metres (L3A) and 17.4 ± 22.8 metres (L3B).
Footprints are broader than the ideal diameter for vegetation analysis (approximately tree crown width) and this increases the likelihood of vegetation and ground signals being combined within the returned waveform thereby complicating interpretation. For footprints containing complex topography and vegetation distribution, apparent vegetation heights derived from waveforms may therefore differ from actual vegetation heights. A further consideration when studying the vegetation profile within waveforms is that laser energy diminishes towards the margins of the footprint and therefore waveforms are most representative of the footprint centre.

Zwally *et al.* (2002), Brenner *et al.* (2003), Kichak (2003), Abshire *et al.* (2005), Harding and Carabajal (2005), Schutz *et al.* (2005) and NSIDC (2006) provide further details regarding the ICESat mission and data.
For this study, the following products were used from data release V026 (Zwally *et al.* 2006): level 1A GLA01 (Global Altimetry data - raw waveform) and level 2 products GLA06 (Global Elevation data – footprint geolocation) and GLA14 (Global Land Surface Altimetry data – alternate model fit).
Waveform structure is formed by the returned energy for intercepted surfaces at and above the ground surface within footprints. Signal Begin and Signal End positions within the waveform indicate the highest canopy surface and lowest ground elevation within footprints and are identified by the signal exceeding a background noise threshold. Waveform amplitude is determined by both area of intercepted surfaces and the intensity of the returned laser pulse. Vegetated footprints on relatively flat terrain are expected to produce a bimodal waveform with a narrow peak from the ground surface and a broader, more complex return from the overlying canopy. The canopy return represents, in part, the surface area of intercepted canopy elements and is therefore explored with regard to the potential to estimate vegetation volume. To facilitate interpretation, the GLA14 product provides a model fit to the waveform using the sum of six Gaussian peaks (Figure 1). These are used in the identification of waveform parameters for this study.

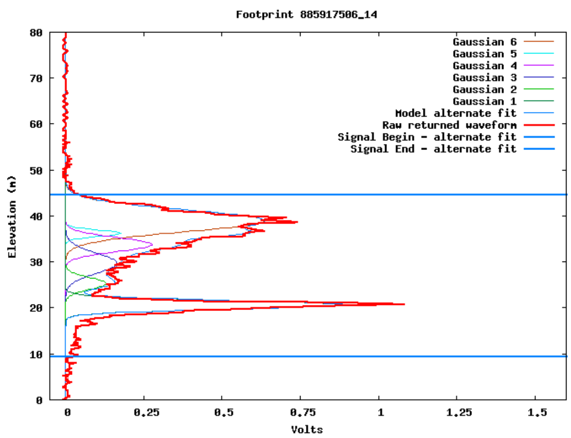

Figure 1. Raw waveform showing alternate fit Signal Begin and Signal End waveform positions plus model decomposition (the sum of six Gaussian peaks)

2.3.2 Waveform parameters: Several waveform parameters were used to explore their potential to estimate stemwood volume for the Forest of Dean. Firstly a method of estimating maximum canopy height presented in Rosette *et al.* (in press) was used. Of the lowest two Gaussian peaks (Figure 1), the centroid of that with the greatest amplitude was used to identify the ground surface. Maximum canopy height was then estimated as the elevation difference between this location within the waveform and the Signal Begin position.
This estimated maximum canopy height was used to isolate the region of the waveform assumed to be returned from the vegetation. Percentiles of cumulative energy within the vegetation return were calculated (adapted from Harding *et al.* 2001).
Waveform-derived maximum canopy height, plus heights of cumulative energy percentiles were then explored as potential estimators of stemwood volume (2.2.1 and 2.2.2).

Previous work has shown that, for this site, area under the canopy return of the waveform did not provide a robust estimator of stemwood volume. However, multiple regression was carried out using the maximum canopy height and heights of percentiles together with area under the canopy return, to assess whether an improvement on the relationships could be achieved. Canopy return area was assumed to be the sum of areas under Gaussian peaks 2-6 if peak 1 had been identified as the ground peak or the total of areas under Gaussian peaks 3-6 if the ground position was assumed to be the centroid of peak 2.

3. RESULTS

3.1 Tallest species stemwood volume estimation

Using the waveform parameters described in 2.3.2, regression analysis was carried out against yield model stemwood volume estimates for the tallest species within each footprint (section 2.2.1). The results for key parameters are shown in Table 1.

Parameters	All species	Conifers	Broadleaf
Max. canopy	0.59 (100.8)	0.59 (99.0)	0.75 (61.0)
99th percentile	0.58 (100.5)	0.59 (98.3)	0.75 (59.9)
98th percentile	0.58 (101.2)	0.58 (99.4)	0.75 (59.1)
95th percentile	0.56 (103.5)	0.56 (102.2)	0.74 (59.1)
90th percentile	0.47 (113.1)	0.46 (114.9)	0.74 (59.0)

Table 1. Waveform-derived estimation of stemwood volume for the tallest species within footprints. Results shown are: R^2 (RMSE m^3/ha)

For stemwood volume estimation of the tallest species within all footprints, the estimated maximum canopy height produced the best relationship with R^2 of 0.59 and RMSE of 100.8 m^3/ha.

3.1.1 Coniferous species: Differentiating between coniferous and broadleaf species did not significantly improve the estimation of stemwood volume for conifers. Using the height of the 99th percentile of cumulative energy produced R^2 of 0.59 and RMSE of 98.3 m^3/ha. This relationship is shown in Figure 2.

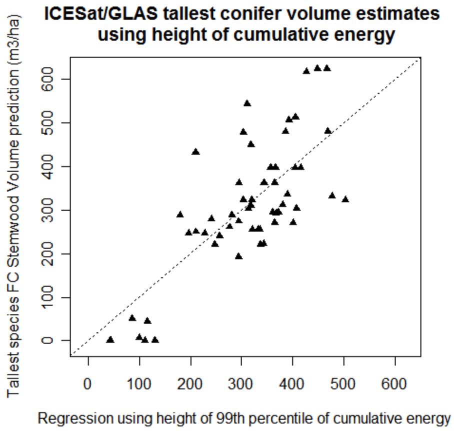

Figure 2. Relationship between stemwood volume estimates and height of 99th percentile of cumulative energy for footprints in which conifers form the tallest species.

3.1.2 Broadleaf species: Considering broadleaf species in isolation however, resulted in a substantial improvement in correlation (R^2 of 0.75 and RMSE of 59.1 m^3/ha using height of the 98th percentile of cumulative energy). This is shown in Figure 3.

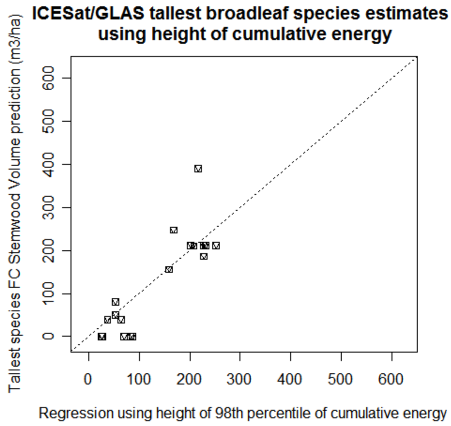

Figure 3. Relationship between stemwood volume estimates and height of 98th percentile of cumulative energy for footprints in which the tallest trees are broadleaf.

3.2 Mixed stand stemwood volume estimation

Weighted stemwood volume estimates accounting for the mixed species composition of stands (section 2.2.2) were used to regress waveform-derived maximum canopy height estimates and heights of cumulative energy percentiles. Key results of these calculations are found in Table 2.

Parameters	All species	Conifers	Broadleaf
Max. canopy	0.46 (102.1)	0.63 (86.6)	0.46 (76.6)
99th percentile	0.47 (100.7)	0.64 (85.5)	0.47 (75.8)
98th percentile	0.48 (99.6)	0.65 (84.3)	0.47 (75.6)
95th percentile	0.50 (97.8)	0.66 (82.5)	0.46 (75.8)
90th percentile	0.49 (97.6)	0.65 (83.7)	0.36 (82.3)

Table 2. Waveform-derived estimation of mixed stand weighted stemwood volume. Results shown are: R^2 (RMSE m^3/ha)

Greatest correlation was seen for all mixed stand weighted stemwood volume estimates using the height of the 95th percentile of cumulative energy. This produced R^2 of 0.50 and RMSE of 97.8 m^3/ha.

3.2.1 Coniferous species: Height of the 95th percentile of cumulative energy also produced the best estimate when only considering coniferous species. R^2 of 0.66 and RMSE of 82.5 m^3/ha was seen and the relationship is shown in Figure 4.

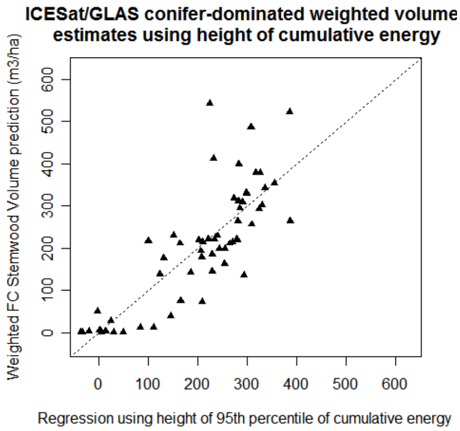

Figure 4. Relationship between mixed stand stemwood volume estimates and height of 95[th] percentile of cumulative energy for footprints dominated by conifers.

3.2.2 Broadleaf species: However, considering broadleaf species separately produced a poorer correlation with R^2 of 0.47 and RMSE of 75.6 m^3/ha for height of the 98[th] percentile of cumulative energy (Figure 5).

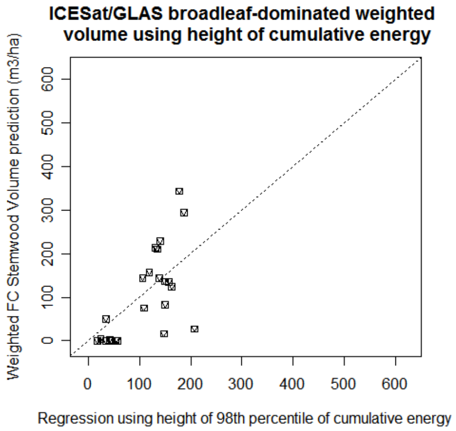

Figure 5. Relationship between mixed stand stemwood volume estimates and height of 98[th] percentile of cumulative energy for footprints dominated by broadleaf trees.

3.3 Area under the waveform

Area under the waveform canopy return (2.3.2) did not produce a statistically significant improvement on the results using either stemwood volume estimate for either broadleaf species or conifers.

4. DISCUSSION

A previously developed method of estimating maximum canopy height (Rosette *et al.* in press) has enabled a new approach to estimating stemwood volume using waveform-derived parameters to be explored. Percentiles of cumulative energy were calculated using the region of the waveform returned from vegetation. Using the heights of these percentiles has allowed different elevations within the canopy return to be considered with respect to their ability to estimate stemwood volume derived from yield models. It is anticipated that, whilst higher elevations are largely the result of returns from the tallest species within footprints, returns from lower canopy elevations might better represent the mixed species composition within stands.

Overall, results for the Forest of Dean are less consistent than previous methodologies which produced similar correlations for both broadleaf and coniferous species (Rosette *et al.* submitted). Stemwood volume estimates for the tallest species within footprints are considerably better for broadleaf species than for conifers (a possible effect of upper canopy shape), whilst for mixed stand estimates, greater correlation is seen for stands with greatest cover formed by conifers than by broadleaf species.

However, improvements are noted on previous methods for stemwood volume estimates for the tallest broadleaf trees (from R^2 of 0.65, RMSE 68.2 m^3/ha to R^2 of 0.75, RMSE 59.1 m^3/ha) and for mixed stands dominated by conifers (from R^2 of 0.57, RMSE 92.3 m^3/ha to R^2 of 0.66, RMSE 82.5 m^3/ha). Mixed stand estimates show marginally higher correlations at higher percentiles of cumulative energy for broadleaf species than for conifers, possibly due to canopy structure and leaf area affecting laser penetration.

Area under the waveform canopy return failed to significantly improve estimates of stemwood volume. An explanation for this could be the considerable variation in reflectivity that may be expected between species. Therefore, for such a species diverse forest, the principal reason for differing waveform amplitude may be reflectivity as opposed to intercepted surface area (anticipated to be related to volume).

Where multiple scattering within the canopy produces a ‘tail’ below the visible ground peak (Figure 1), this method may offer a more constant means of identifying the ground surface within the waveform as it is not dependent on the assumption that the Signal End position represents the lowest ground surface or on the accuracy of a DTM. However, sufficient laser penetration to produce a ground peak may be problematic under dense canopies whilst combined vegetation and ground returns may prevent reliable identification of the ground surface for steep vegetated slopes. For the Forest of Dean, only the greatest slopes (15.5m – 18m within-footprint elevation difference) with continuous vegetation cover did not produce a clear ground return. A further source of error may be dense ground cover vegetation which could cause misidentification of the ground peak.

Limitations of stemwood volume estimations using yield models to assess the potential of using waveform-derived parameters are recognised. Stands are unlikely to respond precisely as anticipated within yield models due to habitat anomalies or changes to management practices for example. In terms of long-term production forecast, Edwards and Christie (1981) suggest this may result in errors of 20% (however, updates are made to the sub-compartment database annually).

Forestry Commission yield models are not dynamic and therefore do not take account of changes in growth or stand composition due to competition, damage affliction or mortality. Estimates for coniferous stands for example, have been found to overestimate actual volume.

Stemwood volume estimates used in this study include some common stands which were contained within the sub-compartment database but not listed as planted. These zero volume values may have improved the relationships and may go some way to explaining the spread among lower waveform estimates: initial observations at footprints locations have revealed the presence of unmanaged trees, shrubs or buildings in some cases which are contributing to waveforms.

An assumption is also made in the calculation of stemwood volume for mixed stands, that components are regularly distributed within sub-compartments rather than individuals forming clusters or being dispersed along a linear feature such as a footpath.

Nevertheless, at a stand level, calibration of yield model estimates using field measurements has produced vegetation height accuracy of 98%. Furthermore, in the course of this study, tree height measurements within 21 footprints at the Forest of Dean produced R^2 of 0.94 when compared with corresponding yield model estimates.

The Forestry Commission sub-compartment database and yield models are widely used in forest management and have provided the best available indication of vegetation distribution throughout the forest. They have therefore formed useful points of reference against which to explore methods of estimating stemwood volume from waveforms.

The study presented in this paper refers to relationships using waveforms acquired whilst vegetation was predominantly still in leaf. Correlation may be anticipated to vary with seasonal differences in LAI.

5. CONCLUSION

This paper has described a method of estimating stemwood volume directly from ICESat/GLAS waveforms. Waveform-derived maximum canopy height and heights of cumulative energy percentiles for the estimated waveform canopy return were compared with yield model stemwood volume coincident with footprints.

Stemwood volume estimates for the tallest species within footprints produced R^2 of 0.59, RMSE 98.3 m^3/ha for conifers and for broadleaf species, R^2 of 0.75, RMSE 59.1 m^3/ha.

Further stemwood volume estimates taking account of the mixed species composition within stands were calculated. Footprints were distinguished depending on whether the greatest percentage cover was formed by coniferous or broadleaf species. For mixed stand estimates, R^2 of 0.66, RMSE 82.5 m^3/ha was found for stands dominated by conifers whilst stands in which broadleaf species are prevalent produced R^2 of 0.47, RMSE 75.6 m^3/ha.

The results demonstrate the opportunity for waveform-derived stemwood volume estimates from satellite lidar to be applied where an appropriate digital terrain model and field data are not available.

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