LASER-SCANNING FOR THE DERIVATION OF FOREST STAND PARAMETERS

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ABSTRACT

Forest stand parameters are derived from airborne laser scanner data. Data from three laser scanner flights by the company "TopoSys" are used, a winter flight with last pulse recorded and two summer flights, with last and first pulse recorded respectively. The laser data are reduced to relative (ground) heights with a high quality ground elevation model (DEM) that was interpolated from the winter data. The proportion of crown coverage of coniferous trees are estimated from data for 50 stands. Stand heights and basal area proportion of coniferous versus deciduous trees are estimated through regression analysis against terrestrial reference data from 110 angle count points, each with approximatly 10 trees. The results are very promising with regression coefficients of 0.8 to 0.95 for all measures. The usual systematic under-estimation of tree heights cannot be proved due to the high sample point density. The mean errors of the tree heights are in the range of ±1.8 – ±2.7 m. Basal and projected crown area proportions can be estimated with similar precision. Summer last and first pulse elevations differ insignificantly, suggesting there is no need to have both flights. Only one winter flight is necessary.

KURZFASSUNG

Forstbestandesparameter werden aus den Daten eines flugzeugbasierten Laser-Scanners abgeleitet. Insgesamt stehen drei Flüge mit dem System der Firma "TopoSys" zur Verfügung: Ein Winterflug mit letztem empfangenen Signal und zwei Sommerflüge mit erstem bzw. letztem Signal. Die Laserhöhen werden um ein aus den Winterdaten abgeleitetes Bodenmodell reduziert. Aus diesen Daten werden Schirmflächenanteile für Nadelbäume im Gegensatz zu Laubbäumen für 50 Referenzbestände abgeleitet. Anhand von 110 Winkelzähl-proben mit je ca. 10 aufgenommenen Bäumen werden Bestandeshöhen sowie Grundflächenanteile über eine Regressionsanalyse ge-schätzt. Für die Baumhöhen ergeben sich Regressionskoeffizienten von 0,8-0,95. Die üblicherweise beobachtete systematische Unter-schätzung der Baumhöhen kann auf Grund der hohen Datendichte nicht verifiziert werden; die mittleren Fehler der Höhen liegen bei ±1,8 - ±2,7 m. Grund- und Schirmflächenanteile ergeben sich mit ähnlicher Qualität. Zwischen den Datensätzen mit den ersten und letzten aufgezeichneten Pulsen der Sommerflüge besteht kein signifikanter Unterschied, sodaß auf einen der beiden Flüge verzichtet werden kann. Der Winterflug muß nur einmal erfolgen.

1 INTRODUCTION

Data of airborne laser scanners include much information about the ground coverage, i. e. vegetation, off-terrain objects, and the similar. This information is provided through the distribution pattern of the reflected laser dots, mainly through their elevation distribution, but also through their plane positions.

In some way laser scanning is similar to photogrammetry. It has been mainly used for the derivation of digital elevation models so far, a field which has been one of the domains of photogrammetry until today. In some cases Laser scanning is an serious competition with DEM due to some benefits that overcome major problems of stereo-photogrammetry, which are;

- the small laser dots (ground diameter approx. 20-25 cm) may penetrate vegetation even through small holes.
- the usage of an active scanning system allows data even in the shadowed ground areas of dense forests.
- only one ray is needed in order to collect an object point compared to the two rays needed for stereo-

photogrammetry which drastically improves the penetration rate.

- the high point density of laser scanner systems, at least partly compensates for low penetration rates, thus even in dense forests there may be enough information available to create good ground elevation models.

However, there are still some major problems with laser scanners that must be overcome or are inherently unanvoidable;

- the penetration rate may be nearly zero in areas with extremely dense vegetation (young deciduous trees);
- the huge point number and the totally arbitrary distribution along with the massive shift towards off-terrain elevations needs new approaches to interpolate DEMs. This is comparable to the unqualified point distribution of image matching techniques which does not always lead to correct DEMs.

Laser scanning in its practical application is a very new technology. It has the potential to provide information far beyond the mere creation of DEMs, particularly in fields outside the photogrammetric community. Thus the technology needs to be promoted to those areas, and algorithms have to be provided that will allow other disciplines to benefit from the information available with laser data. One already well-known field of application is the creation of digital 3D city models, mainly driven by the mobile telephone companies. In this paper, the focus is on the application of laser scanner data in forestry.

2 LASER SCANNING IN FORESTRY

As mentioned, laser scanning has great potential to provide information about vegetation, therefore it may well be used in forestry. In contrast to photogrammetry, or more general, remote sensing – which focuses on the *thematic* aspects in a geo-coded context – the main application of laser data lies in their *geometric* aspects. With photogrammetric methods, the crown surface can be measured; the lack of ground information, however, makes estimation of tree heights very inaccurate. The great advantage of laser scanning in this regard is its ability to penetrate vegetation. Therefore the two techniques complement one another.

Forestry usually needs tree information on a stand basis. A stand in the context of a forest enterprise is an area that is dealt with as one unit in planning and working. The borders of these units frequently follow roads, ridges, valleys, or arbitrary – often simple straight – lines. There may or may not be a connection to the terrain. The size of forest stands depends on several criteria, such as silviculture-methods, steepness, tree species, infra structure, or even legal aspects. The vegetation within a forest stand may change due to differing conditions (valley – ridge; soil changes; etc.) or operative actions within the forest enterprise.

In contrast to the "economic unit", laser scanning simply provides geometric information. Thus laser data can be used in two ways: Either one can take the stand borders as provided by the forest inventory and analyze the laser data within these stands; or one can comprise areas of similar geometric characteristics, i. e.

similar tree height, density, and species, which yields "geometrically homogenous stands".

It is not yet clear which method better fits the needs of forest enterprises. This certainly depends on several aspects and up to now there is little experience available. It may well be that laser scanning will change traditional techniques of forestry, especially along with legal actions. An example; in mountainous countries like Austria there is a growing awareness of the dangers of large clear-cuts on steep hillsides. Thus there is a tendency towards uneven aged stands, cutting only particular trees from time to time. It is very difficult to estimate timber volume of such stands from terrestrial or photogrammetric measurements.

For the following research, "geometric stands" are delineated from laser data along with aerial photographs in order to determine about the characteristics of different tree species, heights, density etc. This information can later be used to find out about the real, often fairly mixed stands.

3 RESEARCH AREA AND DATA

The research area chosen encompassed the eastern part of the Vienna University of Agricultural Sciences research forest, 60 km south of Vienna (Figure 1). The area of interest covers about 10 square kilometers. The terrain is hilly with elevations between 300 to 700 m above sea level. Average hillslope is 34 percent, with extremes up to 100 percent. The following data are available for the region:

- A precise forest inventory;
- Tree and stand information (height, species, breast height diameters, vitality, leaf area index measurements, etc.) for over 1000 trees;
- three laser scanner flights, two summer flights with first and last reflected pulse recorded respectively, and a winter flight (leafless period) with last pulse recorded. The system used is the TopoSys scanner with ground resolution of 10-15cm in flight direction and 1.5 meters across. Approx. 340 million laser dots were collected;
- photogrammetric false color infrared imagery from both summer and winter flights (scale 1:10,000);
- terrestrial measurements from a survey during the winter of 1999 with approx. 2000 ground points and data from more than 1000 trees.

The research forest reflects vegetation typical for Central Europe: Mixed and pure stands of coniferous and deciduous trees with mainly spruce and beech. In between, but less important, fir, oak, larch, pine, and an insignificant number of other deciduous trees.

Laser scanners as used in this research provide only geometric information. For each recorded pulse three coordinates, x, y, z are calculated. No radiance information is collected. Therefore only geometric characteristics may be extracted; however, there is a relation between several (thematic) stand parameters and geometric aspects of the laser data.
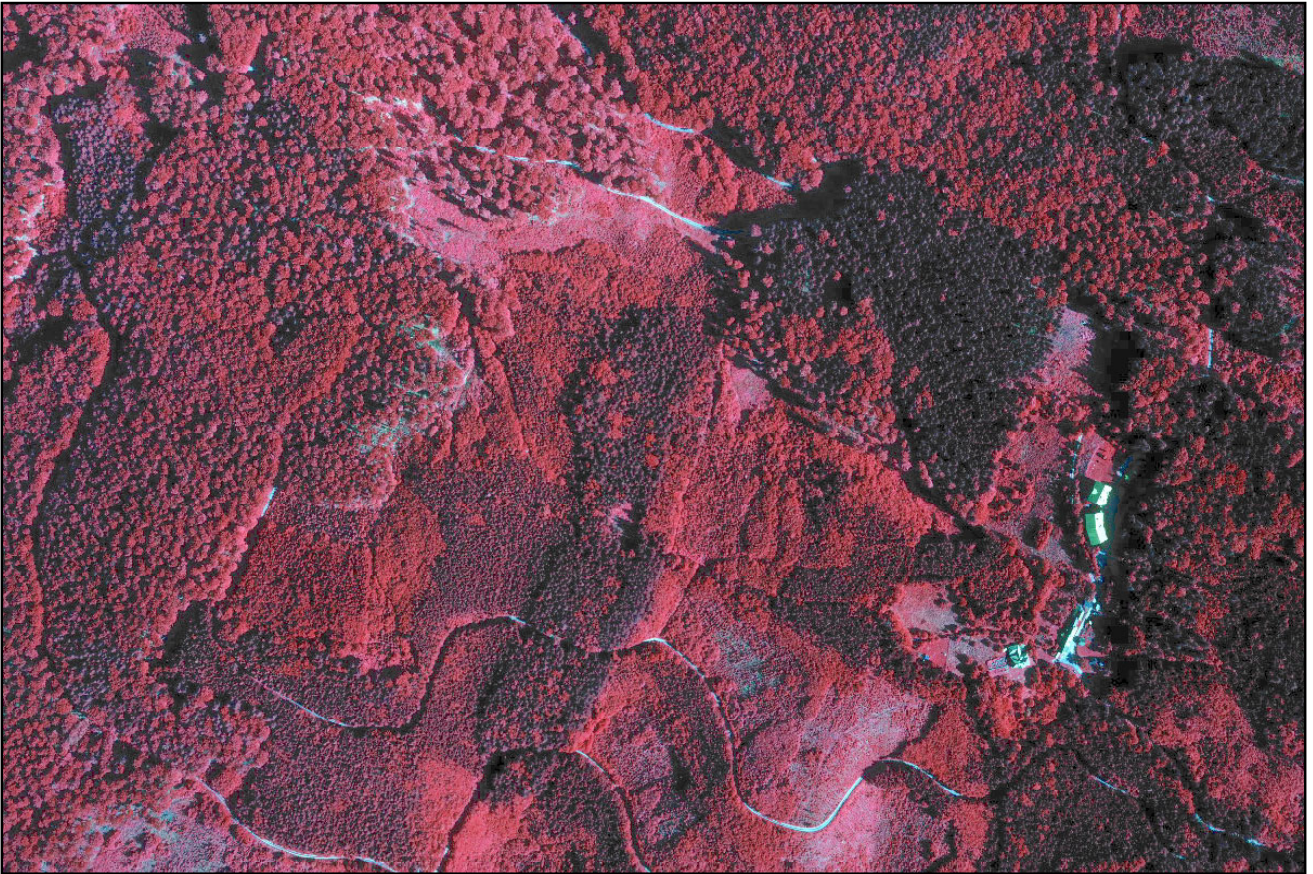
Figure 1 Digital ortho image (infrared) of the central part of the research forest.

- proportion of crown coverage for coniferous trees.

4 CHARACTERISTICS OF LASER DATA

4.1 Laser patterns of geometrically homogenous stands

The main "geometric characteristics" of forest stands that will be dealt with are

- mean stand height;
- tree species, grouped to deciduous / coniferous trees;
- proportion of basal area for coniferous trees;

Within the region of interest, 50 areas with geometrically homogenous vegetation of different types and ages, were chosen and their boundaries digitized. These sites are used to determine main characteristics of different tree species and size and to estimate crown coverage of conifers. Angle count samples were used to estimate stand heights and basal area proportions of conifers.
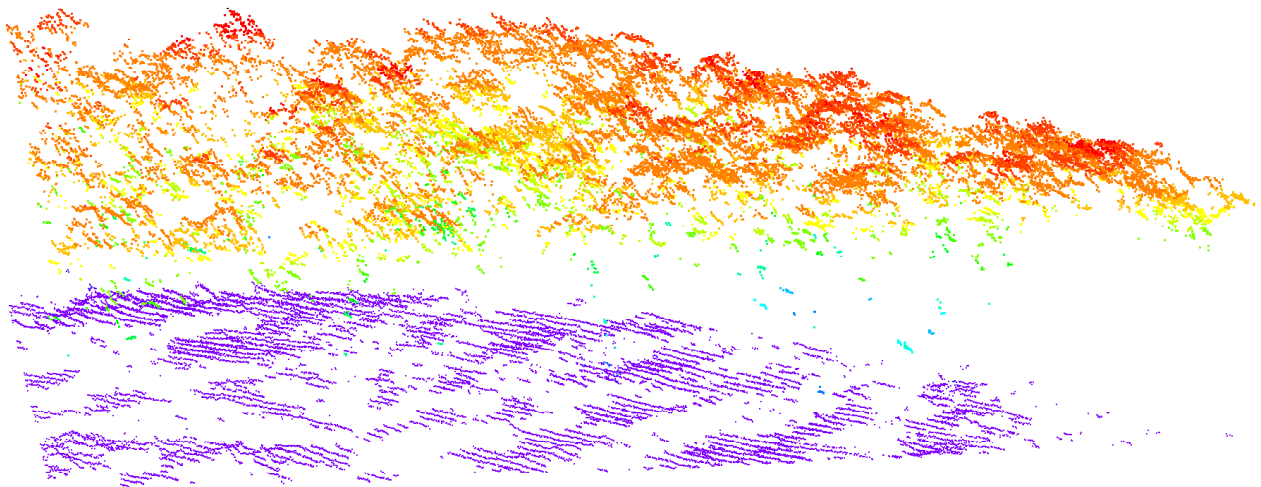

Figure 2 Perspective view of the laser dots for a mature beech stand. Signal: Summer first pulse. In the lower part the ground hits show the lines of flying strips. The "point clouds" in the upper part are crown zones of the trees. Gray corresponds to differing heights (original image was colored; dark areas are at the ground level and close to the peaks).

The three laser flights provide data with absolute (sea level) elevation. In contrast the reference tree data are given relative to the ground level. Thus the laser elevations must be reduced to the ground. This is done by interpolating a high quality ground model (DEM) from the laser data (Pfeifer, 1999). The laser elevations are then reduced by the DEM elevations at the respective positions. Figure 2 shows a perspective view of the laser dots of summer first pulse for a mature beech stand reduced to ground. Figures 3 to 5 show histograms and cumulative frequencies of the

relative elevations for the three flights, summer first (sf), summer last (sl), and winter last (wl), for three selected stands. The height interval for the classification (class width) is 1 m. The histograms are plotted with (tree) height vertically and relative frequency horizontally in order to give a better impression of the close connection between tree forms and (relative) number of reflected signals. The cumulative frequency curves show some typical patterns depending on the tree species:

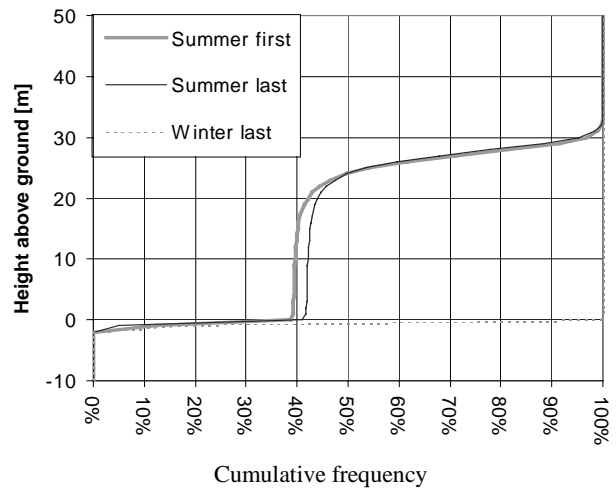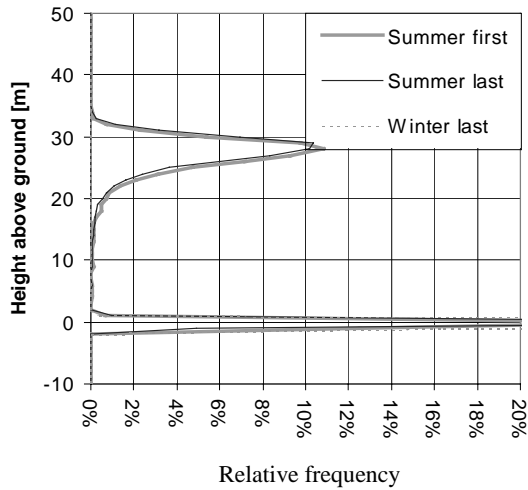- With deciduous trees there are no off-terrain reflections in

Figure 3 Histograms and cumulative frequencies of the tree heights above ground for the three flights for a mature beech stand.
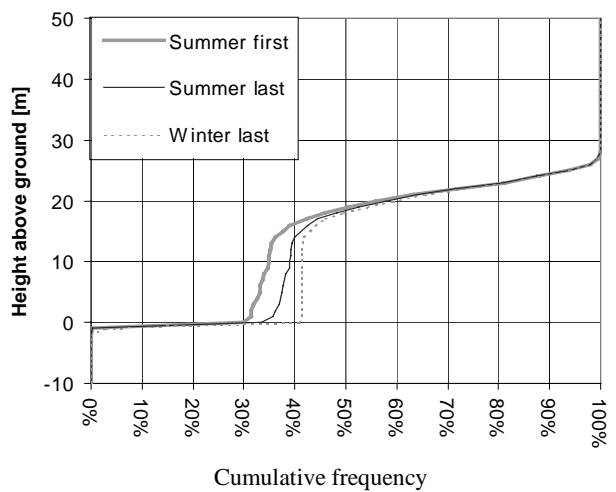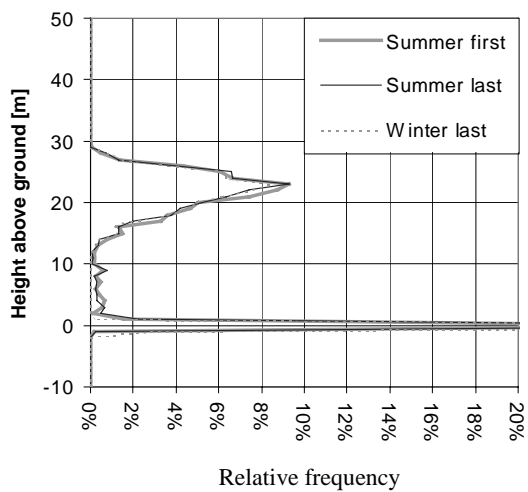

Figure 4 Histograms and cumulative frequencies of the tree heights above ground for the three flights for a spruce stand.
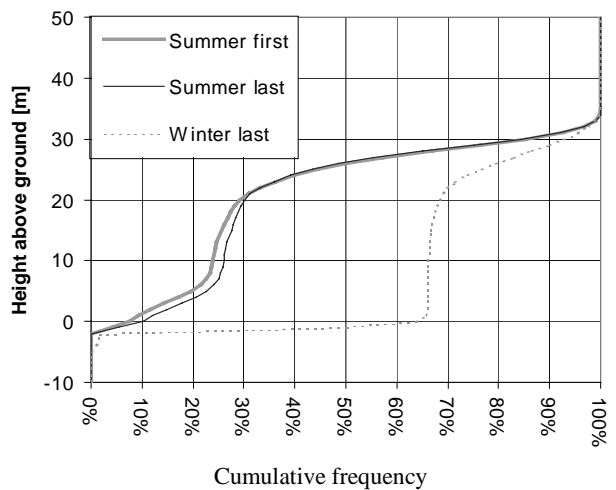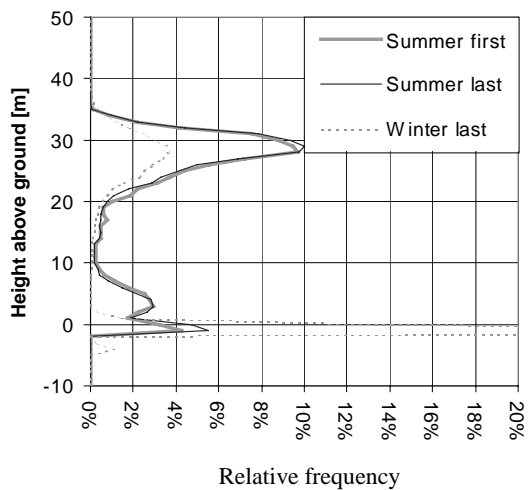

Figure 5 Histograms and cumulative frequencies of the tree heights above ground for a mixed spruce and beech stand.

winter last.

- Coniferous trees show very similar patterns in winter and summer.
- For both deciduous and coniferous trees, there is only a slight difference between summer last and summer first pulse.

The last observation shows that it does not make much sense to go to the extra effort of an additional first pulse flight. The TopoSys scanner does not allow to store more than one reflected signal at a time, so this can save costs.

The penetration rate can be estimated at different heights from the cumulative frequency curves. Results from 50 different stands showed that any penetration rate lower than 100 percent for deciduous trees in the winter last data can be explained by the presence of coniferous trees. The separation between deciduous and coniferous trees is thus very simple with both a winter and a summer flight. Since beech and fir are the dominant tree species in the project area, it was not possible to distinguish between different deciduous or coniferous tree species.

The penetration rate strongly depends on the number of reflected pulses. This is not a constant value. Rather, it depends on the intensity of the reflected rays; signals too low may not be recognized by the laser scanner. Figure 6 shows the number of reflected laser dots. The position of the flight stripes can be clearly recognized as well as different vegetation types. For coniferous trees, generally much fewer laser points are recorded than with deciduous trees. This is quite reasonable, since the laser scanner uses an infrared signal; it corresponds well to the intensity patterns observable in infrared images.

In the winter flight the difference between the two main tree species is much lower which can be partly explained by climatic conditions: The summer flight was undertaken after a long period of hot dry weather, while the winter flight followed a quite humid period. Obviously dry and eventually dusty needles are poor reflectors of the laser signal**.**
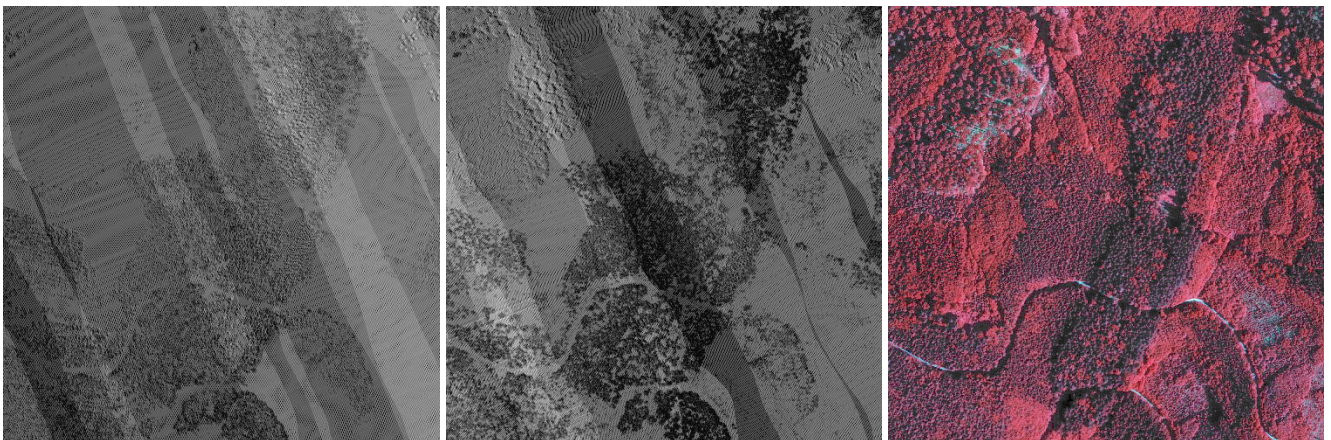
Proportion of crown coverage of coniferous trees

The 50 stands were used to estimate the proportion of conifers. For reference, the data of the forest management plan were used, checked, and eventually corrected with aerial photographs. The range is from 0 to 100 % in units of 10 %. The overall accuracy is unknown but is assumed to be less than ± 10 %. The results of the stepwise variable selection regression for the crown coverage proportion of coniferous trees, C_{CT}, is as follows;

$$C_{CT} = 83.0 + 0.989\ p_{WL} - 0.0202\ p_{WL}^2 + 0.00733\ p_{WL} \cdot p_{SF} \qquad (1)$$
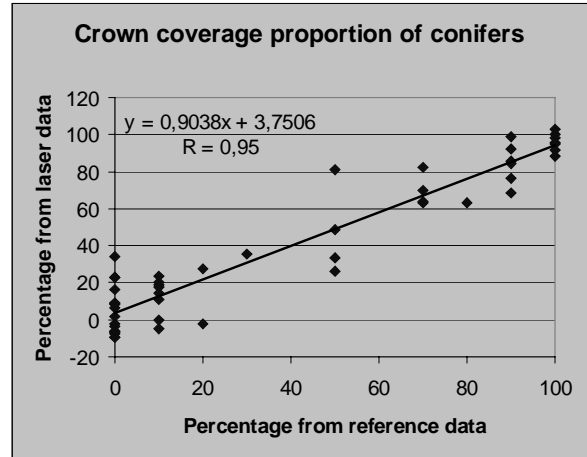

Figure 7 Crown coverage proportion estimated from laser data plotted against reference data which are in 10 % steps

with a regression coefficient R = 0.95 and a standard error of the estimates of ± 13.0 %. Again, compared to the accuracy of the reference data, the result is very good (Figure 7). There is a trend to underestimate the proportion of the conifers, which is partly due to the fact that holes are not considered in the method and thus their area is grouped with the deciduous trees. Taking into account the accuracy of the ground samples the results are very good (± 13% is scarcely less than the accuracy of the reference data). Note that equation (1) allows for negative values or values higher than 100% which certainly needs to be corrected. Yet, the method is simple and reliable.

Figure 6 Number of reflected laser dots per square meter as gray coded images. The values range from 0 (black) to more than 50 dots (white). **Left:** Winter last pulse; **Center:** Summer first pulse; **Right:** Digital ortho image.

4.2 Angle count samples

One hundred and ten angle count samples of the permanent forest inventory were used to estimate stand heights. The samples are permanently marked, and the coordinates of the center points measured at an accuracy of better than ±30 cm. For each of these points an angle count sample of 300 m^2 area with a basal area factor of 4 was collected according to (Bitterlich, 1948). For each contributing tree in each sample the distance, the diameter at breast height (DBH), and the tree height was measured. The latter was collected using the Bitterlich Relascope with a measurement accuracy of ±1.1 m for coniferous trees and ±1.7 m for deciduous trees (standard deviation).

The following common stand heights were estimated for each sample:

- The dominant height is represented by the mean height of the three thickest trees according to (Pollanschütz, 1971);
- the maximum height is represented by the mean height of the three highest trees;
- Lorey´s height, i./e. the mean height weighted by the stem area in breast height.

These values along with the basal areas were calculated in each sample for coniferous and deciduous trees separately. Statistics are shown in Table 1 for the 110 samples.

Variable	Mean	Std. dev.	Min	Max
Stem density [trees/ha]	671	449	175	2977
Basal area [m^2/ha]	38.4	8.3	16.0	64.0
Dominant height [m]	25.2	4.5	10.6	34.3
Maximum height [m]	28.0	3.9	19.5	36.7
Lorey´s height [m]	25.4	3.8	17.1	35.3
Lorey´s hgt. / coniferous [m]	26.2	4.2	15.9	36.0
Lorey´s hgt. / deciduous [m]	24.6	3.9	17.6	35.0

Table 1: Variables calculated from the 110 angle count samples

Estimating stand heights

Several methods to estimate stand heights from the laser data were investigated. These are compared with the terrestrially obtained height values.

For each of the angle count samples all laser points within the sample radius of 9,77 m (corresponding to the area of 300 m^2) were used to plot histograms as shown in Figures 3 - 5. Since the laser data show significant "noise" at the ground level, a height threshold of 3 m was chosen below which points are assumed to be ground points. The following variables were calculated from the histograms:

Name	Description
p	The penetration rate estimated as the percentage of ground points (height above ground lower than 3 m) from the total number of points;

mo	the mode;
me	the median;
std	the standard deviation;
m2	the quadratic mean;
sk	the skewness;
cu	the curtosis;
P90	the 90th percentile.
P95	the 95th percentile.

Table 2: Variables calculated from the laser data

Remark: The estimate used for the penetration rate is only a rough measure. The reflection rates of both ground and trees need to be taken into account in order to obtain a correct value. Unfortunately, these reflection rates are not known and may differ, therefore the simple measure as described above was chosen.

These variables are calculated for the three flights, obtaining the following indices:

WL	Winter last pulse
SL	Summer last pulse
SF	Summer first pulse

All reference heights (Table 1) were checked against the laser variables by a "stepwise variable selection regression" (software SPSS ®) with the reference height as dependent and all other values as independent variables. The results are given in Table 3.

dependent variable	independent variable(s)	correl. coeff.	std.err. of estimate
dominant height	$P90_{SF}$	0.812	±2.65 m
	$P90_{SF}$, p_{WL}	0.850	±2.41 m
maximum height	$P90_{SF}$	0.839	±2.11 m
	$P90_{SF}$, p_{WL}	0.877	±1.87 m
	$P90_{SF}$, p_{WL}, mo_{WL}	0.890	±1.79 m
	$P90_{SF}$, p_{WL}, mo_{WL}, sk_{SF}	0.896	±1.74 m
Lorey´s height / all trees	$P90_{SF}$	0.829	±2.14 m
	$P90_{SF}$, p_{WL}	0.880	±1.83 m
Lorey´s height for conifers	mo_{SF}	0.828	±2.32 m
	mo_{SF}, cu_{SF}	0.844	±2.23 m
Lorey´s height / deciduous trees	me_{SF}	0.881	±1.88 m
	me_{SF}, p_{WL}	0.896	±1.78 m

Table 3: Results of the regression analysis with absolute term.

The standard errors of the estimates range from ±1.7 m to ±2.7 m, which is relatively good compared to the mean standard errors of the terrestrial observations of ±1.1 m for coniferous and ±1.7 m for deciduous trees. Generally the tree heights correlate better with summer first than with winter last, which is reasonable. There is a strong relation between the 90th percentile and the maximum heights. The 95th percentile as being closer to the extremes does not correlate comparably well.

The mode correlates well with Lorey´s mean heights for conifers, while for deciduous trees the median is more reliable; this is

again reasonable since the frequency distributions are skewed to the right (approx. -1.1), thus the mode is larger than the median (by about 1.7 m), and this corresponds to the observation that coniferous trees tend to be higher than deciduous trees within a neighborhood.

Since the intercepts of the regression with only one independent variable do not significantly deviate from zero (with the exception of the maximum height), the same regression was done in a much simpler model without offsets, featuring only summer first pulse data. Normally a winter flight needs to be taken once, from which the ground model can be derived, which does not change over time. Consequently, only summer flights are necessary from time to time. Therefore it may be of particular interest to restrict the estimators to summer first pulse data.

The results are shown in Table 4. The regression is shown in Figure 8. Note that the coefficient for the regression without intercept is not a regression coefficient. Rather, it is the slope of the regression line and may reach values of higher than 1. Here it shows that the maximum height as estimated from $P90_{sf}$ is underestimated by 4 % (a value of 1.04) while the other heights are overestimated, especially Lorey´s mean height for deciduous trees, which is again, reasonable.

dependent variable	independent variable(s)	coeff. (slope)	std.err. of estimate
dominant height	$P90_{SF}$	0.939	±2.65 m
maximum height	$P90_{SF}$	1.040	±2.19 m
Lorey´s height / all trees	$P90_{SF}$	0.945	±2.16 m
Lorey´s h. / coniferous trees	$P90_{SF}$	0.972	±2.67 m
Lorey´s h. / deciduous trees	$P90_{SF}$	0.909	±2.53 m

Table 4: Results of the regression analysis without intercept.
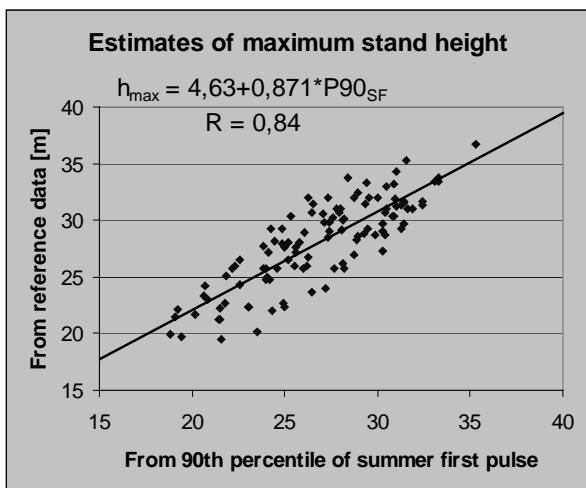

Figure 8 Estimates of maximum stand height from 90th percentile of laser flight summer first pulse

A systematic under-estimation of the tree heights as was observed by (Magnussen, 1998) and (Magnussen, 1999) could not be found, most likely due to the high point density of the laser scanner (6.85 compared to 0.2 points per square meter). Furthermore, the correlation coefficients are much higher than those of (Magnussen, 1999) who only reached values of 0.6 - 0.7

and standard errors of 3 - 4 m using recovering-models based on Weibull or on smoothed likelihood estimates.

Basal area proportion of coniferous trees

The basal area proportion of coniferous trees was estimated for the 110 angle count samples. The method is generally quite inaccurate, since the mean number of trees per angle sample is less than 10 in the test area; a slight shift of the sample point may drop a tree of some species and include a tree of another species which would significantly change the proportion. Thus, according to (Sterba, 1998), at least 3 - 12 angle count samples are necessary to estimate the basal area proportion of a stand with an accuracy of ±10 per cent (standard error).

The average basal area proportion of conifers for the test area is 62 % for all samples and ranges from 0 to 100 %. Again, stepwise variable selection regression was used successfully to provide a model for the basal area proportion of coniferous trees, B_{CT}. The resulting equation reads,

$$B_{CT} = 48.36 + 1.54\,p_{WL} - 0.0197\,p_{WL}^2 + 0.00728\,p_{WL} \cdot p_{SF} \qquad (2)$$

with a regression coefficient R = 0.86 and a standard error of the estimates of ±15.7 %. Compared to the accuracy of the ground samples, the result is very good and suggests that the estimate by the laser data is of similar accuracy as the estimate from the ground data. The values p_X are the penetration rates for the respective flights as described in Table 2. Figure 9 shows the regression. The massive underestimation of the proportion of conifers in some stands is due partly to the fact that holes are not considered. Furthermore, in most of these stands there are shrubs and shelter present, that are higher than 3m and cause significant reflection in winter last pulse flight. In order to obtain more reliable results, this regeneration vegetation needs to be considered.
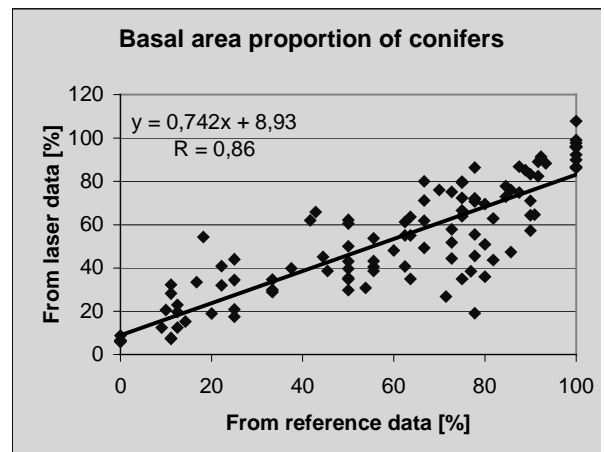

Figure 9 Estimates of basal area proportion of conifers according to equation (2).

5 CONCLUSION

Both the proportion of coniferous and deciduous trees and stand heights can be estimated with high accuracy compared to ground reference data. Better models for the area proportions may yield better results; the equations shown above may lead to negative area proportions or above 100 % for extreme penetration rates. The empirical stand height models need to be further checked for their robustness on other data. A theoretical model needs to be developed, although the 90th percentile is a reasonable variable as such.

6 ACKNOWLEDGEMENTS

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