Possibilities of airborne laser scanning data for forestry applications

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Möglichkeiten von Airborne-Laserscanning-Daten für forstliche Anwendungen

1 Introduction

During the last decade the technology of airborne laser scanning (ALS) has been established as one of the standard technologies for the acquisition of high precision topographic data. Furthermore, ALS data are in use for mapping vegetation, urban areas, ice and infrastructure (e.g. HYYPPÄ et al., 2009). As an active remote sensing technology, 4–10 nanosecond-long infrared laser pulses with a high frequency of up to 400 kHz are transmitted from the sensor to the Earth surface. The sensor as well as the position and orientation unit, consisting of a differential global positioning system (dGPS) and an inertial measurement unit (IMU), are mounted on an airborne platform such as a helicopter or fixed-wing aircraft. Airborne laser scanning sensors have a beam divergence of 0.5 mrad in average that leads to footprint sizes in the order of 0.2 m to 0.5 m for flying heights above ground of 400 m to 1000 m (WEHR & LOHR, 1999). Within footprints the laser pulses may be reflected by several discrete objects such as leaves, branches, bushes and the underlying terrain surface (Fig. 1). The backscattered signals are recorded by the sensor. Discrete ALS systems record the travelling time for the first, last and intermediate echoes and full-waveform ALS systems record the entire waveform (WAGNER et al., 2004). For discrete ALS systems the three dimensional position of each backscattering object is determined based on the measured travelling time, the position recorded by the dGPS, and the pitch, roll, and heading of the aircraft, which are measured by the IMU. In the case of full-waveform systems a decomposition of the recorded signal into a series of echoes in a post-processing step is required (RONCAT et al., 2011; WAGNER et al., 2006). These so-called full-waveform ALS systems have the benefit that in addition to the location of an echo the scattering properties of the target, i.e. the amplitude and the echo width, are obtained. The amplitude of the echo signal provides information on the target's reflectance and cross-section and is comparable with the radiance (wavelengths ~ 1.0 or 1.5 µm depending on the ALS system) measured in e.g. passive aerial photography. As ALS is an active system, meaning the laser beam is transmitted from the sensor, different conditions of sun illuminations (e.g. shadowing caused by clouds, topography and objects) have no influence to the backscattered signals. Therefore, ALS is able to acquire information from shadowed areas such as canopy gaps that are not illuminated by the sun. The echo width provides information on the range distribution of scatterers within the laser footprint that contribute to one echo signal and is therefore an indicator for surface roughness and the slope of the target (HOLLAUS et al., 2011; ULLRICH et al., 2007). Figure 2 shows images of derived amplitudes and echo widths compared to an orthophoto.

Summary

This paper provides a review of research activities in the field of airborne laser scanning (ALS) remote sensing that have been conducted at the Institute of Photogrammetry and Remote Sensing (IPF) at the Vienna University of Technology over the last few years. The focus is on the application of ALS data for forestry use. Many of the described methods were developed in cooperation with the forest administration Stand Montafon Forstfonds and the Austrian Research and Training Centre for Forests, Natural Hazards and Landscape (BFW), Institute of Forest Inventory. Algorithms for assessing forest parameters from ALS data are described and their operational applications are discussed.

Key words: Topography, forest inventory, stem volume, tree height, forest structure, tree species.

Zusammenfassung

Dieser Beitrag gibt einen Überblick über die Forschungsaktivitäten im Bereich Airborne Laserscanning (ALS), welche am Institut für Photogrammetrie und Fernerkundung der TU Wien in den letzten Jahren durchgeführt wurden. Der Schwerpunkt liegt dabei auf Anwendungen des ALS in der Forstwirtschaft. Viele der beschriebenen Forschungsaktivitäten wurden in Kooperation mit dem Stand Montafon Forstfonds als auch mit dem Bundesforschungs- und Ausbildungszentrum für Wald, Naturgefahren und Landschaft (BFW), Institut für Waldinventur durchgeführt. Neben einer überblicksmäßigen Beschreibung der Methoden wird die operationelle Anwendung der abgeleiteten Forstparameter diskutiert.

Schlagworte: Topografische Modelle, Waldinventur, Holzvorrat, Baumhöhe, Bestandsstruktur, Baumarten.

Due to the fact that ALS data do not only provide terrain heights but also information about the horizontal and vertical distribution of forest canopies, a quantitative measurement of forest parameters such as tree height is possible. This makes ALS one of the most promising remote sensing techniques to acquire data that can be used for downscaling sample plot-based forest inventories. In this paper several Austrian case studies using ALS data to estimate forest parameters are presented and discussed. An overview of ALS applications in forestry for boreal countries can be found in Hyyppä et al. (2008).

2 Derivation of topographic models from ALS data

The characteristics of ALS data – i.e. high precision height measurements, high sampling density and independency of sun illumination – allow a continuous description of topographic surfaces. Especially in forested areas, laser beams can hit the terrain through small canopy gaps, and consequently terrain points can be measured and a digital terrain model (DTM) can be determined. For the calculation of a DTM the last reflected echoes are classified into terrain and off-terrain echoes, a process that is commonly called filtering (Pfeifer et al., 1998). Several filtering techniques are

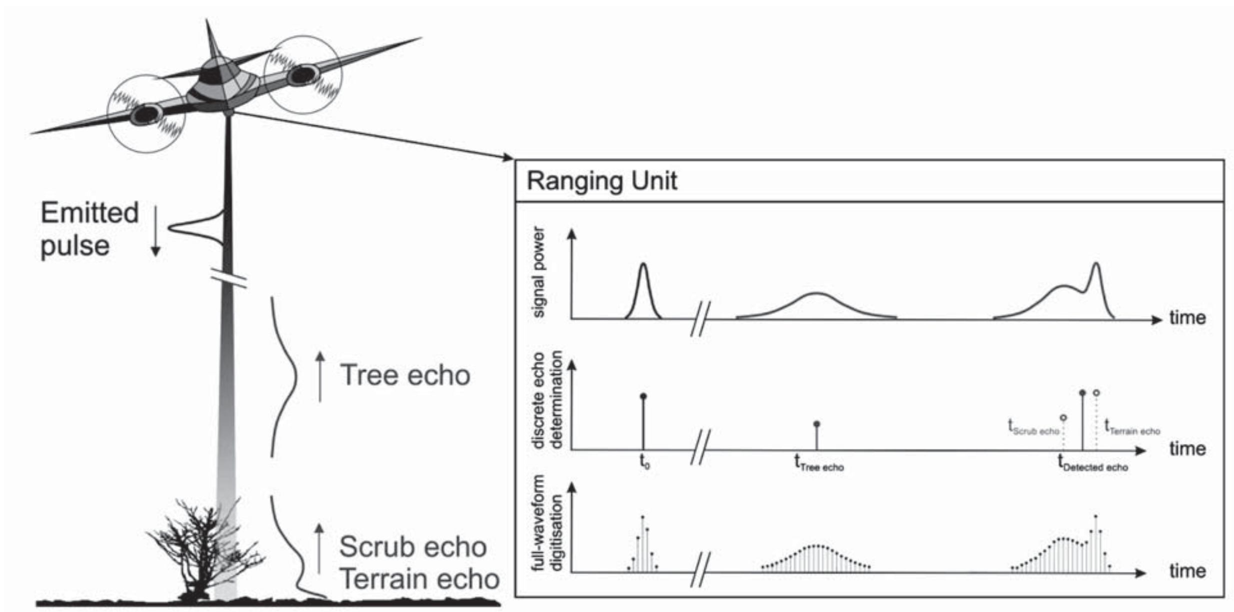

Figure 1: Schematic diagram of discrete and full-waveform ALS systems (adapted from Doneus et al., 2008)
Abbildung 1: Schematische Gegenüberstellung von diskreten und full-waveform-ALS-Systemen (adaptiert nach Doneus et al., 2008)

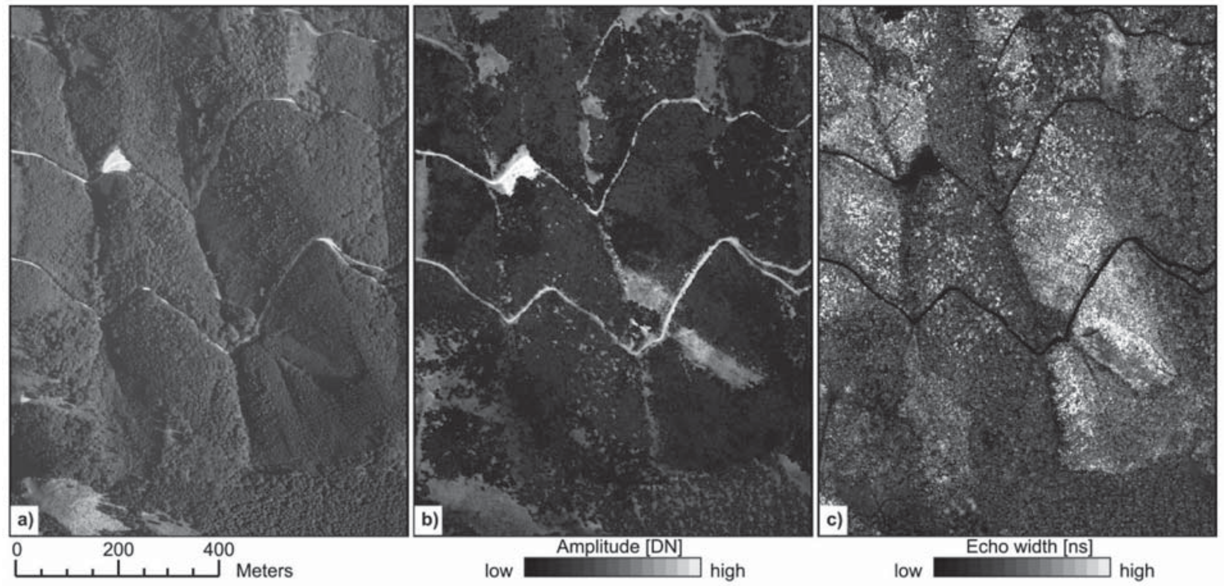

Figure 2: (a) Orthophoto, (b) amplitude, and (c) echo width of echoes, which are located in the topmost at 2.0 m. The spatial resolution of the images is 0.50 m

Abbildung 2: (a) Orthophoto, (b) Amplidute und (c) Echobreite der obersten Echos (2-m-Band). Die räumliche Auflösung der Bilder beträgt 0,50 m

available (SITHOLE & VOSSELMAN, 2004), which are commonly based on the spatial relationship of the 3D echoes. The classification of terrain echoes can be improved by integrating full-waveform information as presented by DONEUS et al. (2008), WAGNER et al. (2008), and ULLRICH et al. (2007). Furthermore, MANDLBURGER et al. (2007) and MÜCKE (2008) used a-priori weights that were derived from the echo widths for expanding the robust interpolation (KRAUS & PFEIFER, 1998) to classify the ALS points into terrain and off-terrain points. This developed approach allows the combination of full-waveform echo information with geometric criteria within the robust interpolation.

In addition to the DTM the digital surface model (DSM) represents the topmost surface that can be seen from the aircraft. As summarized in PFEIFER (2003), the elevation of the DSM in open areas like streets, agricultural fields without vegetation, grassland with short vegetation, or areas with bare soil is equivalent to the elevation of the DTM. In forested areas the DTM represents the ground surface and the DSM the elevation of the topmost canopy surface. For the calculation of the DSM, HOLLAUS et al. (2010) suggested a land-cover-dependent derivation approach that combines the advantages of DSM calculations based on (i) the highest echo within a raster cell and (ii) moving least squares interpolation.

The difference between the DSM and the DTM, the normalized digital surface model (nDSM), comprises tree heights (Fig. 3) and is, especially for forestry applications, commonly called canopy height model (CHM) (HYYPPÄ & INKINEN, 1999; POPESCU et al., 2002). A typical spatial resolution of the described topographic models is 1.0 m. The accuracy of the derived models is influenced by the ALS system components, the land cover and the topography. In general, the DTM accuracy decreases with increasing terrain slope and decreasing ground point density (KRAUS et al., 2004). Several studies (HODGSON & BRESNAHAN, 2004; HOLLAUS et al., 2006; HYYPPÄ et al., 2005; TAKAHASHI et al., 2005) show that the achievable accuracies of DTMs range between of ± 10 to ± 25 cm for smooth surfaces with low slopes and decrease to several decimetres for surfaces with high slopes. In Figure 3 a derived nDSM is compared to an orthophoto.

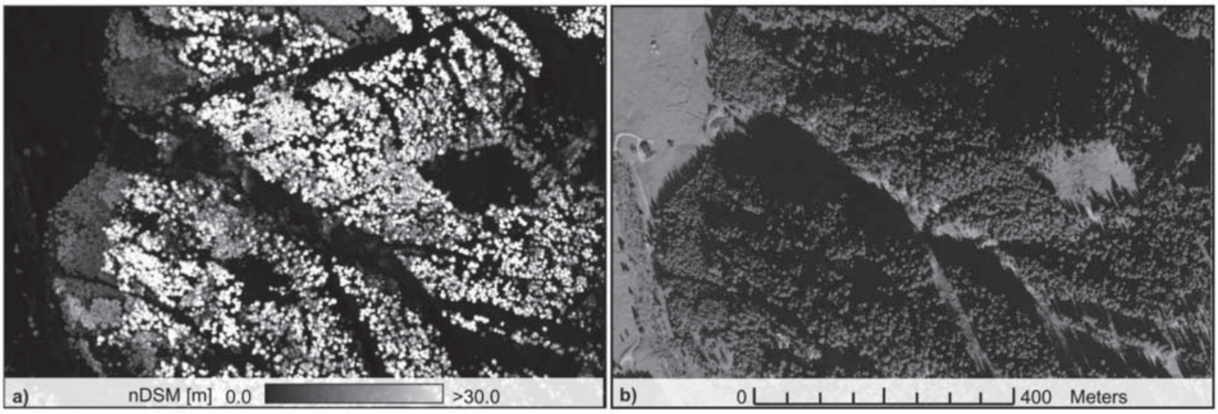

Figure 3: (a) Normalised digital surface model (nDSM) versus (b) colour infrared (CIR) orthophoto. The spatial resolution is 1.0 m for the nDSM and 0.25 m for the CIR orthophoto

Abbildung 3: (a) Normalisiertes digitales Oberflächenmodell (nDSM) versus (b) CIR-Orthophoto. Die räumliche Auflösung des NDSM beträgt 1,0 m, jene des Orthophotos 0,25 m

3 Digital terrain models for forestry applications

For forested areas DTMs with high spatial resolution (e.g. 1 x 1 m) and high accuracy (e.g. ± 0.25 m) can not be derived from traditional earth observation data such as SAR interferometry or stereoscopic images (e.g. aerial photographs, IKONOS, Aster). KRAUS (2002) regards the new capabilities of ALS data for topographic data acquisition as paradigm shift in photogrammetry because a point on the terrain surface has be visible only from one acquisition point. Indeed, ALS has become the state of the art for topographic data acquisition and a high percentage of the Austrian territory is already captured.

A high precision DTM can be used for several forestry applications. First of all it is an excellent data source for generating topographic maps for forested areas and improves the possibilities for navigating in forests due to the fact that even small tracks and topographic features (e.g. small ditches, barrows, etc.) are visible in hill-shaded DTMs (DONEUS & BRIESE, 2006). Furthermore, the DTM provide a basis for forest road planning and construction and can be used for planning and optimizing cable cranes for harvesting (MAIER & HOLLAUS, 2006). The DTM can also be used for describing the topographic site conditions using derived products such as slope, aspect and information about the micro-topography. Finally, information about the terrain roughness can be derived from ALS data (HOLLAUS et al., 2011), which could improve the understanding of different processes of natural hazards (e.g. snow avalanches, rock falls) (GEIST et al., 2009).

4 Tree height estimation and tree crown delineation

The tree height or canopy height are primary quantities that can be measured by ALS. However, as ALS measurements are distributed over a canopy surface independently of the available surface features, it is not guaranteed that each tree top is captured by a laser beam. Of course, with increasing ALS point density, the probability to capture a tree top increases. For example HYYPPÄ & INKINEN (1999) stated that for a successful modelling of single trees ALS point densities greater than approximately 10 hits per square meter are required. Furthermore, laser beams penetrate into the canopy and the first echo is not triggered until the backscattered echo is strong enough. Consequently, the derived tree heights are commonly underestimated. As summarised in HYYPPÄ et al. (2004), factors such as ALS point density and footprint size, the tree species, the existence and height of under-vegetation, the algorithms used in the laser signal processing, and the algorithms used to calculate the topographic models influence the underestimation of tree

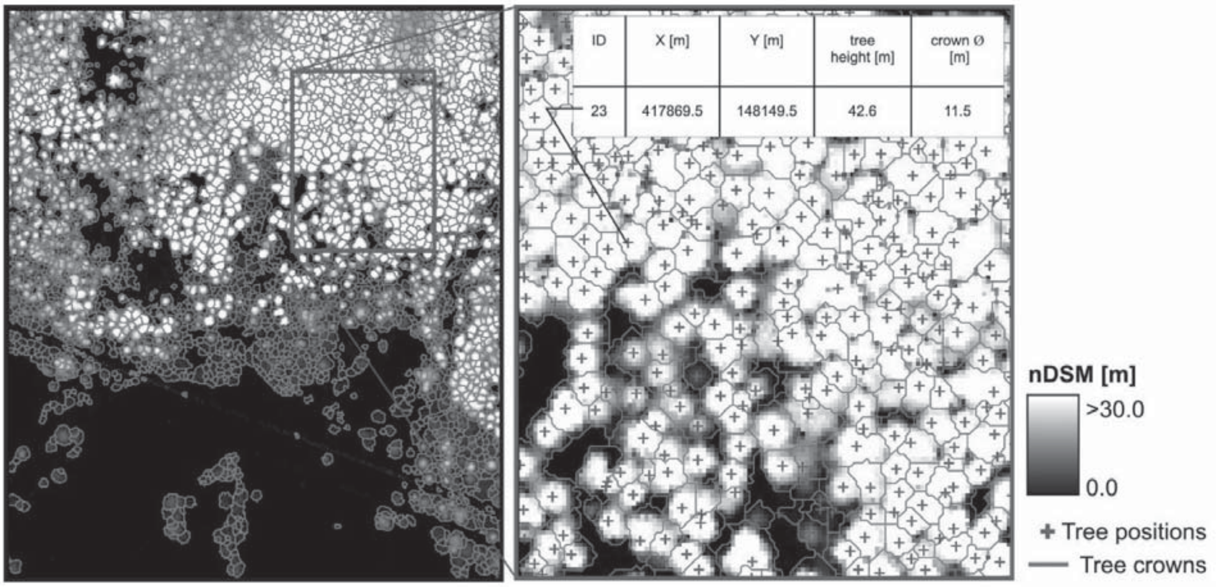

Figure 4: Delineated tree crown segments overlaid over an nDSM. For each detected tree crown the highest echo can be used to estimate the tree height

Abbildung 4: Extrahierte Baumkronen überlagern den nDSM. Für jedes Baumkronensegment kann die Baumhöhe mithilfe des höchsten Echos innerhalb der Krone ermittelt werden

heights. Further information about the penetration of small footprint laser beams into the canopy can be found in Gaveau & Hill (2003).

In order to estimate tree heights it is necessary to detect individual trees in a first processing step. This can be done based on ALS data, orthophotos and/or high spatial resolution satellite images. Here only ALS-based methods are discussed. The finished EuroSDR test about tree extraction from ALS data gives a good overview of the available approaches (Kaartinen & Hyyppä, 2008). As clearly shown in this report, dominant trees can be detected with high accuracy. For finding smaller trees under the dominating storey further research is needed to improve the available models.

For the estimation of tree heights, e.g. the highest echo within a detected tree crown or the highest pixel value of a rasterized nDSM can be selected. Hollaus et al. (2006) investigated the accuracy of tree heights estimation for an alpine study area in Vorarlberg, Austria, and confirmed that reasonable correlations (R^2 = 0.84–0.87) between field-measured single tree heights and ALS-derived tree heights could be achieved. Furthermore, it could be demonstrated that ALS data can be used for mapping canopy heights of complex alpine forests throughout large areas.

In addition to tree height, information about the tree crown (e.g. diameter) can be extracted. In Figure 4 delineated tree crowns and tree heights are shown for a coniferous forest area in the southern part of Vorarlberg. For the tree crown delineation the segmentation method described in Höfle et al. (2008) was applied.

5 Tree species classification

The knowledge of tree species is of particular interest for forestry applications. Passive optical remote sensing data such as colour infrared aerial photographs or high-spatial resolution satellite data (e.g. Ikonos, Quickbird, World-view-2) are commonly used for tree species classifications. Additionally to the radiometric information of these optical remote sensing data, the geometric information of ALS data improves the classification accuracy (e.g. Holmgren et al., 2008; Packalén & Maltamo, 2007).

In addition to the three-dimensional points, most of the available discrete ALS systems provide intensity information, which, if properly calibrated (e.g. Höfle & Pfeifer, 2007), is a promising data source for tree species classification. Also the echo width and amplitude information de-

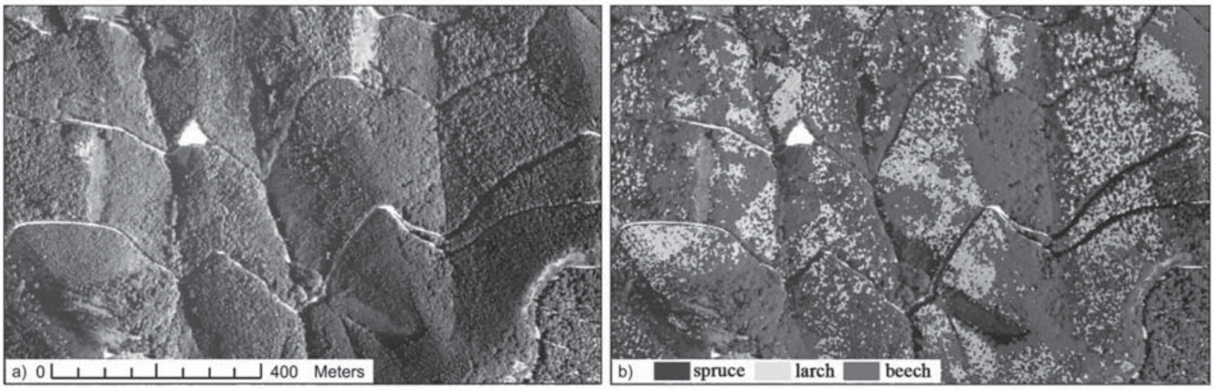

Figure 5: (a) Orthophoto and (b) classified tree species (spruce, larch and beech) (adapted from HOLLAUS et al., 2009b)
Abbildung 5: (a) Orthophoto und (b) Baumartenklassifizierung (Fichte, Lärche, Buche) (adaptiert nach HOLLAUS et al., 2009b)

rived from full-waveform ALS systems have a high potential for tree species identification and tree parameter extraction (HÖFLE et al., 2008; HOLLAUS et al., 2009b; LITKEY et al., 2007; REITBERGER et al., 2008). HOLLAUS et al. (2009b) and MOLNÁR et al. (2010) describe approaches for tree species classification that are based on full-waveform ALS data. Figure 5 shows a subset of the classified tree species (i.e. spruce, larch and beech) for a study area in Lower Austria, whereas an overall accuracy of 75 % could be achieved.

6 Growing stock estimation

For forest planning, management, and decision-making growing stock is a key parameter. In several countries the growing stock as well as other forest parameters are monitored with national forest inventories (NFIs) on a national scale. For example the Austrian NFI is based on a permanent sampling approach in a regular network with a grid spacing of 3.89 km (GABLER & SCHADAUER, 2006) and consequently the statistically derived forest information is representative for relatively large administrative units only, e.g. whole countries or provinces. For several forestry applications, e.g. mobilization of timber and biomass resources in small Austrian forest stands, appropriate information about forest recourses on the local level is missing.

Within several research projects at the IPF an area-based semi-empirical model (HOLLAUS et al., 2009c) for estimating growing stock from ALS was investigated and compared with other models, e.g. the statistical model from NÆSSET (2004). The model was tested for the federal district of Vorarlberg, dominated by coniferous tree species, and for a study area in Lower Austria that is covered by mixed forest. The applied model assumes a linear relationship between growing stock and ALS-derived canopy volume that is stratified according to several canopy height classes to account for height-dependent differences in canopy structure and non-linear tree size-shape relationships (HOLLAUS et al., 2009c). The canopy volume is defined as the entire volume between the top of the forest canopy and the terrain surface. For the calibration of the model the NFI growing stock data was applied, whereas for each NFI sampling point the canopy volume was calculated for a circular sample plot with a diameter of 10.0 m. For the study area Vorarlberg, the model could be calibrated with an R^2 of 0.79 and a cross-validated standard deviation of 31.5 % (HOLLAUS et al., 2009c). This accuracy could be confirmed by independent validation with local forest inventory data that showed a high correlation $R^2 = 0.75$ and a relative standard deviation of 32.4 % between the ALS-based estimations and the terrestrial local forest inventory data. For evaluating these accuracy measures it should be considered that the obtained accuracies are valid for NFI sample plots based on angle count sampling. As the accuracy is strongly dependent on the spatial scale, it is assumed that the accuracy of averaged growing stocks for typical forest stands in Vorarlberg (1–2 ha) would be significantly higher (HOLLAUS et al., 2009a). Figure 6 shows the derived growing stock map overlaid with sample plots from the local forest inventory (FI) for a subset of the study area Vorarlberg.

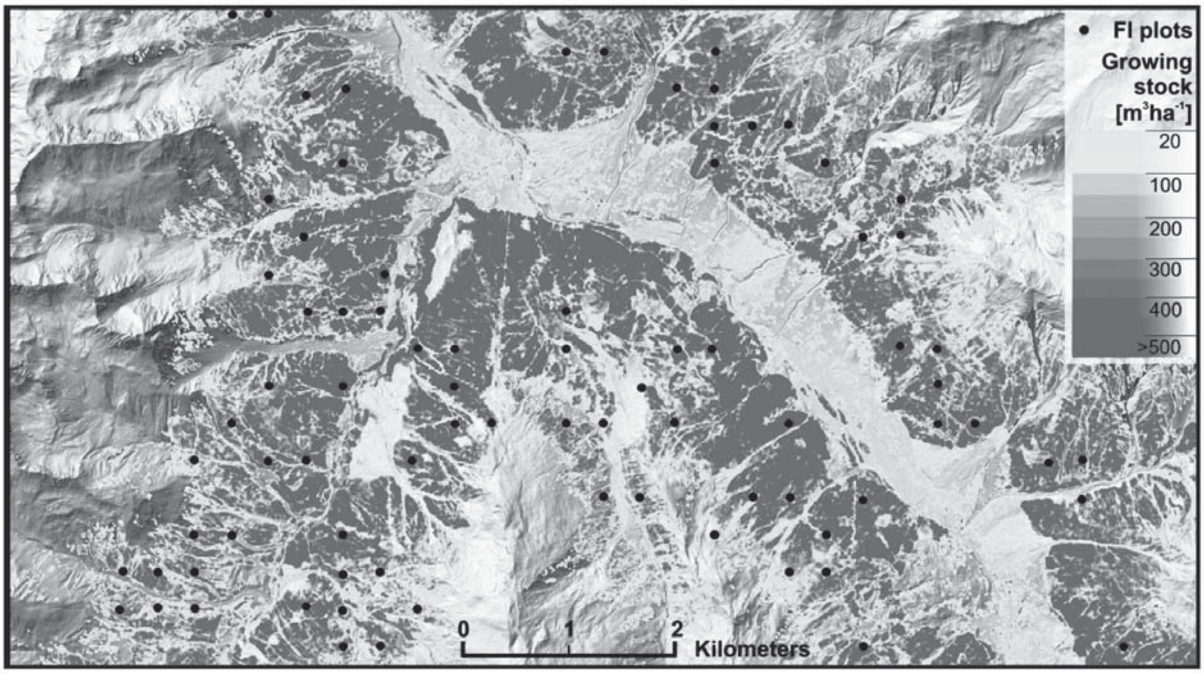

Figure 6: Forest inventory sample plots overlaid over the estimated growing stock map. The map shows an area of the Montafon region in the southern part of Vorarlberg, Austria. The spatial resolution is 1.0 m (adapted from HOLLAUS et al., 2009a)

Abbildung 6: Waldinventur-Stichprobe, der abgeschätzten Holzvorratskarte übergelagert. Das Bild zeigt einen Ausschnitt des Montafons im südlichen Vorarlberg. Die räumliche Auflösung beträgt 1,0 m (adaptiert nach HOLLAUS et al., 2009a)

7 Forest structure assessment

The capability of ALS to derive not only information about the canopy surface but also about stems, branches, leaves and needles in between the terrain and the canopy surface offers new ways to describe the vertical and horizontal structure of forests (e.g. MÜCKE et al., 2010). As described in MAIER & HOLLAUS (2008) and EYSN et al. (2010), forest gaps can be derived from ALS data with high accuracy. The lengths of the forest gaps, combined with a slope map, can be used for a first assessment of the snow avalanche risk. In this way a fast overview of potential risk areas can be derived that could be efficiently investigated in detail by experts on site.

Based on the nDSM, MAIER et al. (2006) developed a generic automated approach for assessing and quantifying forest structure using landscape metrics that act as a quantitative link between landscape structure and ecological or environmental processes. For example, they calculated the Shannon Evenness Index (MCGARIGAL & MARKS, 1995) to differentiate between evenly distributed height classes and those dominated by only one or two height classes. Furthermore, the derived different structure types can be used in the course of protection forest planning, management and monitoring. For each structure type the extent and the crown coverage can be calculated. As summarized in MAIER et al. (2006), these approaches will help to assess structure in an area-extensive and efficient manner.

8 Conclusions

During the last decade, ALS has been established as a standard method to acquire topographic data (e.g. terrain and surface models) and has provided an excellent basis for deriving quantitative forest parameters. This paper summarizes the experiences of the Institute of Photogrammetry and Remote Sensing, at the TU Vienna, using ALS data for forestry applications. While the assessment of tree and canopy height, the estimation of growing stock, and the derivation of forest structure are achieving an operational status now, the research for tree species classification based on ALS data is at its beginning. Especially the full-waveform ALS data and the intensity information from discrete ALS data are promising data sources for tree species identification. If a tree species classification is available, species-specific growing stock and biomass estimations can be made. Future efforts will also concentrate on deriving additional forest parameters such as basal area, height of dominant trees, stem density, diameter at breast height distribution, etc.

Concerning the financial aspects of ALS data it is advised to use already existing ALS data, for example acquired during federal state-wide topographic mapping campaigns, which minimize the data costs significantly. Therefore, the used algorithms for deriving forest parameters have to be able to use ALS data with different properties such as data acquisition time, flying height, point density, discrete versus full-waveform. The funding of a follow-up ALS data acquisition campaign is an open question until now. An alternative way to acquire height information is image matching of digital aerial images, but the use of the derived digital surface models for forestry applications is not properly investigated until now. However, an optimal way would be a combined data acquisition (i.e. ALS and aerial images) and to use multispectral information from the aerial images and the geometric information from the ALS data for deriving various forest parameters. Concluding, it can be stated that the combination of ALS and forest inventory sample plots leads to a significant increase in quality and spatial resolution of forest parameters.

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