Identification of dead trees using small footprint full-waveform airborne laser scanning data

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1. Introduction

Natura2000 is a European cross-border network for the monitoring of endangered and protected animal and plant species (European Commission 2012a). It is a part of the European Union's (EU) so-called Flora-Fauna-Habitat (FFH) directive, which was established in 1992 in order to conserve and protect wildlife and nature (European Commission 2012b). The FFH directive prescribes a regular monitoring cycle of six years for all Natura2000 regions, an area that in total currently covers approximately 778 000 km² (18%) of the EU's land surface. A number of ecologically relevant indicators for the monitoring were defined by the European Commission and expert consortia of the member states, which are to be used for the assessment of the condition of ecosystems. These indicators include the abundance of dead wood in forest ecosystems, which was identified as an important indicator for habitat condition (European Commission 2012c). It offers nutrition, shelter and housing for a number of animal species, and it is of major importance for carbon storage and forest productivity. The assessment of standing and fallen dead trees is therefore part of ecological monitoring and sustainable forest management. However, manual quantification of dead wood in forests is challenging, because extensive fieldwork in sometimes remote and rather inaccessible areas is required. Also, in terms of Natura2000 monitoring, the sheer extent of the areas makes it impossible to carry out the desired monitoring intervals using solely conventional ground-based mapping methods while still being cost-effective.

The EU-funded research project *Changehabitats2* (ChangeHabitats2 2012) aims to develop a monitoring methodology designed for the Natura2000 network, based mainly on remote sensing technologies. Methods of active and passive remote sensing shall be employed in order to support the conventional assessment process and, if possible, replace it partly. For this purpose airborne laser scanning (ALS) and hyper spectral (HS) image acquisition campaigns took place in selected areas in Germany and Hungary in 2011 and 2012. However, for this study we only involve the ALS data, as we want to test the ability of solely ALS to identify dead wood in forested areas. Also, we mainly concentrate on downed and standing dead trees that were partly or completely overgrown by surrounding trees. Their detection with HS data would anyway be difficult if not impossible, as HS imagery depicts the top most canopy and where it can penetrate it, it is highly influenced by object shadows. In several studies (Hyyppä et al. 2004; Næsset et al. 2004; Wagner et al. 2008; Wulder et al. 2012) it was shown that ALS data accurately depict the three-dimensional forest structure down to sub-canopy strata and the forest terrain, and can be employed to derive relevant metrics for quantitative and qualitative description of vegetation. Research has also shown that ALS data provide an excellent basis for the estimation of live and dead biomass in forests. For example, Vehmas et al. (2011) used ALS derived height metrics for the identification of canopy gaps with significant amounts of coarse woody debris (CWD). Bater et al. (2009) identified the coefficient of variation of ALS echo heights as the best variable for prediction of dead tree proportion. Kim et al. (2009) investigated the capability of ALS for the discrimination of live and dead standing tree biomass and found the echo intensity (often also referred to as echo amplitude) to be the most critical measure for accurate estimation. Also Pesonen et al. (2008) derived ALS height density metrics for the prediction of standing and downed dead wood volume. All of the before mentioned examples have in common that they rely on statistical modeling and most often regression analysis for the identification of relevant ALS parameters, correlation analysis and prediction of downed and standing dead wood amounts. To our knowledge only one study exists that investigates the capability of ALS for direct mapping of fallen trees. Blanchard et al. (2011) used methods of object-based image analysis for the mapping of downed logs in gridded ALS data.

Considerable parts of this study are embedded in the on-going research in the *ChangeHabitats2* project, which has a lifetime till the end of 2014. Identification of downed and standing dead trees is a core product of the project. The presented approach for the detection of downed stems has some conceptual similarities to the method described by Blanchard et al. (2011), however we use different input parameters derived from full-waveform (FWF) ALS data. A stepwise process for the detection of fallen trees is proposed, which is based on the combination of point cloud filtering, morphological image processing and map algebra. As opposed to that, our efforts taken for the direct and automatic estimation of standing dead wood in the point cloud were inconclusive up to now. Nevertheless, we present the results of hitherto existing explorative point cloud analysis and give an outlook on future research on this topic within the project.

The following section 2 gives an introduction to the study area, the collected ground truth data and ALS data acquired for the project. Section 3 describes the workflow for the detection of fallen stems and the analysis of the ALS point cloud for the identification of the standing dead trees. All data analysis and processing was conducted using Mathworks Matlab and OPALS software packages (OPALS 2012). Section 4 shows and discusses the results, and section 5 concludes and gives an outlook on future related work.

2. Study area and data

The *Uckermark* is a landscape in north-eastern Germany, its biggest part being situated in the federal state of Brandenburg, the remaining parts in Mecklenburg-Vorpommern. The region is highly fertile, characterized by a number of bigger lakes (the so-called *Naturpark Uckermärkische Seen*) and by various rivers, which are often found together with alder-dominated riparian forests. Apart from that, beech forests, extensive pastures and wet meadows mostly dominate the *Uckermark*. The test site selected for this study is a beech stand (*fagus sylvatica*) with only few other individual species (*quercus robur, picea abies, fraxinus excelsior* and *carpinus betulus*). The structural characteristics of the stand vary from a hall-like appearance (old trees of 30 m and larger with only few to no understory) to successional younger parts (very dense or lots of shrub vegetation). There is only little variation in its relief and a few footpaths and driveways cross the area. Its extents are approximately 1200 x 900 m.

In 2011 and 2012 field-mapping campaigns for the purpose of Natura2000 mapping took place there. During the mapping a significant amount of dead trees (downed and standing) was found. The start- and endpoints of the downed stems (coarse woody debris) with a diameter bigger than 30 cm were measured with a differential GPS (dGPS), additionally their diameter and length were noted. The locations of the standing dead trees with a diameter at breast height (DBH) bigger than 30 cm and higher than 3 m were also measured with dGPS, also additionally their DBH and height were noted. Most of the standing dead trees were broken or decayed to a degree were crown-forming branches were no longer present. Terrestrial photographs were taken of all dead trees found in the area and stored together with the cardinal direction of the image acquisition. In total, 29 downed and 40 standing dead trees were mapped in the study site. Tree stumps and occasional piles of fine woody debris were not considered.

The ALS data were collected in spring 2011 (May 5th and 6th, leaf-on) and in early spring 2012 (March 22nd, leaf-off) using a Riegl LMS Q680i full-waveform system (RIEGL 2012a) mounted on a helicopter. A maximum deflection angle of ± 30°, a minimum lengthwise strip overlap of 50% and a pulse repetition rate of 400 kHz at an average flying height of 500 m a.g.l. resulted in an average point density of 21.8 echoes/m² for the leaf-on and 16.9 echoes/m² for the leaf-off flight (considering all echoes). Echo (i.e. return) extraction from the raw full-waveform data was achieved by Gaussian decomposition (Wagner 2006) implemented in the software package RiPROCESS (RIEGL 2012b). A highly detailed digital terrain model (DTM, grid size 0.25 m) could be created from the last echoes of the leaf-off data using hierarchical robust filtering (Kraus and Pfeifer 1998) and subsequently the ALS point cloud was augmented with the normalized point heights (i.e. the height of the echoes above the terrain). The final point data set included the 3D coordinates of each echo, its amplitude and echo width (i.e. the width of the reflected pulse from full-waveform processing), the echo number, the total number of echoes per emitted pulse and the normalized point height.

3. Methods

3.1 Delineation of downed trees

The high-density point cloud available for this study provides good characterization of downed trees and made a direct identification of the stems possible. The proposed stepwise process (see Figure 1) begins with the selection of the ALS echoes with normalized heights less than 2 m and echo widths smaller than 4.5 ns. The 2 m height threshold is motivated by the fact that the biggest uprooted stems and their vertical root plates are commonly smaller than that. However, shrub vegetation would still be included in this subset and needs to be removed. For this the discriminative power of the echo width is exploited, which was investigated by recent research papers (Doneus et al. 2008; Hollaus et al. 2011; Mücke 2008). The echo width relates to small height variations of scattering elements within the footprint of the laser beam (Wagner 2005). It is therefore a measure of surface roughness and can be used to differentiate between rather smooth (in this case the bare forest ground or the downed stems, which appear also as a smooth surface in relation to the footprint size) and rather rough areas (here the shrub vegetation). In the proposed approach it is used in two ways: (1) directly as a threshold filter for the point cloud in the initial step of the process and (2) as a 0.5 x 0.5 m grid model of the echo width variance of the echoes in between 0.1 and 3 m distance to the DTM (referred to as EW_{var}) for classification purposes in the last step.

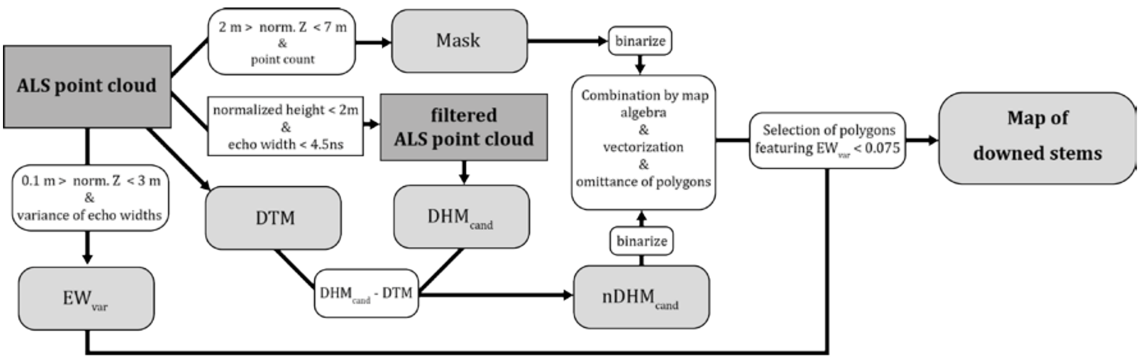

Figure 1: Schematic depiction of the identification workflow for downed stems.

The height and echo width threshold applied together on the point cloud significantly reduced the amount of data, while still including the echoes relevant for stem detection. A highly detailed digital height model is created from the remaining echoes by moving least squares interpolation (further referred to as DHM depicting the stem candidates, $DHM_{cand,}$ grid size 0.25 m). It clearly shows the locations of the downed stems as elongated features (see Figure 2a). Then a difference model is calculated (normalized DHM_{cand}, $nDHM_{cand} = DHM_{cand} - DTM$), to which a height threshold of 10 cm is applied to separate the downed stems as off-terrain features. The resulting model is binarized (1 if $nDHM_{cand} > 0.1$ m else 0) and morphological closing is applied to connect stem areas that have been separated by the height thresholding and

to fill holes. The remaining image includes elongated areas representing the downed wood and spot-like features which are supposed to result from the stems of standing trees (see Figure 2b). To eliminate the spot-like areas we make use of the obvious fact that the stem of a standing tree continues above the initial 2 m height threshold and, due to the high point density, is represented by ALS echoes. A grid mask is created from the ALS echoes above 2 m and below 7 m including the point count per 1 x 1 m grid cell, which is then binarized (1 if the model exists, else 0) (referred to as $MASK_{bin}$). Using map algebra the grid models $nDHM_{cand}$ and $MASK_{bin}$ are combined and the resulting binary image is converted to vector format (ESRI shape), a process during which all polygons smaller than 3 m² are omitted because the chance for them being a stem is highly unlikely. The resulting vector map is spatially joined with the EW_{var} raster map and only the polygons featuring a small echo width variance (standard deviation of EW_{var} per polygon < 0.075) are selected. This final step further eliminates wrongly classified areas that are identified as near-ground vegetation due to higher surface roughness. The final vector map represents the outlines of the identified downed stems (see Figure 2c).
Visual comparison of the field-measured locations of the downed stems and the DHM_{cand} revealed that the positional accuracy of the stems mapped with dGPS was after all not good enough. Although every field-measured tree could be assigned a corresponding one in the DHM_{cand}, deviations of 1-3 m were observed, which made a direct automatic comparison with the automatic identification result (e.g. on pixel or object level) impossible. In fact, we found even more downed trees in the area through examination of the DHM_{cand}. To create a complete evaluation data set, the fallen stems that could be visually identified on the basis of the DHM_{cand} were manually digitized. The so created data set was then used for manual accuracy assessment of the automated method and concentrated only on the fact whether a stem was found (lengthwise overlap of reference and ALS-derived outlines > 75%), partly found (lengthwise overlap < 75%) or not found (no overlap).

3.2 Point cloud analysis for identification of standing dead trees

To investigate the representation of standing dead trees in the ALS point cloud, first sample trees had to be located in the study area. It was expected that the dGPS measured locations of the standing trees were prone to the same errors as the ones of the downed stems. Therefore, these locations were only used as initial positions for manually browsing the point cloud. From the data collected in the field, the height and diameter of the tree, as well as the information whether it still had a crown, was known and useful for identification of the trees. Twelve standing dead trees that distinguished themselves clearly (two of which still had a crown) could be selected. Their dGPS locations were subsequently corrected. Additionally, also twelve live trees were selected for comparison. The locations were used as centre points for a cylindrical extraction with a radius of 2.5 m of the ALS data. For the extracted 24 data sets explorative point cloud analysis was carried out. The different representations of live and dead standing trees concerning the point distribution (i.e. number of echoes in a certain height interval), the FWF attributes echo width and amplitude were investigated per sample tree. The investigations were carried out for the leaf-off and the leaf-on data set, likewise. For visualization purposes boxplots were created, showing the distribution of the tested echo attributes with respect to the corresponding normalized point height (see Figure 3 and Figure 4).

4. Results and discussion

4.1 Delineation of downed trees

The results of the stepwise identification process are shown in Figure 2. The shading of the DHM_{cand} (Figure 2a) clearly shows a number of downed trees in this part of the study area, some of them have a vertical root plate. They are further highlighted by the binarized $nDHM_{cand}$ (elongated shapes in Figure 2b). This image also shows the spot-like areas that are supposed to represent stems of standing trees and remaining areas of near-ground vegetation, which were not removed entirely by the echo width filter applied to the point cloud. Figure 2c shows the final outlines of the automatically identified downed stems. In this part of the study area all but 2 stems were detected, 3 stems were only partly found. For the whole study area, out of a total of 193 manually digitized stems, 72 stems were fully detected (37.3%), 64 partly (33.2%) and 57 were not found (29.5%).

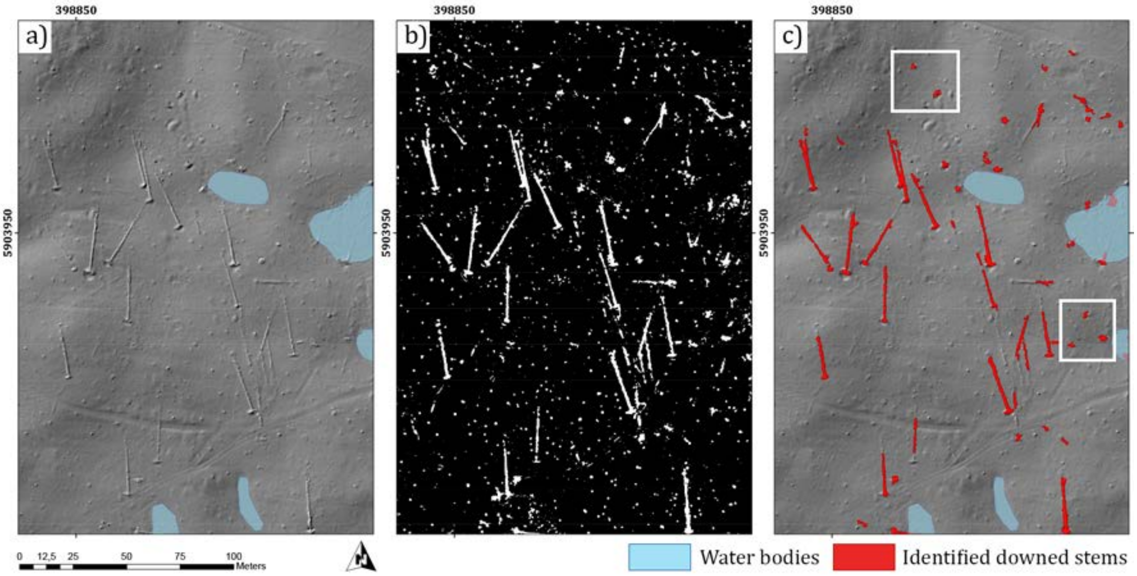

Figure 2: a) Shading of DHM_{cand} overlaid with manually digitized water bodies; b) binarized $nDHM_{cand;}$ c) DHM_{cand} overlaid with identified downed stems (given coordinates are ETRS89 / UTM33 N).

The quality of the result is highly dependent on the DTM. On the one hand, the terrain modelling process (also referred to as filtering) has to be rather rigorous, as the initial echo selection is based on normalized point heights. Consequently, if the downed trees have a diameter smaller than 10 cm or are in an advanced state of decay, the height threshold applied to the $nDHM_{cand}$ excludes them. On the other hand, if the filtering is too rigorous, also small terrain bumps are filtered, which exhibit the same characteristics as downed stems (rather smooth areas in comparison to the laser beam and impenetrable, also often bigger than 3 m²). They therefore appear as spot-like polygons in the final result and are false positives (meaning polygons that were automatically classified as downed stems, but were not represented in the reference data), and cannot be excluded by FWF-ALS criteria. Some of the spot-like polygons in the final vector map (e.g. inside white rectangles in Figure 2c) were identified by the photographs taken in the field as (1) near-ground vegetation (shrubs and creepers), (2) piles of twigs or fine woody debris, and (3) vertical root plates of nearly fully decayed downed trees. We assume that (1) and (2) were too densely intertwined and hence featured comparable surface roughness to the downed stems. While case (1) is problematic, cases (2) and (3) are of course correct and a desirable result, but up to now our efforts to distinguish them were unsuccessful. Using additional geometric criteria, e.g. like perimeter-area ratio, might bring improvement, but evidently it would also delete objects that were identified correctly. Undoubtedly, this is the trade-off between completeness and correctness of the result, which has to be accepted using the proposed method.

4.2 Point cloud analysis for the identification of standing dead trees

For the explorative point cloud analysis, the ALS data were divided into subsets holding only first, last, single and all echoes, in order to investigate the influence of the different return types. In concurrence with other existing studies we found the echo distribution and the echo amplitudes to be the strongest indicators for discrimination between standing live and dead trees. However, significant differences between the different return types were not observed. On the contrary, the more echoes were included in the analysis, the better the discriminatory power turned out to be. The boxplot given in Figure 3 shows that the echoes from dead trees are at both acquisition times more equally distributed than the ones for live trees. This is partly due to the high number of dead sample trees without a crown in our study area, but nevertheless it serves as an indicator for trees at this stage of decay.

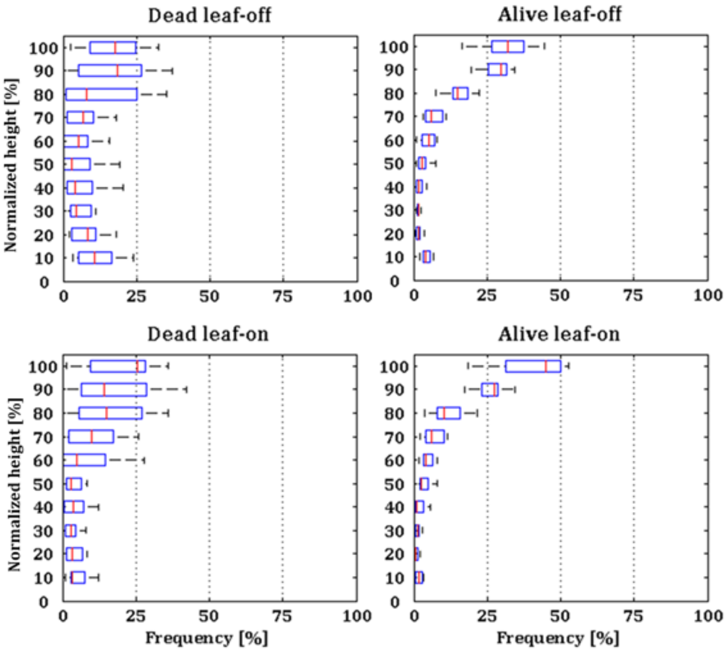

Figure 3: Boxplots showing the point distribution of all ALS echoes from the leaf-off and leaf-on data for the selected standing live and dead trees (red mark = median, blue box = 0.25 to 0.75 quantile, black line = data range without outliers).

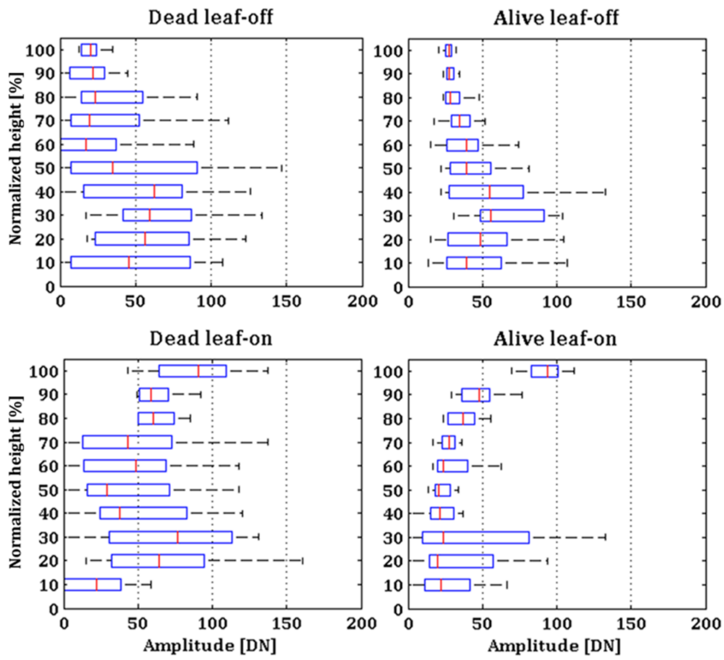

Figure 4: Boxplots showing the echo amplitudes of all ALS echoes from the leaf-off and leaf-on data for the selected standing live and dead trees (red mark = median, blue box = 0.25 to 0.75 quantile, black line = data range without outliers).

A relevant difference between leaf-off and leaf-on data could not be observed, although this is assumed to be a critical indicator for identifying standing dead trees that still have crown-forming branches, as it directly refers to vegetation phenology. Unfortunately, the subset of this tree type in our study area was too small to further elaborate on that matter.
In contrast, the echo amplitudes feature significant differences for leaf-off and leaf-on data, which can be seen in Figure 4. While again the distribution for the dead trees is rather equal for leaf-off and leaf-on, the trend for the live trees behaves contrarily. It shows significantly higher amplitudes in the top 30% of the echoes in the leaf-on than in the leaf-off, which is most likely caused by green foliage and its high reflectivity in the near infrared. This is also the strongest discriminator if employed for identification of dead trees during leaf-off season and live trees during leaf-on season using only the echoes in the top 30% of the tree heights. The high amplitudes in the leaf-on data set in the top most parts of the dead trees are most likely caused by branches of surrounding live trees, partly-overgrowing or growing into the dead tree.

5. Conclusion and outlook

This study investigates the capability of ALS for the identification of individual dead trees in forest ecosystems. The proposed workflow produces a vector map containing the outlines of the downed wood, which can further be used for clipping the ALS point cloud and selecting only echoes from downed trees. Also the vertical root plates are picked up in the data set of a density of approx. 20 echoes per m². Subsequently, cylinder fitting could be carried out in the 3D data to derive the dimensions of the stems. Based on the explorative point cloud analysis we envision a penetration index map on a grid basis for area wide identification of standing dead trees. It comprises the number of echoes in certain height intervals compared to all echoes and is therefore a measure of point distribution and penetration depth. Also, a map incorporating the ratio of amplitudes from the top 30% of all echoes (referring to the normalized echo height) from leaf-off and leaf-on ALS data can be conceived. Both maps will be subject in further studies and will be tested for their significance in identifying standing dead trees.
The information provided by the results of this study can be used to directly assess the state of ecosystems or, multi-temporal data acquisition assumed, highlight the ones where significant changes took place (so-called hot spots). Experts in FFH-mapping are then able to precisely select the Natura2000 habitats where they need to go and others, less affected or changed areas, can be treated with lower priority, thus improving the entire time- and cost-efficiency.

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