3D Point clouds for forestry applications

Markus Hollaus, Wien

Abstract

This article gives an overview of the state of the art 3D data acquisition systems (i.e. airborne laser scanning and digital aerial cameras) and the derivation of forestry related information from the derived 3D points clouds. The described examples are focusing on forest area delineation, growing stock and biomass estimation, forest growth assessment, forest road extraction as well as its changes. The shown examples are located in the Alpine space and discuss the possibilities and limitations of integrating these data sources into operational forestry applications.

Keywords: Forest delineation, growing stock, forest roads, image matching, laser scanning

Kurzfassung

In diesem Beitrag wird ein Überblick über gängige Erfassungsmethoden von 3D Informationen gegeben. Die Nützlichkeit derartiger 3D Informationen für die Forstwirtschaft wurde im letzten Jahrzehnt im Rahmen von wissenschaftlichen Studien und praktischen Anwendungsbeispielen im Alpinen Raum eindeutig dargestellt und belegt. Die aus der Differenz von Oberflächenmodellen und Geländemodellen berechnete normalisierte Kronenhöhe spielt dabei eine zentrale Rolle, da sich daraus direkt Baum- und Bestandeshöhen bestimmen lassen und weiterführend auch Informationen über Holzvorrat oder Biomasse durch Regressionsmodelle oder Strukturparameter mittels einer Analyse der vertikalen Punktverteilung ableiten lassen. Liegen multitemporale Daten wie zum Beispiel Oberflächenmodelle aus mehreren Zeitpunkten vor, so können Fragestellungen wie die Abschätzung der Nutzung aber auch des Zuwachses beantwortet werden. Ebenso eignen sich Airborne Laserscanning (ALS) Daten gemeinsam mit multispektralen Orthophotos für die Detektion von Forststraßen sowie deren geometrische Beschreibung. Die in diesem Beitrag beschriebenen Methoden und Beispiele wurden von der Forschungsgruppe Photogrammetrie des Departments für Geodäsie und Geoinformation der TU Wien, oftmals mit Partner aus der Wissenschaft und Praxis entwickelt und durchgeführt.

Schlüsselwörter: Waldabgrenzung, Holzvorratsschätzung, Forststraßen, Image Matching, Airborne Laserscanning

1. Introduction

Forests have a variety of functions and demands such as being habitat for animals and plants, recreation area, source for renewable resources or to fulfill protection and environmental functions. The production of renewable resources, like timber, has positive effects on climate change consequences attenuation, employment and supports a strong regional value chain, which in turn has an enormous impact on rural development. The objective of preserving and improving the efficiency of forests is a point of public interest and can only be guaranteed if the planning and implementation of all respective measures are integrated into an adequate and well known socio-economic context. Especially, the managing of forests in mountain territories is significantly more cost intensive than in plain ones. This is due to the topographic conditions, climatic adversity and limited access which drive partly the economic context. A good knowledge of the forest biomass location, its characteristics and mobilization conditions (exploitability, service roads, and mobilization costs) is therefore, a prerequisite for effective wood harvesting and transporting, which contributes to a sustainable wood industry. The available traditional in-situ forest inventories, which are commonly based on sample plots, provide this required information only with a limited spatial and temporal resolution due to the used sampling design (i.e. sample plots distributed over an area), which allows only statistical analyses for larger administrative units, and the high costs. In terms of spatial and temporal resolution remote sensing technologies have shown their high potential to acquire additional information. For the operational forest management the most important remote sensing technologies are airborne laserscanning (ALS) and digital aerial photography, which allow the derivation of three-dimensional (3D) information of forests (i.e. tree heights, stand density, horizontal and vertical forest structure).

The objective of this paper is to give an overview, how 3D information derived from these two technologies can be used for current forestry applications. In the following chapters the generations of 3D data from ALS data and digital aerial images, their availability as well as possibilities to extract forestry relevant information are described. The focus of the described methods and its applications is on studies performed at the research group Photogrammetry at the Department of Geodesy and Geoinformation (GEO) at TU Wien. Therefore, this paper doesn't include a thoroughly state of the art on an international level.

2. 3D data acquisition methods

In this article 3D data acquired with different airborne laser scanning systems as well as derived from image matching of digital aerial photos are used for deriving forestry related information. Satellite-based systems (e.g. ICESat/GLAS [1]) are not considered in this paper. In the following two chapters a short state of the art of both technologies is given.

Airborne Laserscanning

Small-footprint airborne laser scanning (ALS), often referred to as LiDAR, is an active remote sensing technique, which was originally designed to measure the topography of the Earth's surface (i.e. of forested areas). A laser mounted in a helicopter, fixed wing airplane or in an unmanned airborne platform emits short infrared pulses towards the Earth's surface and a photodiode measures the backscattered signal. The count of detectable echoes in the backscattered waveform is depending on the used sensor type and the objects within the travel path of the laser pulse. State of the art discrete laser scanner systems measure the round-trip time of multiple echoes from one emitted laser pulse, whereas full waveform (FWF) systems record the entire backscattered waveform [2]. The newest generation of ALS systems has multiple-time-around processing [3] and the capability of multiple wavelengths [4]. The final 3D coordinates of the backscattering objects are derived by the combination of all measurement quantities (e.g. the distance between the sensor and the target, the position (i.e. dGPS) and the orientation (i.e. IMU) of the sensor and the instrument mounting parameters). Further details about the physical principles of LiDAR and about ALS specifications and sensors available in the beginning phase of small-footprint ALS (i.e. 1990's) are given in Kilian et al. [5], Baltsavias [6, 7] and Wehr and Lohr [8].

To achieve a high precision georeferenced 3D point cloud inaccuracies of the individual ALS system components have to be minimized as for example presented by Kager [9], Burman [10] or Filin [11]. Direct georeferencing requires the position and orientation of the measurement platform, which are measured by dGPS and INS. The laser scanner measurements are the beam direction and the ranges per shot. Additionally, the relative orientation of the laser scanner and the navigation components (lever arm, boresight angles) need to be know. In strip adjustment the lever arm and boresight are estimated from discrepancies between overlapping strips. Additionally, systematic errors in angle and range measurements can be compensated.

Image matching

The introduction of digital cameras has restimulated the traditional stereo photogrammetry towards fully automatic 3D reconstruction of objects from multiple overlapping images. Due to good signal-to-noise ratios (digital vs. analogue detection) and high overlaps between the individual images, digital images and the all-digital workflow have advantages compared to scanned analogue ones with respect to accuracy, reliability and density of automatic point measurement [12]. The principle of image based 3D reconstruction consists of detecting and matching corresponding image features (e.g. points) across two overlapping images. And then, the coordinates of the corresponding 3D object are computed using spatial intersection.

Image matching algorithms can be classified in different manners. Matching may either be performed for salient points or at regular pixel positions (e.g. every n-th pixel). Also, correspondences between points in the images may be found by local or global optimization techniques. Three groups of algorithms are currently used: local area-based [e.g. 13], local feature-based [e.g. 14] and (semi-)global cost-based matching [e.g. 15, 16]. This classification reflects also the historical development of the methods. Other possibilities of categorizing matching approaches are sparse and dense matching or local and global matching methods. An overview of the development of image matching techniques in photogrammetry can also be found in Gruen [17].

For area-based matching, points are selected only in one image, whereas the corresponding points in the other image are found by correlation. This type of matching methods is less robust, slow and needs good initial approximations but it is capable of achieving very high matching densities. By using least squares matching [13], which is an evolved variant of area-based matching, very high accuracies (~1/10 pixel) are possible.

Feature-based matching methods extract salient features (usually points) together with descriptive attributes (like grey level gradients) in the overlapping images independently and match corresponding image features as the nearest neighbors in the descriptor space. This type of methods is highly robust, fast, needs only a coarse initial approximation and can achieve accuracies of ~1/3 pixels.

Semi-global matching [15] is a dense image matching method that uses a semi-global optimization. Thereby, for each pixel in the first image the corresponding pixel in the other image is searched for, by minimizing a cost function. The latter consists of the difference of a function of the pixel gray values (e. g. census transform [18]) and smoothness penalty terms. The cost function is evaluated along different paths through the image. The penalty terms increase the robustness of this approach and aim at minimizing the disparity difference of neighboring pixels. This means that neighboring 3D points at the object should have the same depth from the image pair. However, since the gray value differences and the smoothness penalty terms are competing in the cost function, obtaining very small gray value differences by hurting the penalty terms with large disparity differences (e. g. at roof edges) is still possible. As summarized in Wenzel et al. [19] the semi-global matching approach has a high matching stability even though the matching is done pixel wise, which minimizes smearing effects like for local methods.

Due to the high overlaps commonly multi-image matching is used, which reduces errors due to disturbances in the intensity distribution of the images. Most of the available matching approaches still perform a pair wise image matching (for selected pairs among all images) and afterwards compute a fusion of the derived surface models. In contrast, Rothermel and Haala [20] suggested to use an overdetermined spatial intersection based on multiple pairwise image matching with one central/master image.

Due to the fact that in stereo photogrammetry 3D coordinates are derived by spatial intersection areas that are visible from only one exposure position can not be reconstructed. This fact has to be considered if the matched 3D point clouds are used for forestry applications. In Figure 1 the 3D points from an ALS acquisition and the points from image matching are shown for a forest cross section. It can clearly be seen that the points along the top surface of the canopy fit well together and that only ALS points are measured within the forest canopy and at the ground. Further information about the derived 3D point clouds from different image matching approaches in comparison to ALS data can be

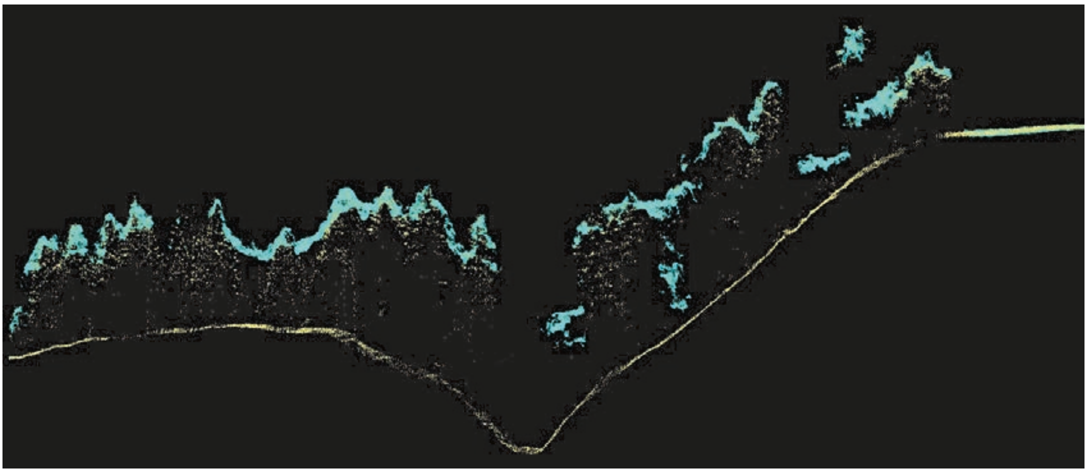

Fig. 1: Cross section of a forest scene. Length of the profile is 200 m, width 2.5 m. The yellow dots are from an ALS acquisition, the blue one from image matching. The image matching points are in the foreground. Aerial photos where acquired with an Ultra-Cam XP with a length overlap of ~80 % and a side overlap of ~50 %. The GSD is ~12.5 cm. For the matching SGM within SURE was applied. The ALS data was acquired in April 2011 with an average laser shot density of ~20 shots/m^2.

found for example in Baltsavias et al. [21] and White et al. [22].

Derivation of topographic models

From the 3D point cloud topographic models, such as the digital terrain model (DTM), the digital surface model (DSM) and the normalized digital surface model (nDSM) are derived. A clear definition of these models can be found in Pfeifer [23].

For the studies outlined at the research group Photogrammetry at TU Wien, the DTMs were calculated using the hierarchic robust filtering approach described in Kraus and Pfeifer [24], implemented into the software Scop++ [25]. An overview of alternative filtering algorithms can be found in Sithole and Vosselman [26]. For forested areas the DTM can only be derived from ALS data because the 3D points from image matching represent the top canopy surface and the terrain for larger forest gaps only. Therefore, it is not possible to derive an appropriate DTM in areas covered with dense forests from matched point clouds. For the calculation of the DSMs a land cover dependent derivation approach [27] is commonly applied. This approach uses the surface roughness to combine two DSMs that are calculated based (i) on the highest 3D point per raster cell (DSM_{max}) and (ii) on moving least squares interpolation (DSM_{mls}) of a local point cloud.

For the final DSM the DSM_{max} is selected for rough surfaces (i.e. forests, building borders, etc.) and the DSM_{mls} for smooth surfaces such as non-forested areas, building roofs, etc. and for raster cells where DSM_{max} is nodata. The nDSM is calculated by subtracting the DTM from the DSM. In addition to these topographic models slope adaptive echo ratio (sER) maps [28], as a measure for local transparency and roughness of the top-most surface, are commonly calculated. The sER map is a useful information source within the forest area delineation workflow. The spatial resolution of the derived raster models is usually $1\times1\ m^2$. The applied workflows for calculating the topographic models as well as the subsequent forest relevant products are commonly implemented as Python scripts including Opals software [29] packages.

Data availability

In Austria the data acquisition of ALS data and aerial images is organized in different ways. The ALS data are commonly acquired in federal state wide ALS campaigns whereas each federal state defines its own requirements to the data properties. For the aerial image acquisition an Austria wide acquisition plan exists with a repetition cycle of three years. The standard properties for this acquisition are four spectral channels (i.e. red, green, blue and near infrared) with a ground sampling distance of 20 cm. More information can be found at www.bev.gv.at and at www.geoimage.at.

For the acquisition of the ALS data no Austria wide repetition cycle exists yet. Until now entire Austria is covered by ALS data, whereas the data sets are commonly available at the federal states. For the federal state Vorarlberg an ALS re-flight was already done after ~6 years in 2011. For the other federal states the discussions about a regular acquisition of ALS data have partly been started yet.

On the European level the data availability is similar for the aerial images. The situation for ALS data is diverse. For some countries a full coverage of ALS data is already available, for some other countries the data acquisitions are still ongoing.

3. Forest relevant parameter from 3D point clouds

Forest area

Forest area delineation has a long tradition in forestry and is critical as a broad field of applications (i.e. obligatory reporting) and users (i.e. governmental authorities, forest community) rely on this information. In the past mainly the 2D content of aerial images were used for a manual or semi-automated delineation. Shadow effects and varying radiometric properties of the spectral images make this process to a challenging task, particularly for detecting small forest clearings and the exact delineation of forest borders on a parcel level. Additionally, the quality of the results of a manual delineation is subjective and variable between interpreters and may lead to inhomogeneous, maybe even incorrect datasets [30].

For the practical applications of forest delineations it is essential that the used approaches can consider e.g. national and/or international forest definitions as for example, the one from the FAO (Food and Agriculture Organization of the United Nations) [31, 32]. Most of the forest definitions are based on the parameters crown coverage, minimum area and width, minimum tree height and the land use. Whereas the area, width and tree height are clearly defined parameters the

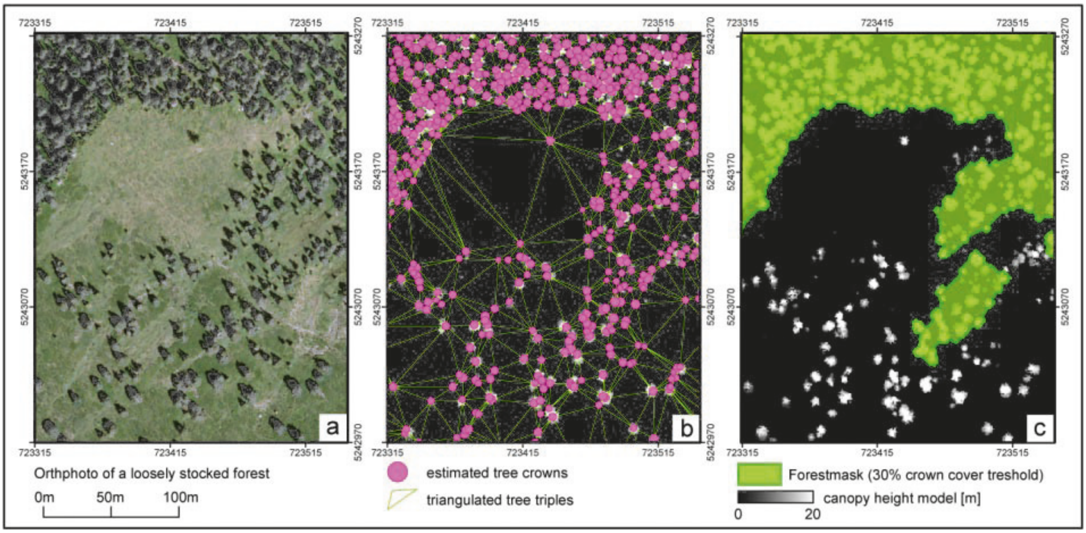

Fig. 2: Delineation of forested areas based on LIDAR data; a) orthophoto of a loosely stocked forest, b) estimated tree crowns and detected tree tripels, c) delineated forest areas (in the background is a z-coded canopy height model) © [39]

crown coverage is often not defined in a unique way, meaning the information about the reference area for calculating the crown coverage is often missing. In general, the crown coverage is defined as the proportion of the forest floor covered by the vertical projection of the tree crowns [33]. With respect to remote sensing based forest area delineation the parameter land use is commonly not extractable from the data itself and therefore, additional information is needed if the land use has to be considered. For example a Christmas tree plantation cannot be differentiated from forests in remote sensing data. Beside this limitation most of the parameters used for forest area delineation need the height information included in 3D data. As shown in Figure 1, ALS provides both the information about the terrain and the canopy surface and is therefore, an excellent data source for this application. If surface models derived from image matching are used a DTM derived from e.g. ALS is needed to calculate the tree heights. This is especially important for areas with high topographic relief energy and a low percentage of forest gaps where it is not possible to assess a reliable DTM from image matching.

In literature several approaches are available that uses 3D data from ALS data and/or images for forest area delineation [e.g. 34, 35-37]. Eysn [38] suggested a new approach for crown coverage estimation based on ALS data which has clear defined geometric properties and which works on a similar way than it is the case for manual assessment of the crown coverage based on aerial orthophotos. This approach uses the area of the convex hull of three neighboring trees as reference unit and thus, overcomes limitations from e.g. pure moving window approaches such as smoothing effects along the forest border or the dependency of the kernel size and shape of the moving window. The positions of single trees are detected by applying a local maxima filter on the nDSMs. Furthermore, Eysn et al. [30] presented a comprehensive approach for forest area delineation based on ALS data by considering the criterions tree height, crown coverage and the minimum area and width. The criterion of land use is not considered in this approach. Based on the sER map, which describes the transparency for laser beams of the top most surface, it is possible to differentiate between buildings and trees. As shown in Figure 2, a reliable and objective forest area can be derived from ALS data by applying this approach.

If ALS-based DTMs and DSMs derived from image matching are used for forest area delineation the surface roughness and/or the spectral properties of the aerial images can be used for excluding buildings from the forest mask instead of the sER map.

Growing stock and biomass

Growing stock is a key parameter in forest management and provides the basis for the estimation of biomass. The term growing stock is commonly used as a synonym for stem volume and is given in m^3/ha. Biomass is often derived from the growing stock by using tree species specific biomass expansion factors [40, 41]. For the estimation of growing stock and biomass from ALS data two principle approaches are available. The first one models individual trees [e. g. 42, 43] based on ALS data with point densities greater than e. g. 3–5 points/m^2 whereas the second one works on a larger scale e. g. on a plot- or stand level. These so-called area-based approaches can be applied for large areas and for ALS data with lower point density for assessing e. g. the mean canopy height (m), growing stock (m^3/ha) or basal area (m^2/ha). Due to their robustness this type of models are already included into operational forest inventories [e. g. 22, 44, 45-49]. The area-based approaches can further be divided into empirical, semi-empirical and physical models, whereas the application of the physical models is often limited due to missing data for the model parameterization. For the calibration of the empirical and semi-empirical regression models reference data are needed. Commonly data from local or national forest inventories (i. e. inventory plots) are used for this purpose. Often these models have the limitation of a lacking sensitivity to local forest conditions. This means that growing stock or biomass models are often calibrated for large areas (e. g. entire federal districts) and thus, local changes of the forest structure are not considered, which has the effects that the resulting models are smoothing the local situation. Within several research projects at the research group Photogrammetry at the TU Vienna, the semi-empirical regression model from Hollaus et al. [50] was applied to different strata. This model assumes a linear relationship between the growing stock/biomass and the ALS derived canopy volume, stratified according to four canopy height classes to account for height dependent differences in canopy structure. For the stratification different information obtained from remote sensing data can be used. This information can for example be a tree species classification based on aerial images as presented in Waser [51] or from full-waveform ALS data presented in Hollaus et al. [52]. In addition to tree species information crown coverage based stratification has shown a high potential to consider local forest conditions. For our studies we used the criterion "species" to classify the forest into deciduous, mixed and coniferous forest and the criterion "crown coverage" to differentiate between dense and sparse coverage. To use a stratified growing stock assessment it is beneficial if the information needed for the stratification can be derived from the analyzed data (i. e. ALS data, aerial images that are used for reconstructing the canopy surface) itself. Otherwise issues concerning different spatial resolution and acquisition times as well as geo-referencing issues have to be solved. For operational large area applications the stratification should be possible in a highly automatic way. Our studies have shown that the stratification based on the main tree species group and the crown coverage leads to an enhancement of the assessed growing stock by reducing the relative standard deviation of ~4%. Furthermore, the

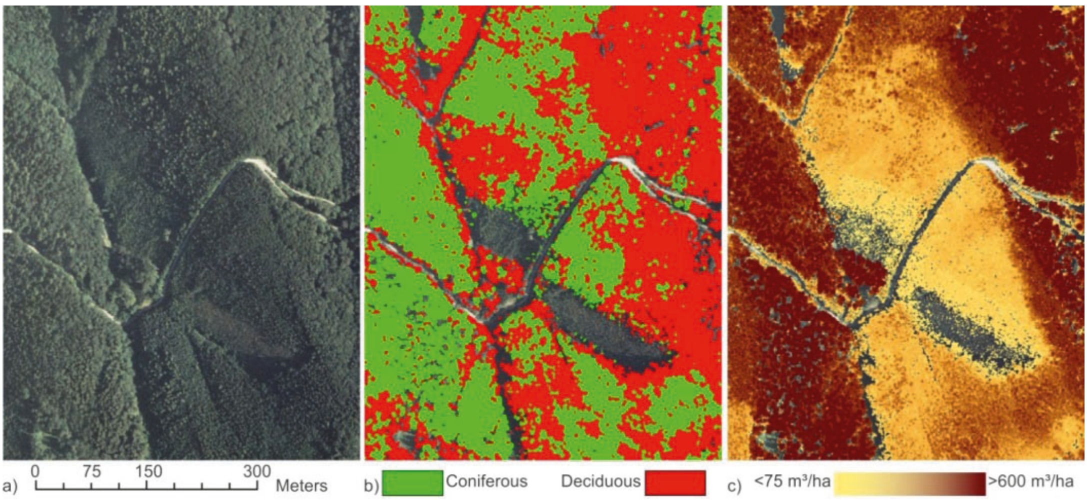

*Fig. 3: **(a)** Orthophoto © bing maps, **(b)** classified tree species map and **(c)** tree species dependent growing stock map © [57]*

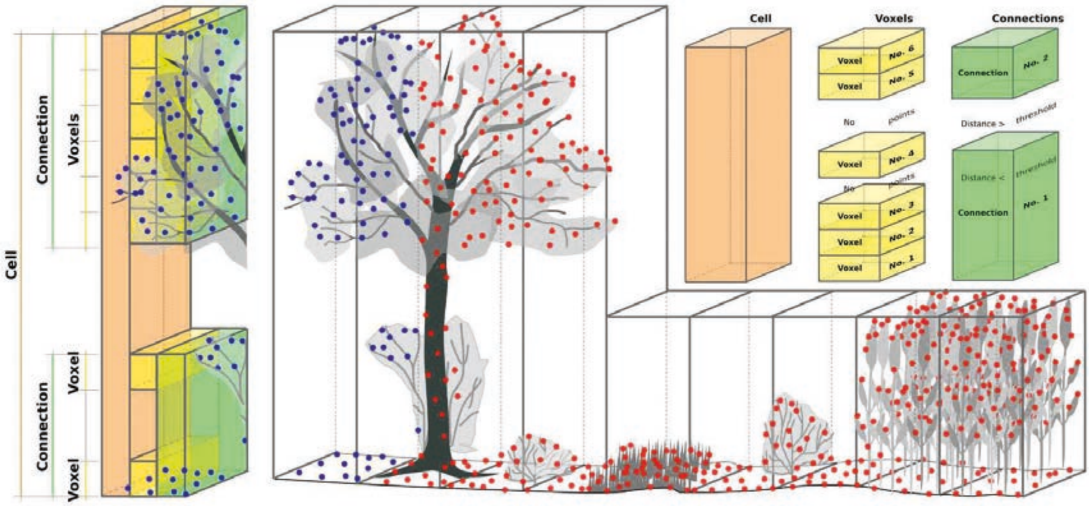

Fig. 4: Schematic view of vertical structure extraction from 3D point clouds © [68]

analyses have shown that growing stock maps with very high spatial resolution can be derived from ALS and forest inventory data. These maps allow comprehensive forest management for large areas and serve as input data for various forest planning activities. In Figure 3 an example from a stratified (i.e. coniferous and deciduous forests) growing stock map is shown. The stratification was based on full-waveform ALS data.

In literature most of the studies about growing stock estimation are based on ALS data. Due to the increasing availability of multi-epoch DSMs from image matching a research project was done together with the Austrian research center for forests (BFW) to investigate the potential of image matching in combination with ALS-based DTMs for estimating growing stock and its changes for different Austrian test sites [53]. It could be shown that compared to previous ALS studies similar accuracies of the assessed growing stock could be achieved. The high potential of 3D point clouds derived from stereo images in combination with ALS-DTMs for stem volume estimation is also confirmed in e.g. Straub et al. [54] and Bohlin et al. [55]. Finally, regional stem volume estimations derived from e.g. ALS data provide an excellent data source for calibrating as well as validating biomass models derived from optical satellite data [e.g. 56].

Forest structure

The information on horizontal and vertical forest structure and its diversity is one of the most valuable indicators for forest habitat quality assessment. Diversity of structure indicates diversity of species and also different ecological niches are created [58]. For mapping the vertical structure ALS provides excellent data because the laser beams are able to penetrate through small gaps in the top canopy surface and depict the vertical canopy structure down to the forest ground [e.g. 59, 60-63]. Especially, full-waveform ALS system sample the full backscattered pulse information, which allows the extraction of more echoes compared to discrete ALS systems [64, 65]. This makes full-waveform ALS data to an excellent data source for describing the highly complex structure of dense forests such as old unmanaged deciduous forests or tropical rainforests. An overview of the potential of full-waveform ALS data for forest structure extraction is given in Hollaus et al. [66]. In Mücke [67] different methods for extracting structure information from ALS data on pixel and plot levels are given. This structure information includes the number of vegetation layers (e.g. one-, two- or multi-layered forests) and the amount of standing and fallen deadwood. One of the most important forest structure quantities is the number and the geometric extend of the vertical vegetation layers. This information can be derived from ALS derived 3D point cloud or from 2,5D rasterized topographic models such as the nDSM derived from ALS or image matching. Depending on the used input data (i. e. 3D point cloud, nDSM) different reference areas can be analyzed. If 3D ALS point clouds are available Vetter et al. [68] suggested a voxel-based approach for extracting detailed vertical layers. In Figure 4 it can be seen that so-called connections, which represent a forest layer, are defined by connecting voxels that are occupied by laser echoes. This type of analyzes can be done on a voxel level. Also Leiterer et al. [60] developed a physically-based extraction method of canopy structure variables on grid level. In the opposite of these analyzes the study of Maier [69] uses the nDSM as an input data, whereas larger reference units (e. g. forest stand, forest plots) are used. The canopy height is classified into three classes (i. e. height layers), which are used for classifying a forest stand for example into single- and multi-layered forests.

Change detection

The high potential of ALS data for forestry applications has been confirmed in many studies during the last decade. The open question is still the application of ALS data for monitoring applications. Due to the ALS data acquisitions costs re-acquisition are rare and only few regular acquisition plans are available until now. Consequently there is on the one hand a lack of data and on the other hand a lack of knowledge of using multi-temporal 3D data for forest monitoring tasks. Therefore, the capabilities of 3D data for operational forest monitoring applications were analyzed in several research projects.

For change detections applications it is essential that height differences between the individual topographic models originating from inaccuracies in the georeferencing are minimized. To avoid errors for example in the assessed growing stock change originating from DTM errors due to different terrain point densities one reference DTM can be used for both dates. It can be assumed that the DTM within the forests don't change during two acquisitions. Therefore, the DTM with the highest accuracy should be used, which can normally be determined from the ALS data set with the highest terrain point density. In our projects the quality checks of the topographic models have shown that even for stable objects (i. e. open areas, roofs and streets) height differences occur. For the change detection analyses of our projects these height differences were minimized by applying a least square matching (LSM). Calculating the LSM of the identified stable objects 3D shift parameters are determined and applied to one of the DSMs. Using the LSM the DSM differences could be halved (e. g. <10 cm). Due to this height adjustment the remaining height differences can mainly be connected to changes of tree heights and consequently to growing stock changes.

Based on DSM difference maps changes in the wooded land can be detected. For differentiating between exploitation and forest growth the area is classified into areas with an (a) increased (= forest growth) and (b) decreased (= exploitation) surface height. As for each 3D data set small differences in the tree crown representation

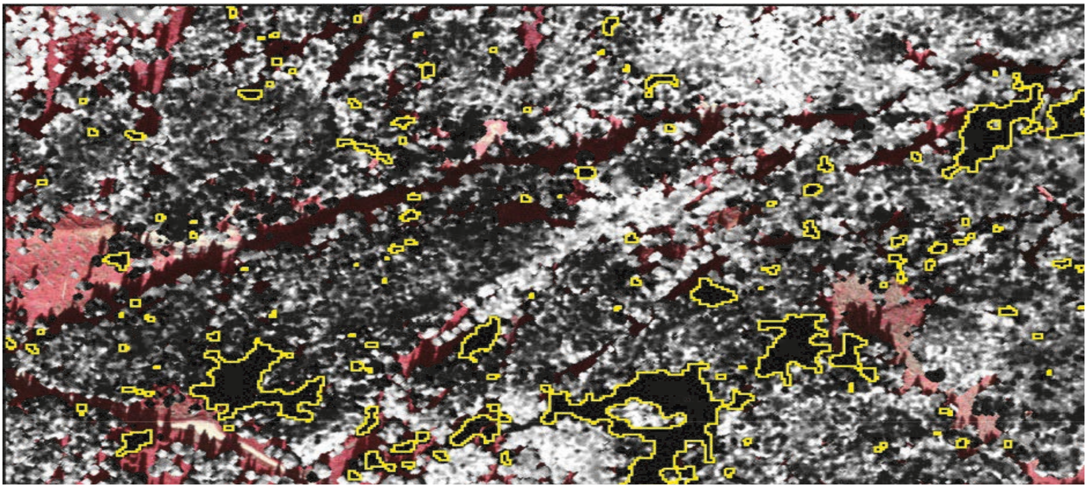

Fig. 5: Difference map of estimated growing stocks (2011–2004) overlaid with the detected outlines of the harvested forest areas. In the background a CIR orthophoto is shown [53].

within the DSMs can occur, morphologic operations (i.e. open / close) and a minimum mapping area of e.g. 10 m^2 are applied to the DSM difference map.

The calculated nDSMs are used as input for the growing stock regression models (see previous chapter), whereas each data set is calibrated with the corresponding forest inventory data. For each classified area (exploitation, forest growth) the changes for the assessed growing stock are analyzed separately. Finally the derived growing stock maps are validated with the corresponding FI data. It could be shown that the total amount of growing stock changes, divided into exploitation and forest growth, derived from the estimated growing stock maps from the entire study area, are similar to those derived from the statistical analyses of the in-situ forest inventory data. In Figure 5 a difference map of estimated growing stocks (2011–2004) overlaid with the detected exploitation areas is shown. The visual validation shows that the applied work flow for detecting harvested areas work well even on the level of single trees. Using GIS tools the total amount of harvested growing stock can be calculated for example for each exploitation polygon. For the estimation of the forest growth an averaging within homogenous areas (e.g. forest stands) is required to avoid errors originating from different tree crown representations (i.e. due to varying ALS point density, ALS sensors, ALS acquisition properties, image matching quality, wind effects, etc.) on a single tree level.

Forest road extraction

An optimal planning of forest harvesting and logging relies on an up-to-date forest roads network. Ideally this network allows automatic routing for optimizing the transportation routes. Additionally the combination of growing stock maps and a routable forest roads graph enables efficient planning and optimizing of cable crane positions. In contrast to public roads, which are of high interest for the society, forest roads are often not mapped or were mapped with insufficient information for routing. Therefore, the task of updating the forest roads network is fundamental for heading into the direction of an efficient forest management and wood supply chain. Within several research projects at the research group Photogrammetry, a semi-automatic method for extracting forest roads from ALS data was developed. ALS data can deliver terrain information below dense canopies which enables an extraction of forest roads even in dense forested areas. This is an advantage compared to methods which purely rely on orthophotos. The developed algorithm relies on a weighted graph, automatically extracted from ALS data using watershed methods and slope information of the terrain. Additionally information from orthophotos is used. Based on this graph the forest roads are extracted as follows: A human interpreter defines starting and ending points of road sections. Between these points the shortest, best voted path within the weighted graph is automatically found. Using this method the forest roads network is sequentially extracted by the interpreter in an efficient way.

The weighted graph methodolgy enabled fully automatically pre-processing of the input data and can be applied for different terrain conditions. To enable comfortable digitizing of forest roads in a functional Open Source GIS environment, a Quantum GIS Plugin was implemented. Based on the weighted graph and knowledge from a human interpreter a topologically correct forest road network can be extracted using this Plugin. The sequentially digitization process delivers user controlled results where errors can be corrected immediately during the process. This is a big advantage to fully automatically methods where only little user interaction is given. The semi automatically digitization process was found to be more efficient than a manually extraction as large road segments can be digitized easily. Additional attributes as for example road width, curve radii and gradient of segments can be derived for the extracted roads (see Figure 6). This information is important for routing purposes. Attributes can also be extracted from existing datasets originating from other sources as for example Open Street Maps or GIP [70] where only the street axis is available.

4. Conclusion

During the last decade the technological developments of airborne laserscanning and digital photogrammetry lead to efficient workflows for gathering 3D information. Especially for forestry applications the object heights, which are included in the 3D data, provide new information for the monitoring of quantitative forest parameters such as e.g. tree growth, growing stock or harvested biomass. Even though several success stories can be found in literature, there are still open issues to be solved until these data sources are included into operational forest management applications on large scale. On the one hand there are open questions about the data availability on

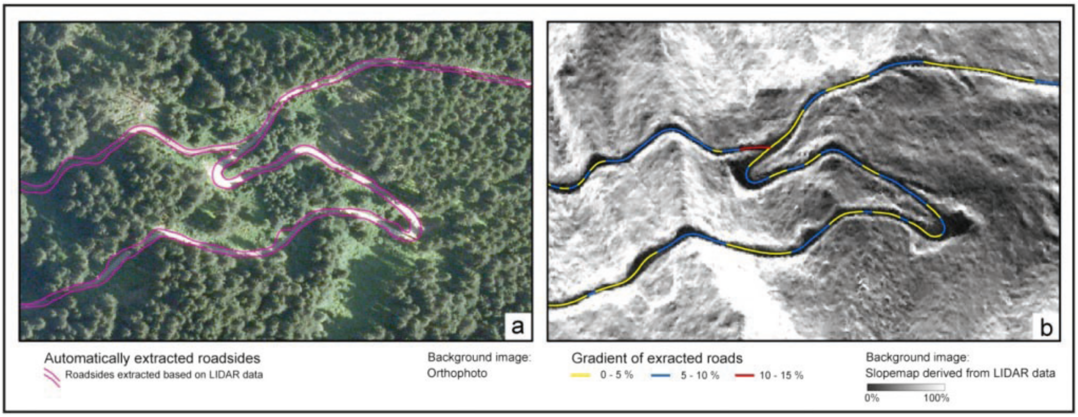

Fig. 6: Example for extracted forest roads. ***a)*** *forest road outlines overlaid over an orthophoto and* ***b)*** *gradient of extracted forest road network overlaid over a shaded DTM. The road segments are colour coded by gradient (adapted from [71].*

a regular base with reasonable costs. For operational applications of remote sensing data in forest community the availability of comparable data over several decades is of special importance. With respect to this demand country-wide data acquisition plans with a minimum of data quality standards are highly desirable. On the other hand the huge amount of data implies new challenges for available methods and software programs. For example, the requirement to the georeferencing accuracy of ALS data is much higher for change detection studies than for analyses using only one acquisition time and often the available data has to be re-processed for improving the positional accuracy. Furthermore, the combined analyses of 3D data originating from different acquisition methods (i.e. image matching, ALS) need the adaption of available methods to consider the properties of the different data sources (e.g. ALS data describe the entire vertical profile of forests whereas image matching provide mainly information about the top most canopy surface). At the research groups of Photogrammetry and Remote Sensing at GEO at the TU Wien, several research projects are ongoing in which these research questions are studied together with national and international partners from the remote sensing as well as the forest community.

Acknowledgement

This work is founded from the European Community's Seventh Framework Programme (FP7/2007–2013) under grant agreement No. 606971, the Advanced_SAR (Advanced Techniques for Forest Biomass and Biomass Change Mapping Using Novel Combination of Active Remote Sensing Sensors) project. The Basics of this work were done in the previous research projects NEWFOR financed by the European Territorial Cooperation Alpine Space, LASER-WOOD (822030) funded by the Klima- und Energiefonds in the framework of the program "NEUE ENERGIEN 2020", ChangeHabitats2 (Marie Curie – FP7-PEOPLE-2009-IAPP - Grant Agreement Number 251234), TransEcoNet implemented through the CENTRAL EUROPE Program co-financed by the ERDF and the project "Ableitung des Forststraßennetzes in Österreich aus Airborne Laserscanning Daten" financed by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management. Finally I would like to thank my current and former colleagues at the research groups Photogrammetry and Remote Sensing at TU Wien for their contribution to the mentioned research projects.

References

[1] *Zwally, H.J.; Schutz, B.; Abdalati, W.; Abshire, J.; Bentley, C.; Brenner, A.; Bufton, J.; Dezio, J.; Hancock, D.; Harding, D., et al.*: ICESat's laser measurements of polar ice, atmosphere, ocean, and land. Journal of Geodynamics 2002, 34, 405-445.

[2] *Wagner, W.; Ullrich, A.; Melzer, T.; Briese, C.; Kraus, K.*: In From single-pulse to full-waveform airborne laser scanners: Potential and practical challenges, International Society for Photogrammetry and Remote Sensing XXth Congress, Vol XXXV, Part B/3, 12–23 July 2004, Commission 3, Istanbul, Turkey, 2004; Altan, O., Ed. Istanbul, Turkey, p 6.

[3] *Rieger, P.; Ullrich, A.*: Resolving range ambiguities in high-repetition rate airborne light detection and ranging applications. Journal of Applied Remote Sensing 2012, 6.

[4] *Briese, C.; Pfennigbauer, M.; Lehner, H.; Ullrich, A.; Wagner, W.; Pfeifer, N.*: Radiometric Calibration Of Multi-Wavelength Airborne Laser Scanning Data. ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. 2012, 1-7, 335-340.

[5] *Kilian, J.; Haala, N.; Englich, M.*: Capture and evaluation of airborne laser scanner data. International Archives of Photogrammetry and Remote Sensing 1996, XXXI, B3, 383-388.

[6] *Baltsavias, E.P.*: Airborne laser scanning: existing systems and firms and other resources. ISPRS Journal of Photogrammetry & Remote Sensing 1999, 54, 165-198.

[7] *Baltsavias, E.P.*: Airborne laser scanning: basic relations and formulas. ISPRS Journal of Photogrammetry & Remote Sensing 1999, 54, 199-214.

[8] *Wehr, A.; Lohr, U.*: Airborne laser scanning - an introduction and overview. ISPRS Journal of Photogrammetry & Remote Sensing 1999, 54, 68-82.

[9] *Kager, H.*: Discrepancies between overlapping laser scanner strips - simultaneous fitting of aerial laser scanner strips. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 2004, XXXV, 555-560.

[10] *Burman, H.*: Laser strip adjustment for data calibration and verification. International Archives of Photogrammetry and Remote Sensing 2002, XXXIV, 3, 67-72.

[11] *Filin, S.*: Recovery of systematic biases in laser altimetry data using natural surfaces. Photogrammetric Engineering & Remote Sensing 2006, 69, 1235-1242.

[12] *Haala, N.; Wolf, K.; Hastedt, H.; Ressl, C.; Baltrusch, S.; Stößel, W.*: Digital Photogrammetric Camera Evaluation - Generation of Digital Elevation Models PFG Photogrammetrie, Fernerkundung, Geoinformation 2010, 2, 99-115.

[13] *Förstner, W.*: In On the Geometric Precision of Digital Correlation, Proceedings of the ISPRS Symposium Mathematical Models, Accuracy Aspects and Quality Control, Finland, 1982; Finland, pp 176-189.

[14] *Förstner, W.; Gülch, E.*: In A Fast Operator for Detection and Precise Location of Distinct Point, Corners and Centers of Circular Features, Proceedings of the ISPRS Conference on Fast Processing of Photogrammetric Data, Interlaken, 1987; Interlaken, pp 281-305.

[15] *Hirschmüller, H.*: Stereo Processing by Semiglobal Matching and Mutual Information. IEEE Transactionon on Pattern Analyses and machine Intelligence 2008, 30, 328-341.

[16] *Pierrot-Deseilligny, M.; Paparoditis, N.*: A multiresolution and optimization-based imagematching approach: An application to surface reconstruction from SPOT5-HRS stereoimagery. In IAPRS, Vol. XXXVI-1/W41 in ISPRS Workshop On Topographic Mapping From Space (With Special Emphasis on Small Satellites), Ankara, Turkey, 2006.

[17] *Gruen, A.*: Development and status of image matching in photogrammetry. The Photogrammetric Record 2012, 27, 36-57.

[18] *Zabih, R.; Woodfill, J.*: In Non-parametric local transforms for computing visual correspondence, Proceedings of 3rd European Conf. Computer Vision, Stockholm, 1994; Stockholm, pp 151-158.

[19] *Wenzel, K.; Rothermel, M.; Haala, N.; Fritsch, D.*: SURE – The ifp Software for Dense Image Matching In Photogrammetric Week '13, Fritsch, D., Ed. Wichmann, Berlin/Offenbach: 2013; pp 59-70.

[20] *Rothermel, M.; Haala, N.*: Potential of dense matching for the generation of high quality digital elevation models. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2011, XXXVIII-4/W19, 271-276.

[21] *Baltsavias, E.; Gruen, A.; Eisenbeiss, H.; Zhang, L.; Waser, L.T.*: High-quality image matching and automated generation of 3D tree models. International Journal of Remote Sensing 2008, 29, 1243-1259.

[22] *White, J.C.; Wulder, M.A.; Vastaranta, M.; Coops, N.C.; Pitt, D.; Woods, M.*: The Utility of Image-Based Point Clouds for Forest Inventory: A Comparison with Airborne Laser Scanning. Forests 2013, 4, 518-536.

[23] *Pfeifer, N.*: Oberflächenmodelle aus Laserdaten. Österreichische Zeitschrift für Vermessung & Geoinformation (VGI) 2003, Heft 4/2003, 243-252.

[24] *Kraus, K.; Pfeifer, N.*: Determination of terrain models in wooded areas with airborne laser scanner data. ISPRS Journal of Photogrammetry and Remote Sensing 1998, 53, 193-203.

[25] *Scop++. Programpackage for Digital Terrain Models, http*://photo.geo.tuwien.ac.at/software/scop/; http://www.trimble.com/Imaging/Inpho.aspx?tab=Geo-Modeling_Module. Last accessed June 2015.

[26] *Sithole, G.; Vosselman, G.*: Experimental comparison of filter algorithms for bare-Earth extraction from airborne laser scanning point clouds. ISPRS Journal of Photogrammetry & Remote Sensing 2004, 59, 85-101.

[27] *Hollaus, M.; Mandlburger, G.; Pfeifer, N.; Mücke, W.*: In Land cover dependent derivation of digital surface models from airborne laser scanning data, ISPRS Commission III Symposium PCV2010, Saint-Mandré, France, 2010; Saint-Mandré, France, pp 6-6.

[28] *Höfle, B.; Mücke, W.; Dutter, M.; Rutzinger, M.; Dorninger, P.*: Detection of building regions using airborne LiDAR – A new combination of raster and point cloud based GIS methods. GI_Forum 2009 - International Conference on Applied Geoinformatics, Salzburg 2009, accepted.

[29] *Pfeifer, N.; Mandlburger, G.; Otepka, J.; Karel, W.*: OPALS - A framework for Airborne Laser Scanning data analysis. Computers, Environment and Urban Systems 2014, 45, 125-136.

[30] *Eysn, L.; Hollaus, M.; Schadauer, K.; Pfeifer, N.*: Forest Delineation Based on Airborne LIDAR Data. Remote Sensing 2012, 4, 762-783.

[31] *Zhu, Z.; Waller, E.*: Global forest cover mapping for the United Nations Food and Agriculture Organization Forest Resources Assessment 2000 program. Forest Sci 2003, 49, 369–380.

[32] *FAO/FRA. Definitions of Forest and Forest Change. In Forest Resources Assessment Programme. In FAO*: Rome, Italy, 2000; p 15.

[33] *Jennings, S.B.; Brown, N.D.; Sheil, D.*: Assessing forest canopies and understorey illumination: canopy closure, canopy cover and other measures. Forestry 1999, 72, 59-59.

[34] *Wang, Z.; Boesch, R.; Ginzler, C.*: Forest delineation of aerial images with "Gabor" wavelets. Int. J. Remote Sens 2011, 33, 2196-2213.

[35] *Wang, Z.Y.; Boesch, R.; Ginzler, C.*: Integration of High Resolution Aerial Images And Airborne Lidar Data for Forest Delineation. In ISPRS XXI Congress, Beijing, China, 2008; pp 1203-1208.

[36] *Mustonen, J.; Packalén, P.; Kangas, A.S.*: Automatic segmentation of forest stands using a canopy height model and aerial photography. Scandinavian Journal of Forest Research 2008, 23, 534-545.

[37] *Straub, C.; Weinacker, H.; Koch, B.*: A Fully Automated Procedure for Delineation and Classification of Forest and Non-Forest Vegetation Based on Full Waveform Laser Scanner Data. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2008, 37, 1013-1019.

[38] *Eysn, L.; Hollaus, M.; Schadauer, K.; Roncat, A.*: In crown coverage calculation based on ALS data, 11th International Conference on LiDAR Applications for Assessing Forest Ecosystems (Silvilaser 2011), Hobart, Australia, Oct. 16-20, 2011; Hobart, Australia, p 10.

[39] *Eysn, L.; Hollaus, M.; Berger, F.*: In NEWFOR - Enhancing the wood supply chain within the alpine space – An insight in forest delineation, stratification of growing stock models and forest roads extraction based on LIDAR data, ForestSat 2014, At Riva del Garda, Italy, 2014; At Riva del Garda, Italy, p 6 pages.

[40] *Weiss, P.; Schieler, K.; Schadauer, K.; Radunsky, K.; Englisch, M.*: Die Kohlenstoffbilanz des Österreichischen Waldes und Betrachtungen zum Kyoto-Protokoll; Forstliche Bundesversuchsanstalt; Umweltbundesamt: Wien, 2000; p 93.

[41] *Cháidez, J.*: Allometric equations and expansion factors for tropical try forest trees of eastern Sinaloa, Mexico. Trop. Subtrop. Agroecosyst 2009, 10, 45-52.

[42] *Hyyppä, J.; Inkinen, M.*: Detecting and estimating attributes for single trees using laser scanner. The Photogrammetric Journal of Finland 1999, 16, 27-42.

[43] *Popescu, S.C.; Wynne, R.H.; Nelson, R.F.*: Measuring individual tree crown diameter with lidar and assessing its influence on estimating forest volume and biomass. Canadian Journal of Remote Sensing 2003, 29, 564-577.

[44] *Næsset, E.*: Practical Large-scale Forest Stand Inventory Using a Small-footprint Airborne Scanning Laser. Scandinavian Journal of Forest Research 2004, 19, 164-179.

[45] *Maltamo, M.; Packalén, P.; Peuhkurinen, J.; Suvanto, A.; Pesonen, A.; Hyyppä, J.*: In Experiences and possibilities of ALS based forest inventory in Finland, ISPRS Workshop Laser Scanning 2007, Espoo, Finland, 09-12-2007 - 09-14-2007, 2007; Espoo, Finland, pp 270-279.

[46] *Hollaus, M.; Dorigo, W.; Wagner, W.; Schadauer, K.; Höfle, B.; Maier, B.*: Operational wide-area stem volume estimation based on airborne laser scanning and national forest inventory data. International Journal of Remote Sensing 2009, Accepted on march 15, 2009.

[47] *Schardt, M.; Ziegler, M.; Wimmer, A.; Wack, R.; Hyyppä, J.*: Assessment of Forest Parameters by Means of Laser Scanning. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 2002, XXXIV (Part 3/A), 302-309.

[48] *Jochem, A.; Hollaus, M.; Rutzinger, M.; Höfle, B.*: Estimation of aboveground Biomass in Alpine Forests: A Semi-Empirical Approach Considering Canopy Transparency Derived from Airborne LiDAR Data. Sensors 2011, 11, 278-295.

[49] *Næsset, E.*: Area-Based Inventory in Norway – From Innovation to an Operational Reality. In Forestry Applications of Airborne Laser Scanning: concepts and Case Studies, Maltamo, M.; Næsset, E.; Vauhkonen, J., Eds. Springer Netherlands: 2014; Vol. 27, pp 215-240.

[50] *Hollaus, M.; Wagner, W.; Schadauer, K.; Maier, B.; Gabler, K.*: Growing stock estimation for alpine forests in Austria: a robust LiDAR-based approach. Canadian Journal of Forest Research 2009, 39, 1387-1400.

[51] *Waser, L.T.*: Airborne remote sensing data for semi-automated extraction of tree area and classification of tree species. Zürich, E., Ed. 2012; p 153 S.

[52] *Hollaus, M.; Mücke, W.; Höfle, B.; Dorigo, W.; Pfeifer, N.; Wagner, W.; Bauerhansl, C.; Regner, B.*: Tree species classification based on full-waveform airborne laser scanning data. SilviLaser 2009, October 14-16, 2009 – College Station, Texas, USA 2009.

[53] *Hollaus, M.; Eysn, L.; Karel, W.; Pfeifer, N.*: In Growing stock change estimation using Airborne Laser Scanning data, 13th International Conference on LiDAR Applications for Assessing Forest Ecosystems (SilviLaser 2013), Beijing, China, 2013-10-09 - 2013-10-11, 2013; Beijing, China, p 8.

[54] *Straub, C.; Stepper, C.; Seitz, R.; Waser, L.T.*: Potential of UltraCamX stereo images for estimating timber volume and basal area at the plot level in mixed European forests. Canadian Journal of Forest Research 2013, 43, 731-741.

[55] *Bohlin, J.; Wallerman, J.; Fransson, J.*: Forest variable estimation using photogrammetric matching of digital aerial images in combination with a high-resolution DEMx. Scandinavian Journal of Forest Research 2012, 27, 692-699.

[56] *Lefsky, M.A.; Turner, D.P.; Guzy, M.; Cohen, W.B.*: Combining lidar estimates of aboveground biomass and Landsat estimates of stand age for spatially extensive validation of modeled forest productivity. Remote Sensing of Environment 2005, 95, 549-558.

[57] *Hollaus, M.; Mücke, W.; Eysn, L.*: Forest structure and stem volume assessment based on airborne laser scanning. Ambiência 2012, 8, 471-482.

[58] *Tews, J.; Brose, U.; Grimm, V.; Tielbörger, K.; Wichmann, M.C.; Schwager, M.; Jeltsch, F.*: Animal species diversity driven by habitat heterogeneity/diversity: the importance of keystone structures. Journal of Biogeography 2004, 31 79-92.

[59] *Coops, N.C.; Hilker, T.; Wulder, M.A.; St-Onge, B.; Newnham, G.; Siggins, A.; Trofymow, J.A.T.*: Estimating canopy structure of Douglas-fir forest stands from discrete-return LiDAR. Trees 2007, 21, 295-310.

[60] *Leiterer, R.; Morsdorf, F.; Schaepman, M.; Mücke, W.; Pfeifer, N.; Hollaus, M.*: In Robust characterization of forest canopy structure types using full-waveform airborne laser scanning, SilviLaser 2012, Vancouver, British Columbia, Canada, 2012-09-16 - 2012-09-19, 2011; Vancouver, British Columbia, Canada, p 8.

[61] *Hall, S.A.; Burke, I.C.; Box, D.O.; Kaufmann, M.R.; Stoker, J.M.*: Estimating stand structure using discrete-return lidar: an example from low density, fire prone ponderosa pine forests. Forest Ecology and Management 2005, 208, 189-209.

[62] *Zimble, D.A.; Evans, D.L.; Carlson, G.C.; Parker, R.C.; Grado, S.C.; Gerard, P.D.*: Characterizing vertical forest structure using small-footprint airborne LIDAR. Remote Sensing of Environment 2003, 87, 171-182.

[63] *Lim, K.; Treitz, P.; Wulder, M.; St-Onge, B.; Flood, M.*: LIDAR remote sensing of forest structure. Progress in Physical Geography 2003, 27, 88-106.

[64] *Wagner, W.; Ullrich, A.; Ducic, V.; Melzer, T.; Studnicka, N.*: Gaussian decomposition and calibration of a novel small-footprint full-waveform digitising airborne laser scanner. ISPRS Journal of Photogrammetry & Remote Sensing 2006, 60, 100-112.

[65] *Reitberger, J.; Schnörr, C.; Krzystek, P.; Stilla, U.*: 3D segmentation of single trees exploiting full waveform LIDAR data. ISPRS Journal of Photogrammetry and Remote Sensing 2009, 64, 561-574.

[66] *Hollaus, M.; Mücke, W.; Roncat, A.; Pfeifer, N.; Briese, C.*: Full-Wavform Airborne Laser Scanning Systems and Their Possibilities in Forest Applications. In Forestry Applications of Airborne Laser Scanning: concepts and Case Studies, Maltamo, M.; Næsset, E.; Vauhkonen, J., Eds. Springer Netherlands: 2014; Vol. 27, pp 43-61.

[67] *Mücke, W.*: Full-Waveform Airborne Laser Scanning for Landscape Ecological Mapping: Methods and Applications. Vienna University of Technology, Vienna, 2014.

[68] *Vetter, M.; Höfle, B.; Hollaus, M.; Gschöpf, C.; Mandlburger, G.; Pfeifer, N.; Wagner, W.*: In Vertical Vegetation Structure Analysis And Hydraulic Roughness Determination Using Dense Als Point Cloud Data - A Voxel Based Approach, ISPRS Workshop Laser Scanning 2011, Calgary, Canada, 2011-08-29 - 2011-08-31, 2011; ISPRS: Calgary, Canada, p 6.

[69] *Maier, B.*: Characterising Mountain Forest structure using Airborne Laser Scanning. Master thesis, Salzburg University, Salzburg, 2007.

[70] *GIP. Graphenintegrations-Plattform. http*://www.gip.gv.at/. Last accessed June 2015.

[71] *Hollaus, M.; Eysn, L.; Grafl, A.; Schadauer, K.; C., B.*: Digitale Forststraßen bei der Waldinventur. Forstzeitung 2014, 125, 10-11.

Contact

Dipl.-Ing. Dr. Markus Hollaus, TU Wien, Department of Geodesy and Geoinformation (E120-7), Gusshausstraße 27-29, 1040 Vienna, Austria.
E-Mail: Markus.Hollaus@GEO.tuwien.ac.at