A ROLE FOR AIRBORNE LASER SCANNING INTENSITY DATA IN VERTICAL STRATIFICATION OF MULTILAYERED ECOSYSTEMS

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ABSTRACT:

Airborne laser scanning (ALS) based height and intensity information was exploited for the vertical stratification of vegetation layers in a multilayered Mediterranean ecosystem. A new methodology for the separation of different strata was implemented using supervised classification of a two-dimensional feature space spanned by ALS return height (terrain corrected) and discrete return intensity. The approach was validated using extensive field measurements from treated plots, ranging from a single vegetation strata to a more complex multi-layered ecosystem. It was possible to derive maximum, minimum and mean layer height with satisfying accuracies, the bias between field and ALS based layer properties being in order of some decimetres, while standard deviation were generally less than a meter. Fractional cover of the layers could be estimated with errors of about 10 to 15%, even for lower layers potentially concealed by higher vegetation. Concluding, ALS based height and intensity information based on discrete return data was found to be well suited to derive vertical stratification of vegetation layers, however full-waveform data should be able to provide additional information on the physical properties of these layers.

1 INTRODUCTION

LiDAR (Light Detection And Ranging) remote sensing is unique among optical earth observation technologies in that it provides a direct methodology for assessing the elevations of the earth's surface. The range distance between objects on the surface and a measurement platform is measured by recording the time of flight of a laser pulse. In combination with known orientation and position of the measurement platform the three-dimensional location (e.g. in a national coordinate grid) of the scattering object can be estimated. In addition, for most systems [Baltsavias, 1999], several range distances can be recorded for one single laser pulse if the object on the surface is vertically dispersed within the laser footprint, as e.g. for vegetation canopies. This additional capability led to a breakthrough in the generation of digital terrain models (DTM), as terrain information beneath a forest canopy may now be captured [Kraus and Pfeifer, 1998]. This established airborne laser scanning (ALS) as one of the commercially most successful airborne observation technologies. ALS [Wehr and Lohr, 1999; Lefsky et al., 2002] have proven efficient at the landscape level to provide three-dimensional information and stand properties of various forest ecosystems [Hyde et al., 2005]. Large footprint ($>$ 10 m) LiDAR systems are suitable for estimating common forest parameters (e.g. forest height, forest biomass and vertical structure of forest canopies) at the stand level with high accuracies [Dubayah and Drake, 2000], while small footprint ($<$ 1 m) LiDAR systems can be used to estimate forest properties down to the level of single trees [Hyyppä et al., 2001; Morsdorf et al., 2004, 2006]. Up to now, ALS data has been less successful in providing accurate information about vertical components of grasslands and shrub-lands where vegetation height commonly is underestimated due to difficulties discriminating between the ground and low shrubs [Rango et al., 2000; Jason and Bork, 2007]. Shrubland communities and forest ecosystems with important shrub layers are dominant wildland fuel types in the Mediterranean region, for which data about height and cover density are valuable information in predicting potential fire behaviour. A first attempt in the Mediterranean region at exploiting the structural information of ALS in combination with imaging spectrometry has been carried out by Koetz et al. [2008]. In this study, multiband images of ALS based height and density metrics were generated and combined with imaging spectrometry data to form a multi-dimensional dataset. This unique approach increased the accuracy of a support vector machine (SVM) based classification of fuel related land cover types opposed to using imaging spectroscopy alone. The present study uses airborne laser scanning data to explore the possibilities to detect and characterise the vertical stratification of vegetation types in the French Mediterranean region, including lower vegetation layers such as the shrub layer. It will mainly focus on the structural information comprised in the ALS data, based on assessing it's explanatory value in comparison with detailed field measurements in a controlled environment. The main objectives of this study are to use small footprint airborne laser scanner data to derive algorithms for automatically describing the vertical stratification of plant communities. This should ultimately lead into a robust methodology for mapping forest fuel layer properties, including fuel treatments. Special considerations are given to the possibility of using ALS intensity information for improved classification of fuel layers. The method will be tested and validated on treated field plots, where the different vertical strata were either isolated or combined.

2 SITE AND DATA

An airborne survey was conducted early October 2006 over two forested areas in the French Mediterranean region: the Lamanon study area, southeast of Avignon ($05°03'41"E$, $43°42'45"N$) and the Bois-des- Roussettes/Montaiguet study area south of Aix-en-Provence ($05°28'37"E$, $43°29'44"N$), which is not further addressed in this specific study. The study areas comprise similar vegetation types ranging from open shrublands to dense multi-layered forest ecosystems. The study area has been selected because it contains gradients from simple one-layered ecosystems with distinct vertical stratification to complex multi-layered ecosystems with a continuous vertical stratification, making them suitable for testing LiDAR under difficult conditions and identifying possible limitations due to the density or complexity of the plant cover.

2.1 Field site and data

The Lamanon study area is an experimental study site in a G4.E[1] Mixed Mediterranean pine - evergreen oak woodland with Aleppo pine (*pinus halepensis*) in the upper and holm oak (*quercus ilex*) in the lower tree canopy layer, and the shrub layer dominated by box (*buxus sempervirens*). The experimental study site is composed of three treatments and one control plot without replicates: (1) "oak", bush clearing and removal of pine trees; (2) "pine", bush clearing and removal of oak trees; (3) "pine-oak", bush clearing with tree layer intact; and (4) "control", untreated plot. The study site is thus a setup of simple and complex ecosystems ranging from single species forest with a discontinuity between the ground and tree canopy, to a mixed species forest with a vertical continuum from the ground to the top of the tree canopy. The size of the treated plots were 30 x 30 m, and for the control plot 40 x 30 m, with subplots 5 x 5 m. All plots have a 15 m wide buffer zone.

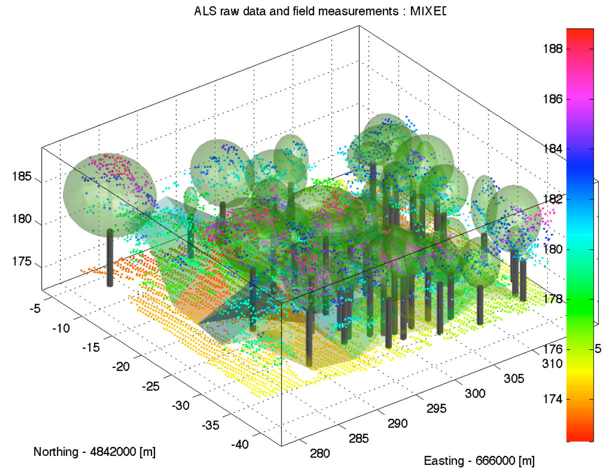

Figure 1: Side view rendered representation of data available for the mixed field plot. Colored dots denote raw ALS echos with their respective heights, while pine tree geometry was reconstructed using ellipsoids according to field measurements. Oak layer depth was assessed on subplots as top and bottom height (transparent surface).

The study plots were established 2001 and bush clearing and clear felling of trees were carried out winter 2005/2006. The perimeter of the four differently treated plots is presented in Figure 2. The field data was collected on grids constructed of 7 by 7 (Oak, Mixed and Pine) and 7 by 9 (Control) subplots being 5 by 5 meter in size. On these grids, the vertical abundance of *quercus ilex* and the plants constituting the shrub layer were measured as a fractional cover for height layers spaced 25 cm apart. Pine tree locations were measured relative to this grid along with their height and crown dimensions consisting of two orthogonal diameters and crown base height. For each of the dominant species, volume fraction $[\frac{m^3}{m^3}]$ and bulk density $[\frac{kg}{m^3}]$ were estimated based on vertically distributed sampling. The initially only relative geolocation within the sample plots was translated to absolute coordinates using differential GPS reference points of the outer plot boundaries acquired with sub-centimetre precision. However, since the grids were initially laid out using a tape measure and a compass, internal accuracy within the sample plots is expected to in the order of some decimeters. Most of the field measurements were provided in vectorised form (as e.g. for the pine trees), thus the information on the presence of the various canopy layers was converted to a voxel grid using a geometric representation of the pine trees as depicted in Figure 1. The grid had a voxel size of 25x25x25 cm and a voxel was considered to be filled with canopy material, when it was contained or intersecting with any of the vectorised plant layers, e.g. if a voxel was contained within in one of the reconstructed tree crowns depicted in Figure 1. The volumes contained within the voxels were converted to canopy volume by a multiplication with the volume fraction of the respective species. If crowns were intersecting, the respective voxel's canopy volume were added on to each other.

2.2 Airborne laser scanning data

A helicopter operated by Helica OGS[2] was equipped with an airborne laser scanner, the laser terrain mapper ALTM 3100 (Optech Inc., Canada) and an AISA Eagle hyperspectral line scanner. The ALTM 3100 system comprises a laser rangefinder recording up to four returns of the laser signal at a wavelength of 1064 nm. The survey was conducted with a nominal flying altitude of 800 m above ground level (AGL), a scan angle of ±20° and pulse repetition frequency (PRF) of 70 kHz, leading to an average point density of 3.7 points per square meter (p/m2). A smaller area (600 x 200 m) was scanned using a higher resolution (lower flying altitude of about 500 m AGL) leading to an average point density of 6-8 p/m2. The latter dataset was used in this study. The beam divergence was set to 0.8 $mRad$, leading to footprint diameters of 0.64 (@ 800 m AGL) and 0.4 (@ 500 m AGL). For the small area, full-waveform data was collected as well, but due to issues in the processing of the data, it was not yet available for exploitation in the context of this study. Effects of atmospheric transmission in the laser's wavelength can be considered minimal, as the atmospheric correction of the imaging spectrometer data, flown on the same platform as the LiDAR, has shown a clear atmosphere with a visibility of up to 30 km [Koetz et al., 2008]. The processing of the raw ALS data was carried out by Helica OGS, including the integration of GPS and INS measurements using the Applanix POSPAC software. In a second step, using Optech's REALM software, the raw data was processed to x,y,z-coordinates in the UTM-WGS 84 system. Calibration was then done using the Terramatch software, using a total of 22 ground control points (GCPs), provided either by differential GPS measurements or by national surveying[3] points within the area. The data was then classified into ground and vegetation echos and delivered in binary LAS format. The latter ensured that the multiple echos were still linked for each laser pulse, using the special bit coding that the LAS format offers. The classified raw data was interpolated into gridded terrain and surface models with 1 m resolution for the large areas and 0.5 m resolution for the smaller high-resolution areas.

3 METHODS

3.1 Exploiting the intensity information

Intensity has not been extensively used in ALS (discrete return) based vegetation studies, due to problems in calibrating and interpreting the digitally numbers obtained by the instruments. Those problems are many-fold, and range from not known instrument

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[1] Corine Landcover class

[2] www.helica.it

[3] provided by Institut Geographique National (IGN)

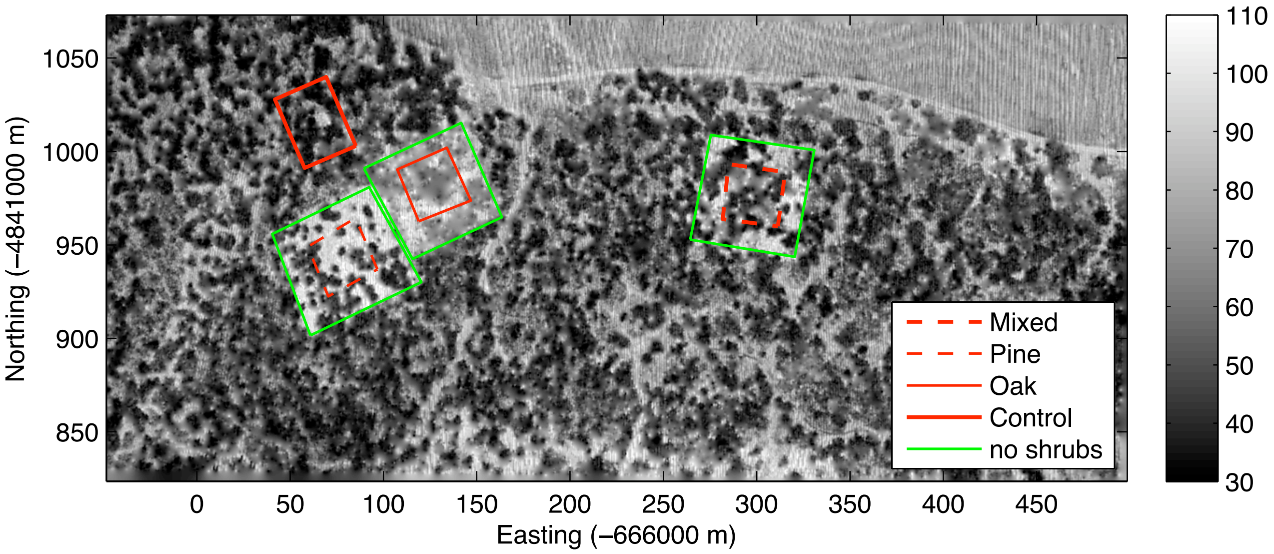

Figure 2: ALS derived intensity values for the small test area and location of field plots. Intensity values are uncorrected digital numbers of single echos interpolated into a raster with 0.5 m resolution. The ground within the shrub cleared plots (mixed, pine and oak) appears brighter than areas still containing shrub as lowest layer.

specifications (time-varying pulse energy, unknown receiver response function) to issues caused by the fuzziness of the vegetation itself. For plane, homogeneous targets the intensity would directly be correlated with target reflectance, assuming the scattering process could be considered Lambertian. However, as vegetation is vertically dispersed within the footprint and is itself a composition of canopy elements of different sizes and orientations and different associated reflectance values, such a simple relationship is not evident. Still, as the sum of these optical and structural properties might be more or less constant for trees of the same species (or at least for the same age class of a specific species), ALS intensity data might be useful for identifying different species. As mentioned before, several issues have to be overcome before intensity data might be used for these purposes. One of them is due to the maximum energy in LiDAR pulses available for reflection not being constant, caused either by changes in the LASER output energy or by changes in the optical path. Moffiet et al. [2005] presented a way of testing for influence of sensor and/or platform movement related effects in LiDAR intensity data. They correlated the ground and vegetation intensity of first pulses for different plots and obtained high correlation. To correct for the latter, a range dependent correction of intensity data was tested according to Höfle and Pfeifer [2007] (for full-waveform data however), but as terrain undulations of the small test area are within a few meters, it did not provide significantly different results and was thus not included. However, for the generation of maps of larger spatial extent (and thus larger terrain differences) the range dependency of the intensity data needs to be corrected. Kaasalainen et al. [2009] presented an approach of radiometric calibration of ALS intensity using flat reference targets with known optical properties, but this method would only work for echos from even surfaces. Another problem in dealing with ALS intensities is due to the vertical dispersion of the canopy elements and the inhomogeneous energy distribution within the footprint. These effects, combined with the impossibility of locating single scatterers within the footprint, make the interpretation of multiple echo intensity data very difficult. On the other hand, for single echos, this effect should be less evident. Single echos do occur as well in the vegetation, in cases where the vegetation at one (presumably thin) layer is dense enough to trigger such an echo; their information has been exploited before for e.g. the estimation of LAI [Morsdorf et al., 2006]. Normally, single echos are mostly triggered from solid objects completely contained within the laser footprint. Consequently, for single echos, the two classes of oak and pine are quite distinct in the two-dimensional feature space spanned by intensity and echo height (Figure 3). Digital numbers for intensity of pine trees range from slightly above 20 to about 60, while for oak trees the range is from above 40 to about 100. In addition, the standard deviation of intensity values is much larger for the lower oak layer than for the pine layer, establishing intensity as an additional feature for discrimenating the different vegetation strata. As there are by far not as many single echos from vegetation as there are multiple returns and the single echo height distribution is skewed in comparison to the multiple echos height distibution (more single echos at the to of the canopy), we still use multiple echo intensity for the classification in the next section. This is a viable option, since the effect of multiple echo intensity discussed above only introduces noise to the intensity signal. Furthermore, no bias will be added, as a comparison of single echo and multiple echo intensity of pine and oak layer returns showed. Thus, it is very likely that the effect will average out for a larger number of returns, as we obtained for the 20 by 20 (30) meter sized plots present in this study.

3.2 Vertical fuel stratification by 2D - cluster analysis

Based on the observations described above, we propose a methodology based on cluster analysis of the 2D feature space spanned by echo height and echo intensity to derive physical properties of the three main fuel classes (pine, oak and shrub) abundant in our study area. Those physical properties include the mean, minimum and maximum height of the layers and their fractional cover. The vertically projected fractional cover of each layer is estimated by computing the area contained within the echo's footprint of each class and dividing it by the total area of each plot. To avoid to too high cover values (the surface area is oversampled by the laser footprints), special computational means were applied in order to ensure that the area of intersecting footprints was accounted for correctly. This way we were able to produce more consistent values of fractional cover opposed to using simple ratios of height thresholded echo numbers.

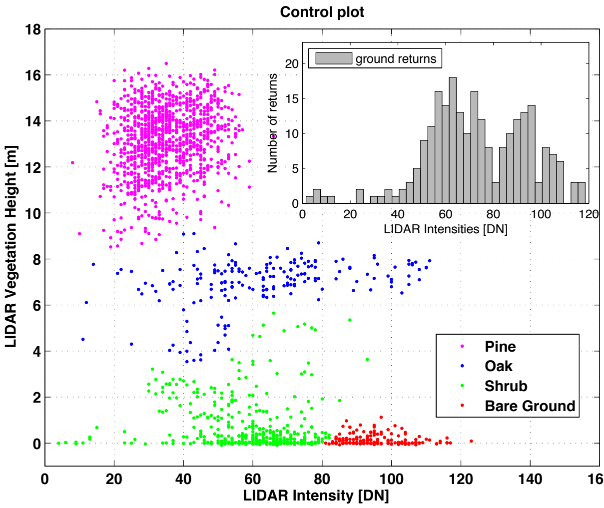

Figure 3: Scatter plot of ALS measured single echo intensity and corresponding echo height, for control plot including shrub and ground layers. Colors represent assignment to different clusters based on a supervised classification of the point cloud prescribing a maximum of four clusters.

In Figure 3, the classification results of single echos from the control plot are presented as an illustration of the clustering algorithm. Choosing the maximum number of clusters to be four, were able to separate the three vegetation layers on the control plot. The pine layer tops out at about 16 meter height and extends down to 9 meter and covers a rather low intensity range of about 20 to 60. Beneath the pine layer, the oak layer is visible as a distinct layer topping out at about 8 meters and reaching down to about 4 meters, where the shrub layer begins. The shrub layer reaches down to the ground of the control plot, rendering echo height alone unusable for discrimination of low shrubs and ground. However, single echo intensity distribution at ground level is grouped into two distinct peaks, with a relative minimum of number of echos at about 80 [DN] (small panel in Figure 3). This effect can as well be observed in Figure 2, where the ground within the shrub cleared plots appears to be brighter (green polygons). Hence, this effect might be used in future studies to separate very low shrubs (< 0.5 m) from bare and/or littered ground, even though a full-waveform based echo width should provide better information on low shrubs [Ducic et al., 2006]. The maximum number of clusters to segment was manually fixed to the appropriate value for each of the four field plots. For an operationalistaion of the method, this could easily be automated by e.g. fitting Gaussian mixture models to the data.

4 RESULTS

4.1 Canopy volume profiles

In Figure 4, the canopy volume profiles computed from the field measurements (methodology was described in Section 2.1) are plotted along with the respective ALS return distribution (all returns). Profiles have been converted to be relative to terrain height by subtracting the height information provided by the DTM. In the pine plot (Figure 4, top left), only one vegetation layer remained after the clearing; it's upper and lower boundaries at 15 and 5 meter respectively seem to be very well captured by the ALS return statistics. The general shape of the profiles is in good agreement, which was not necessarily expected, since the reconstruction of the field measurement was carried out using ellipsoids without any random or fuzzy distribution of canopy material within the tree crowns. For the multi-layered plots (mixed and control), the intermittent peak due to the oak layer at about 4 (mixed) and 7 (control) meters vegetation height are at the same location and of similar magnitude for both ALS based estimates and field measurements. To assess the agreement of the canopy profiles quantitatively we computed the correlation of the number of ALS returns per height bin and the field measured canopy volume profile for each of the four plots. The single layered plots show highest correlation, being 0.96 for the oak and 0.91 for the pine plot. The multi-layered plots show lower, but still strong correlation values of 0.85 for the mixed plot and 0.73 for the control plot. These lower correlations are due to the differences of the histograms at lower heights, and it is very likely that the effects discussed above are causing these discrepancies.

To further validate our results, we computed physical properties from the differently colored classes in Figure 4, such as mean, minimum and maximum height and percentage of cover and compared them to the respective field measured values. In Table **??** the values measured in the field for each of the three different layers (pine,oak and shrub) are compared with respective ALS based estimates (*italic*) for each of the four differently treated plots. The maximum height of the pine layer is underestimated in average by about a meter, while the maximum height of the oak layer is overestimated by about 0.5 meters. Standard deviations of the height values are generally quite small, being in the order of some decimetres, with the exception of crown base height of the pine layer, where the standard deviation is one meter. The bias of estimated mean canopy height for the pine layer is quite small, being only 0.2 m, while the standard deviation is about half a meter. Crown base height was estimated with a smaller bias (0.07 m) and larger standard deviation (1.0 m) for the top pine layer in comparison with the intermediate oak layer, where the bias was as large as 1.37 m, but the standard deviation was only 0.49 m. Percentage of cover is only slightly underestimated for the top pine layer (8%), while a larger overestimation can be observed for the lower oak layer (15%), with standard deviations being in the same orders of magnitude (7.6 and 15 % respectively).

5 DISCUSSION

A new method for deriving the vertical stratification of canopy elements for a multilayered ecosystem was implemented and validated using extensive field measurements from southern France. ALS based canopy profiles from the sample plots were in very good agreement with field measurements, with higher correlations for the simpler, one layered plots and somewhat lower, but still significant values for the two- respective three-layered plot. A novel approach of deriving physical properties of the different vegetation strata using a two-dimensional feature space spanned by ALS echo height (terrain corrected) and echo intensity was applied. Differences of layer height were in the order of some decimetres, and a trend towards larger errors for the more complex plots was not visible. This could be attributed to the not too high cover (40-50 %) of the dominant pine layer on our study plots, thus occlusion is less likely to occur. The differences in height estimations observed between pine and oak layer may be due to the ellipsoidal model used to reconstruct the pine tree crowns, which might be unrealistic in terms of biomass distribution within a pine tree crown. Ecologically calibrated models of tree geometry based on L-systems might provide better results, but these were not available in the context of this study. It appears

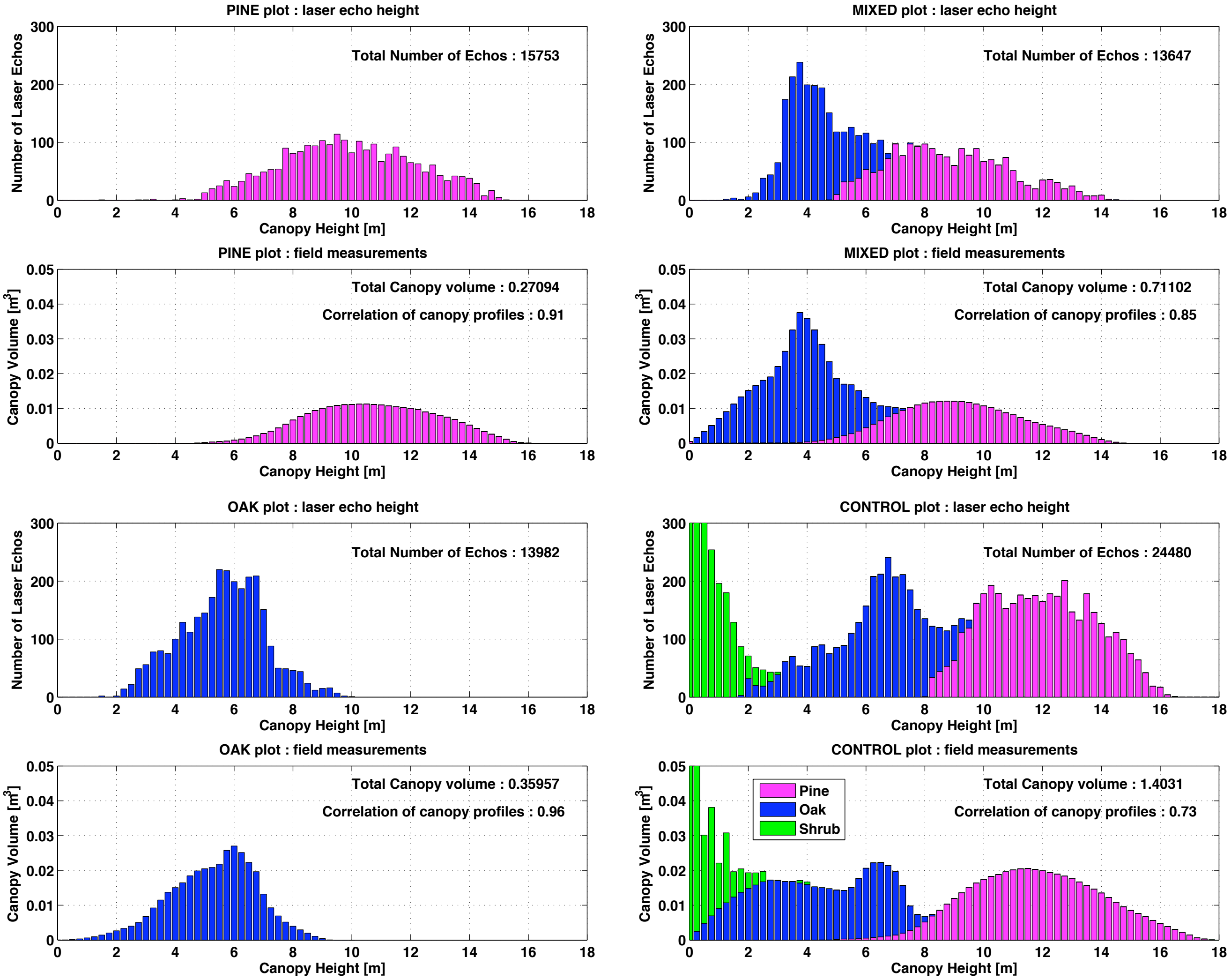

Figure 4: Height distribution of all LiDAR returns (top panels) and canopy volume profile as derived from geometric reconstruction of the field measurements (bottom panels). Different colors denote different vegetation layers. For ALS, laser returns have been assigned to those layers by a 2d supervised cluster analysis of the feature space spanned by echo height and intensity. Thus, the interleaving vertical extent of the different strata can be captured.

Field plot	Control		Mixed		Pine		Oak		**Field-ALS**	
As estimated by:	Field	*ALS*	Field	*ALS*	Field	*ALS*	Field	*ALS*	**Mean**	**Std.**
Pine tree layer										
Maximum canopy height [m]	17.8	*16.5*	14.8	*14.4*	16.3	*15.2*	-	-	**1.1**	**0.45**
Average canopy height [m]	11.8	*11.9*	9.0	*8.9*	10.8	*9.9*	-	-	**0.2**	**0.51**
Crown base height [m]	8.3	*9.2*	5.8	*5.8*	7.2	*6.1*	-	-	**0.07**	**1.0**
Cover [%]	52	*61*	43	*43*	44	*59*	-	-	**-8**	**7.6**
Oak tree layer										
Maximum canpoy height [m]	8.6	*9.7*	7.7	*7.7*	-	-	9.4	*9.9*	**-0.53**	**0.55**
Average canopy height [m]	6.4	*6.3*	4.6	*4.3*	-	-	6.2	*5.6*	**0.33**	**0.25**
Crown base height [m]	4.8	*3.2*	3.6	*2.8*	-	-	4.8	*3.1*	**1.37**	**0.49**
Cover [%]	46	*51*	72	*43*	-	-	74	*53*	**15**	**18**
Shrub layer										
Maximum shrub height [m]	4.0	*3.0*	-	-	-	-	-	-	**-1.0**	**-**
Average shrub height [m]	1.2	*0.6*	0.2*	-*	0.3*	-*	0.2*	-*	**-0.6**	**-**
Cover [%]	61	*50*	8*	-*	12*	-*	8*	-*	**-11**	**-**

Table 1: Maximum, minimum and mean height of percentage of cover of the three strata on the four field plots, as measured in the field and estimated by ALS (italic). For each of the vegetation layers, a bias and a standard deviation was computed (bold values).*Please note that the shrub layer on the mixed, pine and oak plot was removed by the time of the ALS survey.

as if the boundary between pine and oak layer would benefit more from using the additional intensity information opposed to the boundary between shrub and oak. The range of intensities is not as discrete (Figure 3) and the associated errors in layer properties tend to get larger, as e.g. the error for crown base height of the oak tree layer.

6 CONCLUSION AND OUTLOOK

The presented method allows the separation of vegetation layers not only based on laser echo height information, but as well based on echo intensity. This way, the interleaving nature of different vegetation strata vegetation can be captured using solely ALS data. As demonstrated by our field measurements, this is a behavior which is quite likely to occur in natural, multi-layered ecosystems. Small-footprint full-waveform data would very likely provide more explanatory value for the discrimination of different vegetation classes by providing not only the intensity, but as well the echo width, while keeping the high spatial resolution generally obtained by small-footprint systems. Even for full-waveform systems, the intensity will suffer from the not known energy distribution for objects being vertically dispersed within the footprint. On the other hand, echo width has shown to be useful for classifying ground and vegetation returns [Ducic et al., 2006; Wagner et al., 2008]. The echo width is not affected by scatterers above or below the recorded echo of which the width information is exploited; it is a measurement being directly related to the physical properties of the scattering object (as illuminated by the laser beam), and thus might provide a more robust classifier than intensity. This only holds true, of course, if differences in echo width could be linked to single species. Of even greater benefit for a study like this would be the use of a multi-spectral laser scanner with wisely chosen wavelengths, which could pick up the spectral differences of the different strata.

7 ACKNOWLEDGMENTS

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References

Baltsavias, E. P., 1999. Airborne laser scanning: existing systems and firms and other resources. ISPRS Journal of Photogrammetry & Remote Sensing 54, pp. 164–198.

Dubayah, R. and Drake, J., 2000. Lidar remote sensing for forestry. Journal of Forestry 98, pp. 44–46.

Ducic, V., Hollaus, M., Ullrich, A., Wagner, W. and Melze, T., 2006. 3d vegetation mapping and classification using full-waveform laser scanning. International Workshop 3D Remote Sensing in Forestry Vienna, Feb., 14-15, 2006, pp. 211–217.

Höfle, B. and Pfeifer, N., 2007. Correction of laser scanning intensity data: Data and model-driven approaches. ISPRS Journal of Photogrammetry and Remote Sensing 62(6), pp. 415–433.

Hyde, P., Dubayah, R., Peterson, B., Blair, J., Hofton, M., Hunsaker, C., Knox, R. and Walker, W., 2005. Mapping forest structure for wildlife habitat analysis using waveform lidar: Validation of montane ecosystems. Remote Sensing of Environment 96(3-4), pp. 427–437.

Hyyppä, J., Kelle, O., Lehikoinen, M. and Inkinen, M., 2001. A segmentation-based method to retrieve stem volume estimates from 3-d tree height models produced by laser scanners. IEEE Transactions on Geoscience and Remote Sensing 39, pp. 969–975.

Jason, S. and Bork, E., 2007. Characterization of diverse plant communities in aspen parkland rangeland using lidar data. Applied Vegetation Science 10, pp. 407–416.

Kaasalainen, S., Hyyppa, H., Kukko, A., Litkey, P., Ahokas, E., Hyyppa, J., Lehner, H., Jaakkola, A., Suomalainen, J., Akujarvi, A., Kaasalainen, M. and Pyysalo, U., 2009. Radiometric calibration of lidar intensity with commercially available reference targets. IEEE Transactions on Geoscience and Remote Sensing 47(2), pp. 588–598.

Koetz, B., Morsdorf, F., van der Linden, S., Curt, T. and Allgöwer, B., 2008. Multi-source land cover classification for forest fire management based on imaging spectrometry and lidar data. Forest Ecology and Management 256(3), pp. 263–271.

Kraus, K. and Pfeifer, N., 1998. Determination of terrain models in wooded areas with airborne laser scanner data. ISPRS Journal of Photogrammetry & Remote Sensing 53, pp. 193–203.

Lefsky, M. A., Cohen, W. B., Parker, G. G. and Harding, D. J., 2002. Lidar remote sensing for ecosystem studies. BioScience 52(1), pp. 19–30.

Moffiet, T., Mengersen, K., Witte, C., King, R. and Denham, R., 2005. Airborne laser scanning: Exploratory data analysis indicates potential variables for classification of individual trees or forest stands according to species. ISPRS Journal of Photogrammetry & Remote Sensing 59, pp. 289–309.

Morsdorf, F., Kötz, B., Meier, E., Itten, K. and Allgöwer, B., 2006. Estimation of LAI and fractional cover from small footprint airborne laser scanning data based on gap fraction. Remote Sensing of Environment 104(1), pp. 50–61.

Morsdorf, F., Meier, E., Kötz, B., Itten, K. I., Dobbertin, M. and Allgöwer, B., 2004. Lidar-based geometric reconstruction of boreal type forest stands at single tree level for forest and wildland fire management. Remote Sensing of Environment 3(92), pp. 353–362.

Rango, A., Chopping, M., Ritchie, J., Havstad, K., Kustas, W. and Schmugge, T., 2000. Morphological characteristics of shrub coppice dunes in desert grasslands of southern new mexico derived from scanning lidar. Remote Sensing of Environment 74(1), pp. 26–44.

Wagner, W., Hollaus, M., Briese, C. and Ducic, V., 2008. 3d vegetation mapping using small-footprint full-waveform airborne laser scanners. International Journal of Remote Sensing 29(5), pp. 1433–1452.

Wehr, A. and Lohr, U., 1999. Airborne laser scanning - an introduction and overview. ISPRS Journal of Photogrammetry & Remote Sensing 54(2-3), pp. 68–82.